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Book of Abstracts

International Conference on Resilient Systems (ICRS) 2026, Delft, The Netherlands

Editors

prof. dr. Tina Comes, prof. dr. ir. Remco Dijkman, dr. Jonas Jörin, prof. dr. Max Mühlhäuser, dr. Maria Pregnolato, prof. dr. dr. Christian Reuter, dr. Christian Schaffner

23- 25 March 2026

Preface

Gathering global experts in resilience, the International Conference on Resilient Systems (ICRS) 2026 will take place from 23 to 25 March 2026 in Delft, the Netherlands. Continuing the tradition of previous editions, ICRS serves as a vibrant meeting place for researchers, practitioners, and thought leaders from around the globe to exchange ideas on the design, analysis, and governance of resilient social-technical-environmental (STE) systems.

ICRS 2026 is organised by 4TU Centre for Resilience Engineering, consisting of Delft University of Technology, Eindhoven University of Technology, University of Twente, Wageningen University & Research; together with Singapore-ETH Centre, ETH Zürich, Technische Universität Darmstadt and DLR Institute for the Protection of Terrestrial Infrastructures.

The growing momentum within the international resilience engineering community is evident in this year's conferece. With 250 submissions, 200 accepted contributions, and participants from 47 countries across 5 continents, we are proud to present a program that reflects both quality and diversity, creating a truly international forum for interdisciplinary collaboration.

Homes, supply chains, and critical infrastructures are increasingly frequently disrupted by natural disasters, the effects of climate change, and geopolitical tensions. These events underscore the need for innovative approaches that not only anticipate disruptive events, but also enable systems to adapt and recovery from these events. Against this backdrop, the theme of ICRS 2026, "Resilience in an Age of Disruption," reflects the urgency of the topic of resilience engineering. This book brings together a collection of abstracts that present research that advances these goals.

The breadth of topics at ICRS 2026 illustrates the complexity of resilience in practice. Contributions span supply chain resilience, critical infrastructure, urban planning, AI and data-driven resilience, disaster risk management, energy systems, governance frameworks, and resilience assessment methodologies. A common theme across these topics is the 'engineering perspective', which focuses on the development of practical applicability of methods, tools, and techniques, and the creation of actionable insights.

We want to thank all authors, reviewers, track organizers, student assistants, and organizers whose help is indispensable in organizing this conference. Finally, we want to thank you, our reader. We hope that you find the research presented in these proceedings insightful and that it inspires you to continue to work towards a more resilient world.

On behalf of the Organizing Committee,
Prof.dr. Tina Comes, prof.dr.ir. Remco Dijkman, dr. Jonas Jörin, prof.dr. Max Mühlhäuser, dr. Maria Pregnolato, prof.dr.dr. Christian Reuter, and dr. Christian Schaffner

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Prof. Dr. Tina Comes
Director of the Institute for the Protection of Terrestrial Infrastructures at the German Aerospace Centre (DLR).



Prof. Dr. Ir. Remco Dijkman
Professor of Information Systems, Eindhoven University of Technology



Prof. Dr. Max Mühlhäuser
Technical University of Darmstadt, Telecooperation Lab (TK for short)



Dr. Jonas Jörin
Managing Director of the Illinois Advanced Research Center at Singapore Ltd.



Dr. Maria Pregnolato
Associate Professor at Delft University of Technology



Prof. Dr. Dr. Christian Reuter
Technical University of Darmstadt, Science and Technology for Peace and Security (PEASEC)



Dr. Christian Schaffner
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TABLE OF CONTENTS

1. Resilient Supply Chain . . . 9
   - Yvonne Lont: Analyzing maladaptation in supply chains . . . 9
   - Jan Walger: Integrating raw material data into company decision making . . . 11
   - Jaya Prasanth Rajakal: Resilience analysis for energy and water sector imports a Qatar case study 13
   - Surender Raj Vanniya Perumal: Macroeconomic impacts of single and multi hazards across European regions . . . 18
   - Oscar Kwame Sottie: Impact of high tech on economic performance and resilience of fruit and vegetable food systems a systematic review . . . 25
   - Shauhrat S. Chopra: National resilience for critical mineral value chains . . . 26
2. Infrastructure Utilities And Economic Systems . . . 27
   - Kristina Wolf: Enhancing transport system resilience during mass participation events . . . 27
   - Elco Koks: A rapid decision support tool to assess flood induced accessibility disruptions . . . 31
   - Surender Raj Vanniya Perumal: Critical infrastructure failure escalates the macroeconomic impacts of disasters . . . 36
   - Alberto Fernandez Perez: Pan european analysis of flood induced supply chain disruptions . . . 42
   - Elisa Nobile: Cascading economic impacts of critical infrastructure failures on supply chains . . . 46
   - Akaraseth Puranasamriddhi: The fiscal implications of probabilistic disaster risks to infrastructure 49
   - Marcello Arosio: Estimating (contingent) business interruption losses for insurance pricing. . . . 54
3. Resilience Of Infrastructure Systems . . . 61
   - Yunshan Wan: Predicting multi period flood cascades and community failure in ev charging networks 61
   - Eva Lotte Schriewer: Flash flood damage analysis of the rail road infrastructure . . . 62
   - Ann Kathrin Seyfried: Impact of diversity on energy system resilience . . . 63
   - Angela Ordonez: Integrative infrastructure management for municipality's climate resilience . . . 68
   - Max De Vries: Meaningful boundaries that enhance flood resilience a comparative study of three integrated flood risk management projects . . . 77
   - John C. Morris: Assessing local capacity in Alabama us to plan for climate resilient infrastructure 82
   - Shauhrat S. Chopra: Equitable resilience for social sustainable urban infrastructure . . . 86
   - Kevin Logan: Consumer impact on resilience of water distribution systems . . . 88
4. Resilience Of Coupled Energy And Transport Systems Under Deep Decarbonization . . . 93
   - Manuel Perez Bravo: Framework for climate resilient low carbon transport application to Spain . 93
   - Si Chen: Assessing the robustness of the urban transportenergy nexus evidence from the glasgow city region . . . 100
   - Denissa Sari Darmawi Purba: Evacuation behaviours of electric vehicle drivers route and charging choice experiments . . . 105
   - Denissa Sari Darmawi Purba: Vulnerability assessment of electric vehicles and charging stations network d . . . 111
   - Madhura Yeligeti: Monitoring future energy systems resilience during a heatwave . . . 116
5. Pathways To Resilient Sustainable Energy Systems . . . 120
   - Francesco Lombardi: Near optimal energy planning strategies with modelling . . . 120
   - Aleksander Grochowicz: Preparing for the worst long term and short term weather extremes in resource adequacy assessment . . . 121
   - Francesco De Marco: Climate resilient energy transition via surrogate assisted optimization . . . 131
   - Freja Bruncrona: Strategic resilience enhancement planning for future renewable power grids . . 135
   - Paul Runte: Structural indicators for quantifying power system resilience . . . 138
   - Dimitrios Pezaros: Securing digital twins at the energy transport nexus . . . 144
   - Francesco Sanvito: Resilient integrated transport energy system configuration spaces for deep decarbonization pathways . . . 148

Wolfgang Manner: Resilient scenarios for ghg neutral methanol imports to europe 153
Michel Obrist: Balancing the energy trilemma measuring energy supply security in the rheintal valley 158
6. Critical Infrastructure Resilience 160
Ali Cheshomi Finding bottlenecks before they trigger crises stress testing critical infrastructures systems for high impact low probability events 160
Marc Menne: Resilience based threat assessment to evaluate infrastructure protection 167
Stergios Mitoulis: Sustained resilience in prioritising critical infrastructure recovery in war impacted built environments 172
Mikhail Sirenko: From static maps to risk clocks spatio temporal labels for healthcare accessibility 178
Saimir Osmani: Integrated framework for risk and resilience assessment of critical transport infrastructures using traffic module analysis 182
Jonathan Sattler: A particle filter estimation of taylors law fluctuation scaling in water demand . 186
Beatriz Martinez Pastor: Operationalizing the capability approach in the context of critical infrastructure disruptions and resilience 189
Arto Niemi: Resilience assessment framework based on criticality and resilience properties 191
Jenny Martinez: A narrative based framework for power grid resilience assessment 195
Rui Teixeira: On the role of sensitivities in safety driven infrastructure systems 199
Maximilian Graser: Machine learning for power grid control a project for enhancing resilience through data quality 200
Rishwanth Darun Annamalaisamy Sannasiraj: Resilience in marine rc infrastructure global structural performance under depth dependent corrosion 203
Richard Dawson: Optimization of temporary and demountable flood protection strategies for resilient infrastructure systems 210
Sadhana Nirandjan: From risk to resilience assessing geophysical and climate vulnerability and adaptation strategies for transport infrastructure 215
Anna Klose: Climate risks for inland ports a two level analysis in the upper rhine region 220
Jens Reinert: Quantifying system limits flood oriented stress testing for adaptive risk governance 223
Mohammed Al Humaiqani: integrating extreme event attribution for the resilience of infrastructure networks in the hot climate conditions 226
Kevin Logan: Experimental validation of design and operation concepts for resilience in water distribution systems 232
Thomas Muller: Requirements analysis for a modern crisis communication system involving multiple stakeholders 237
7. Progressing Climate And Disaster Resilience 239
Alistair Ford: An integrated modelling framework for assessing climate risks and adaptation options for urban transport infrastructure 239
Daniel Peregrina Gonzalez: Impact of large scale pluvial flooding on an interdependent electricity and road network 243
Zizhen Xu: The impact of climate change on critical services accessibility during flooding 249
Derya Deniz: Seismic resilience of critical urban infrastructure lessons learned from the 2023 turkiye earthquakes 254
Gabriel Chikelu: Developing resilience strategies for ports against extreme weather events 257
Matheus Puime Pedra: Flood impact assessment through machine learning effectiveness of government interventions on economic loss reduction in s 258
Eleonora Panizza: Integrating sociocultural characteristics 262
Ines Hofmann: Systemic climate risk mapping in rural municipalities a semantic gis framework for vulnerability assessment and resilience planning 263
Jonathan Ciurlanti: Advancements in flood vulnerability models and risk assessments quantitative analysis of adaptation strategies for building 269
Steffen Neuner: From review to practice digital integration of bim and gis for multi hazard vulnerability analysis and climate resilience of b 273
Kyujin Kim: Integrated resilience and circularity assessment of building facade retrofit scenarios 278
Ahmed Owais Durrani: Strategic green roof implementation for pluvial flood risk reduction . . . 282
Hao Su: From challenges to solutions a framework for nature based solutions selection in deltas . 286
Margaret Kurth: Advancing engineering assessment planning and design to achieve natural infrastructure resilience 287
Sophie Charlotte Kuhlmann: Climate resilient water management in low range mountain areas . 288

Haripriya Kesavan: Accelerated delhi heat action with artificial intelligence ai and machine learning ml . . . 294
Garbhit Naik: Designing a serious collaborative learning game for flood resistant housing reconstruction in nepal . . . 301
Mohammad Zaher Serdar: Road network robustness under sea level rise a generalizable framework integrating geospatial modeling traffic simulat . . . 303
8. Shocks Shifts And Solutions . . . 310
Patience Saungweme Two sides of the same precarious coin addressing conflict climate crises through mindanaos lens . . . 310
Julien Magana: Would I help you if I needed to save myself? Local initiatives in disaster responses adding social cohesion urgency and motivation to help others to the Protection Motivation Theory . . . 312
Laszlo Vreedenburgh: Who stays who goes uncovering climate displacement dynamics with mobile phone data . . . 329
Josue Gnowa: Determinants of infrastructure access in refugee and internally displaced persons ridp settlements . . . 334
David Oliver Kasdan: Sunk costs sunk coastlines the argument for wholesale climate retreat and letting developments bygones be bygones . . . 341
Juha Pekka Japola: Future costs of climate change for humanitarian aid . . . 342
Invited speaker Mizuki Aosaki . . . 347
9. Complex Adaptive Social Systems . . . 348
Bruce Edmonds: Walking towards a cliff edge can a combination of participatory futures and agent based modelling approaches help make ses tipping points feel real . . . 348
Rosewine Joy: Assessing global vulnerability to natural disasters a structural equation modeling sem analysis of the world risk index . . . 351
Franziska Stefanie Hanf: Understanding socio ecological urban flood risk complexity using causal loop dia . . . 355
Eefje Hendriks: Using household motivations abilities and opportunities to customize humanitarian assistance for hazard resistant housing . . . 356
Mahshid Khazaeiathar: Predicting short length discharge data using fuzzy logic models . . . 357
Asmaa Maaroufi: Moroccan local adaptive systems balancing resilience and development . . . 360
Shangjia Dong Mobility data driven assessment of dialysis access and resilience . . . 363
Ylenia Casali: Flood robustness of urban road networks across geographical contexts . . . 368
Richard Dawson: A geospatial generative adversarial network approach for future urban and infrastructure resilience . . . 370
Aulia Imania Sukma from households to communities collective action pathways for equitable heat adaptation . . . 375
Sylwia Widzisz: Pronobis managing grassroots initiatives in the context of spatial change and public health . . . 380
10. Resilience Assessment Methodologies . . . 384
Mila Van Druten: Social vulnerability methodology for panama canal climate risk assessment . . . 384
Shreya Deep Bansod: High frequency survey data reveals the role of infrastructure in shaping household vulnerability and resilience to climate shocks evi . . . 389
Su Li Heng: The heat is on a scenario based resilience framework to capture community and planning perceptions and priorities for urban heat . . . 394
Christoph Euringer: Valuing water co productively a value led approach to drought resilience in the eastern netherlands . . . 400
Emily Voigt: How climate resilient is the maldives water system insights from a socio metabolic risk smr analysis . . . 405
Michaela Lestakova: Monitoring water distribution systems for resilience using unknown input observability . . . 408
Floris Van Steijn: Measuring adaptation to successive disruption in multiple performance dimensions 412
Joel Mongeon: Graph theory based resilience framework with regionalized lca data to quantify sustainability resilience trade offs in agri food systems . . . 416
Nicholas Currie: A practical approach to multiscale resilience modelling . . . 419
Sarhang Abdalrahman: Structural vs nonstructural roles in seismic resilience ai based managerial trade offs in rc frames . . . 422

Simona Bianchi: Harmonizing methods for multi hazard resilient buildings from risk matrices to uncertainty based frameworks . . . 426
Martina Piefke: Human factors resilience methods of assessment and training of resilience in security agencies and organisations . . . 430
Thi Thanh Nguyen: Explore aspirations and capabilities theory in migration in moroccan oases under drought an agent based approach 2 . . . 433
Seyed Ashkan Zarghami: Optimizing project resilience balancing costs and benefits . . . 436
Renate Schubert: Assessing social resilience through archetypes methodology and insights from singapore . . . 438
Sevan Gerard: A lens for resilience applying the sociotechnical ecosystem framework to complex adaptive systems . . . 441
Maren Jabs: Assessing regional drought resilience crossing sectoral and federal borders . . . 446
11. Digital Resilience . . . 451
Amal Aldawsari: Optimization under attack resilience vulnerability and the path to collapse . . . 451
Shamira Ahmed: Quantum information and communications technologies ecosystems as drivers of digital resilience case study of the netherlands . . . 455
Isabel Florence Franke: Resilient emergency response in human AI teams a systematic review of information prioritization strategies and metrics . . . 459
Markus Sommer: REC: resilient edge computing in emergency scenarios . . . 466
12. Digital Foundations Of Resilient Built Environments . . . 470
Erica Arango: Digital twins in flood resilience: potential challenges and reliability for urban applications . . . 470
Hamed Hafeznia: Simulation informed learning for surrogate models of infrastructure resilience . . . 474
Wei Bi: Advancing network modelling for flood resilience assessment of urban rail transit under power dependencies . . . 478
Matthew Joyner: Digital twins for resilience adaptation of buildings to thawing permafrost . . . 480
13. Best Practices And Innovation Potential For Enhancing Urban Resilience . . . 481
Huangbin Liang: Resilience oriented value of structural health monitoring for infrastructure systems 481
Emlyn Yang: Dynamic and interactive modeling of social resilience to flood impacts in the mekong river basin . . . 486
Thanh Phuoc Ho: Enhancing urban flood resilience through governance and institutional innovations a case study of can . . . 487
Aashly Vs: A review of global and indian frameworks for urban flood resilience . . . 488
Mikhail Sirenko: Its not just risk its responsibility changing drivers of home flood protection . . . 492
Marcin Korecki: Allotment gardens for urban resilience . . . 493
Joachim Schulze: Prototype Litfasssaule 4.0 - An integrated approach to building urban resilience 495
14. Resilience Of Local Authorities . . . 500
Niklas Frings: Analysis of intra and interorganizational interdependencies in municipal crisis management . . . 500
Sandra Maria: Pichler disasters as critical moments towards a field theoretical approach to the resilience of disaster management . . . 503
Alexandra Schmitt: Assessing and enhancing crisis management in german municipal administrations . . . 507
Gertrud Alirani: Institutional transformation under external pressure reconstructing civil defence within a swedish county administrative board . . . 511
Paula Gnielinski: Eroding administrative capacity understanding the creeping crisis in public administration . . . 514
Jurgena Kamberaj: Civil protection exercises as laboratory of governance . . . 517
Timm Wielgosch: Enabling resilient decision making through effective information management . . . 521
Ali Nejat: Local government resilience lessons from post disaster recovery in three u.s. states . . . 527
Fynn Spilling: Resilience at the heart of crisis management evidence for crisis management teams in public administration . . . 530
Sophie Kolmodin: Resilience in the making temporal perspectives on local disaster and civil defence management in sweden . . . 534
Maike Vollmer: Increasing resilience of state and public administration in germany sustainably and continuously . . . 537
Mrudhula Koshy: Rethinking adaptive and robust disaster risk self governance mechanisms as a leverage for addressing complex trade offs during disasters i . . . 541

Felix Martin: Investigating risks in the event safety process using fault tree analysis 545
Alexandra Schmitt: Krisenfit assessing and enhancing crisis management in german municipal administrations 550
Kai Fischer: Simulative resilience quantification of public administrations and organizations with safety and security responsibilities 554
Detlef Kurth: Resilient neighborhoods integration of resilience aspects into urban development plans in ukrainian cities 558
15. Resilience Social Structures And Transformation 561
Camilo Andres Benitez Avila: resilience reproducing urban organizing legacies conceptualizing indetermination structuration and institutio 561
Elena Lomeli Aguirre: Nested agency and the human architecture of resilience 565
Aditi Natarajan: Re-imaginaries of resilience: feminist perspectives on politics of socio cultural transformation 567
Ereesha De Silva: Gendered resilience and road infrastructure: social structures flood vulnerability and transformation: a case study from Sri Lanka 570
Joel Mongeon: Fairness as a lever for food system resilience insights from west African value chains 575
Juan David Parra: Scrutinizing the global learning crisis a cartography of literature through a critical realist pedagogy of crisis (PoC CR) framework 581
Diana Martin: Engineering responsibility and the ethics of structural change: a macro object perspective on resilience 585
Marcin Korecki: Distilling resilience 587
Thijs Heijmeskamp: The ethics of rotterdam resilience 589
16. Open Track 592
Pechladda Pechpakdee: From canal to commons participatory revitalization and social innovation for community resilience in Bangkok's samsen corridor 592
Thomas Muhlbradt: Resilience assessment with behavioral markers in healthcare 598
Milad Zamanifar Desilience when resilience interventions create further risks 602
Ann Kristin Winkens: Bridging resilient systems and education: a multi year case study on fostering resilience thinking in engineering 607
Niels Van Vliet: Inclination effects of timber foundation piles in urban quay walls: a finite element study on the marnixkade case 611
Julian Schindler Autonomous road vehicles at disasters threat or solution 617
Rhea Srivastava: Rethinking resilience in interdependent urban infrastructure systems 622
Valentina Palermo: Enhancing climate resilience in european cities insights from the covenant of mayors initiative 623
Verena Florchinger: Enhancing Community-Centered Psychosocial Crisis Management through Network-Orientated Approaches 629

1. Resilient Supply Chain

Analyzing Maladaptation in Supply Chains

Yvonne Lont

Abstract

Geopolitical conflicts compel organizations to adapt supply chains; however, recent evidence shows adaptations may backfire (this is known as maladaptation). Maladaptation, per the IPCC, increases vulnerability; thus, measurement is essential yet lacking. To fill this gap, we integrate climate and supply chain theory and propose an exploratory modelling metric. Exploratory modelling systematically varies simulations to reveal relationships and worst cases. Building on this, we develop an ABM-DES of managers and workers across three organizations. Parameters capture disruption dynamics and delays. We test sequential and assemble-to-order configurations under gradual shifts, demand peaks, and regime changes. Therefore, our results guide resilient, non-maladaptive adaptation.

Keywords **:** *maladaptation; adaptation process; supply chain resilience; evaluation method*

Introduction

Climate shocks and geopolitical conflicts increasingly force businesses and public organizations alike to adapt their supply chains. Conventionally, these dynamic adaptations to a changing environment are thought to ensure supply chain viability in the long run. However, emerging evidence from COVID-19 shows that these adaptation efforts can even have adverse consequences—a phenomenon known in climate change literature as *maladaptation*.

Maladaptation, as defined by the IPCC (IPCC 2023), refers to adaptation actions that inadvertently increase vulnerabilities or create new risks. Understanding when and why maladaptive outcomes occur is critical for improving adaptation strategies. However, there is to date no method to measure maladaptation in supply chains, and to understand how different supply chain structures drive maladaptive outcomes.

To address these gaps, theory from climate change and supply chain literature is combined to propose a metric and assessment method based on Exploratory Modelling. Exploratory Modelling involves the systematic exploration of a wide range of scenarios by varying model parameters in a simulation to analyze relationships between variables and identify potential outcomes, including worst-case scenarios.

Methods

The researchers developed an agent-based discrete event simulation model (ABM-DES) to simulate the adaptive behavior of actors in the supply chain. The model extends Epstein's model of Growing Adaptive Organizations (Epstein 2006). The model defines three organizations with two types of actors: managers and workers, where managers coordinate and make adaptation decisions based on their performance level. Input parameters include variables that influence disruption dynamics and adaptation behavior, like causing delays in information transfer and changing the structure within an organization.

The researchers investigate supply chain adaptive actions in various types of configurations such as a sequential chain and an assemble-to-order configuration. These configurations are exposed to three distinct patterns of shocks: a continuously evolving environment with gradual changes, a pattern characterized by demand peaks and a sudden regime shift. The experiments aim to explore how each configuration responds to these shocks and to identify conditions under which maladaptive outcomes might arise.

Conclusions

The study contributes to the field of supply chain resilience by providing critical elements for measuring and understanding the emergence of maladaptation. Using a stylized case study inspired by a military supply chain organization, the study demonstrates how the proposed method analyze the impact of disruption patterns and different supply chain structures. By assessing short- and long-term adaptations, the method identifies conditions under which maladaptive outcomes may arise. Managers may use this method to evaluate objectives, such as the speed to recover, and to adapt more effectively by understanding how maladaptation emerges.

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Integrating raw material data into company decision-making

Jan Walger [1], Luis Alberto Tercero Espinoza [2]
1 Fraunhofer ISI, Germany, jan.walger@isi.fraunhofer.de
2 Fraunhofer ISI, Germany, luis.alberto.tercero.espinoza@isi.fraunhofer.de

Abstract

The global demand for mineral raw materials is accelerating, driven by climate policy, energy transition, and industrial growth in emerging economies. Supply chains have become longer and more complex in the face of globalization. Consequently, the European manufacturing sector is highly dependent on imported raw materials sourced from highly concentrated markets. While policy initiatives such as the EU Critical Raw Materials Act seek to strengthen strategic autonomy, in the global context of the supply chains the options for individual companies to reduce risks are limited not only by their scale compared to the scale of raw materials markets overall but also by the paucity of actionable insights available.

Especially small and medium-sized enterprises with their limited resources are at a disadvantage when it comes to understanding and managing raw material supply risks. Yet integrating supply-risk data into the decision-making processes is crucial to strengthening the company's resilience. These decisions can be about the material composition of products, company raw material inventory levels or use of financial products to secure raw material prices.

Our aim is to develop a holistic approach to using existing criticality and resilience data in digital tools for decision-making. We pilot the approach in cooperation with five Fraunhofer Institutes in the development of a digital ecosystem for resilient and sustainable supply of functional raw materials. The challenge is linking global data, such as market concentration, import dependence or supplier-country risks, to product-level decisions. We propose devising an intermediate level that sets the individual context of the company the decision is made by. A first test case for product-level decisions is the adaptation of different material compositions for the stainless steel used in bipolar plates. By using a technological demonstrator as a proxy for a manufacturing company, we aim to include individual vulnerabilities and resilience capacities into the decision-making process.

The overall framework includes charting risk pathways from raw materials markets to company impacts, leading to realistic options to increase company resilience. Herein, we focus on the first element of this framework, namely, achieving a better understanding of the risk pathways linking underlying global causes to risk events and impact on a company by modeling cause-and-effect relationships of the risk pathways. Risk events are discrete occurrences, such as export restrictions, natural disasters, strikes, or logistics disruptions in the raw material supply chain, with a measurable impact on the company. After thorough research, we selected the five impact categories at company level (1) increased production costs, (2) production downtime, (3) reputational damage (4) reduced product quality, and (5) contractual/legal penalties to show the coupling of the different categories to risk events and to one another.

Since the overall aim of the work is to provide options at the company level, we also explore the significance of dampening and amplifying factors involved in the identified cause-and-effect relationships. The factors we test include purchase volume, value creation potential compared to international competitors, inventory size, share of long-term purchase agreements and access to financial instruments like hedging. Modelling the risk pathways should allow us to visualize and test the application and limits of preventive and reactive measures. This should show how risk exposure to the company can be reduced and where the limitations of the measures lie depending on the risk pathway.

To increase the resilience of the European manufacturing industry the raw material supply risks must be considered at company level. Reducing the complexity of the implementation for small and medium-sized enterprises is a key step. To address this, we aim to establish a set of company

indicators that can complement the global raw material supply risk data when assessing the individual supply risk, and the modelling described above constitutes the basis for it.

Keywords: Supply risk; Resilience; Criticality; Digital tools; Company perspective;

Resilience Analysis for Energy and Water Sector Imports: A Qatar Case Study

Jaya Prasanth Rajakal[1], Dhabia M. Al-Mohannadi[2]
College of Science and Engineering, Hamad Bin Khalifa University, Doha, Qatar, jvasudevan@hbku.edu.qa
College of Science and Engineering, Hamad Bin Khalifa University, Doha, Qatar, dalmohannadi@hbku.edu.qa

Abstract

The oil and gas, power, and water sectors are identified as critical sectors in Qatar. The planned expansions and continuous operation of these critical sectors remain highly dependent on imported machinery, equipment, replacement parts, and spares. Qatar's limited domestic capacity to meet these demands coupled with recent global supply chain disruptions have increased the risks associated with maintaining stable operations and pursuing planned expansion. This study aims to evaluate the import risks of machinery, equipment, replacement parts and spares related to oil & gas, power, and water sectors by accounting for the probability, exposure, and impact of risks. The study uses Herfindahl–Hirschman Index, volume of import, and degradation of system performance as indicators to quantify probability, exposure, and impact of risk. The generated values for each indicator are plotted in a 3-dimensional graph, which serves as a useful tool to derive insights into characteristics of risks associated with each import category. The characterisation would enable towards developing targeted policy support to strengthen the resilience of critical sector supply chain.

Keywords: Risk Analysis; Critical Sectors; Resilient Supply Chain

Introduction

The oil and gas (OG), power, and water sectors are identified as critical sectors in Qatar. The OG sector is a major driver of Qatar's economy. Power and water sectors are also crucial in supporting the growing manufacturing base in the country. It is worth noting that Qatar relies on energy intensive desalination process to meet the industrial and domestic water demand, further integrating the power and water sectors. However, the planned expansions and continuous operation of these critical sectors remain highly dependent on imported machinery, equipment, replacement parts, and spares. It is worth noting that such machinery and components account for about 30% of Qatar's total imports in 2023, highlighting the scale of this dependency (NPC, 2025). Given the country's limited domestic capacity to meet these demands coupled with recent global supply chain disruptions, the risks associated with maintaining stable operations and pursuing planned expansion have increased. This creates systemic vulnerabilities that could cascade to other sectors in the economy. Ensuring the resilience of these supply chains is therefore essential not only to establish a robust OG, power, and water sectors but also broader stability in Qatar's economy. Therefore, this study aims to

evaluate the import risks of machinery, equipment, replacement parts and spares related to O&G, power, and water sectors.

Risks can be conceptually defined as shown in Eq (1). It can be noted that risk is a function of three dimensions: likelihood of occurrence (probability), the extent of system vulnerability (exposure), and the severity of the consequences (impact of the risk) (Yeh et al., 2025).

$$Risk = f(Probability, Exposure, Impact) \quad (1)$$

Several indicators are proposed in the literature to quantify the three dimensions. For instance, indicators considered for probability of risk include concentration of resources, political stability, climate change, regulations, etc (Hosseini et al., 2016). Likewise, the exposure to risk is quantified using strategic reserves, consumption volume, population using the material, etc (Hosseini et al., 2016). Finally, indicators used to measure the impact of a risk include changes in system performance, revenue impacted, amongst others (Hosseini et al., 2016). It can be noted that certain indicators have been interchangeably used across dimensions. For example, import dependence has been used as indicator for both probability and exposure. Several works in the literature have used these indicators to evaluate the risks associated with import of food, crude oil, critical minerals, etc. However, none of the previous works have characterized the risk of disruption in the imported supplies by holistically accounting for the three dimensions. Moreover, very limited works have assessed the imports of machinery, equipment, replacement parts, and spares for critical sectors, where impact of risk on system performance has larger implication on the economy. Therefore, this study accounts for the probability, exposure, and impact of risks in evaluating the critical import categories.

Methodology

As discussed above, the risk considered in this study is the disruption in the supply of imported machinery, equipment, replacement parts, and spares used in OG, power, and water sector. At first the dataset on import categories for critical sector were extracted from the trade database published by National Planning Council of Qatar (NPC, 2025). The dataset included 29 import categories which are presented in Table 1.

Table 1. Critical Sectors Import Categories

Import Categories			
Boiler Equipment	Heating Units	Sealing & Fastening Components	Spares (Turbine)
Gas Generators	Material Handling	Separation Units	Structural Components
Industrial Fans	Mechanical Components	Spares (Boiler)	Surge Protection
Drilling Equipment	Pipeline Components	Spares (Drilling Equipment)	Transformers
Drilling & Completion Fluids	Pipes (Metal)	Spares (Heating Units)	Turbine
Electrical Cables	Pipes (Polymer)	Spares (Material Handling)	
Electrical Panel	Pipes (Rubber)	Spares (Pump)	

Electrical Switching	Pump	Spares (Separation Units)	

Later, the indicators to quantity the probability, exposure, and impact of risk is determined based on the availability of data and relevance to Qatar's context. These include:

- The probability of risk for the different import categories are evaluated using Herfindahl–Hirschman Index (HHI). It is an established statistical methodology used to analyse market concentration in economic analysis (Peleckis, 2022; Brown, 2018). High import concentration represents a higher probability of supply disruption, as reliance on a limited number of trading partners exposes the supply chain to risks. HHI values for import categories $i \in I$ for the period t, $X_{i,t}^{\text{Probability}}$ is estimated as shown in Equation (1)

$$X_{i,t}^{\text{Probability}} = \left(\sum_{j=1}^{J} \frac{y_{i,j,t}}{Y_{i,t}} \right)^2 \qquad \forall i \qquad (1)$$

  where, $y_{i,j,t}$ (QAR) is the import of category $i \in I$ from country $j \in J$ during period t and $Y_{i,t}$ (QAR) is total import of category $i \in I$ during period t.
- The exposure of critical sectors to supply disruptions is measured using the volume of imports (number of units imported), which serves as an indirect indicator of the scale of machinery, equipment, and spares utilized within these sectors. The import volumes are normalized to a scale of 0 to 1 to enable comparability across import categories. The normalized values of import categories $i \in I$ for the period t, $X_{i,t}^{\text{Exposure}}$ is estimated as shown in Equation (2)

$$X_{i,t}^{\text{Exposure}} = \frac{F_{i,t} - F_t^{\min}}{F_t^{\max} - F_t^{\min}} \qquad \forall i \qquad (1)$$

  where, $F_{i,t}$ is the volume of imports categories $i \in I$ during period *t*. $F_t^{\max}$ and $F_t^{\min}$ are the maximum and minimum recorded import volumes across all categories $i \in I$ during period *t*.
- The impact of risk was assessed based on the change in system output, which was qualitatively determined through expert judgment. Subject matter experts ranked the severity of disruptions across critical import categories using the scale provided in Table 2.

Table 2. Criteria to rank system degradation of import categories

Score	Category	Description
0.9 – 1.0	Critical	Sector operations are highly dependent; disruption would directly halt production or critical operations.
0.6 – 0.8	High Importance	Disruption would cause major delays or outage, leading to reduced output or interruptions in supply.
0.3 – 0.5	Moderate	Disruption would slow down projects or reduce efficiency, but production and core operations could continue.
0.0 – 0.2	Low	Disruption would have limited short-term impact, with minimal effect on ongoing operations.

It is to be noted that the exposure and impact dimensions are quantified relatively between the import categories and are not absolute values. The estimated values for each import category across the three dimensions are plotted in a 3-dimensional graph.

Results

Figure 1 shows the values of the HHI (probability), volume of imports (exposure), and system output degradation (impact) presented in a 3-dimensional plot. The plot serves as a useful tool to derive insights into characteristics of risks associated with each import category. Table 3 presents the risk characteristics of the import categories. The risk characteristics are inferred based on the criteria shown in Table 4. The identification of risk profiles of import categories enables targeted policy support that strengthens the resilience of supply chain for critical sector imports.

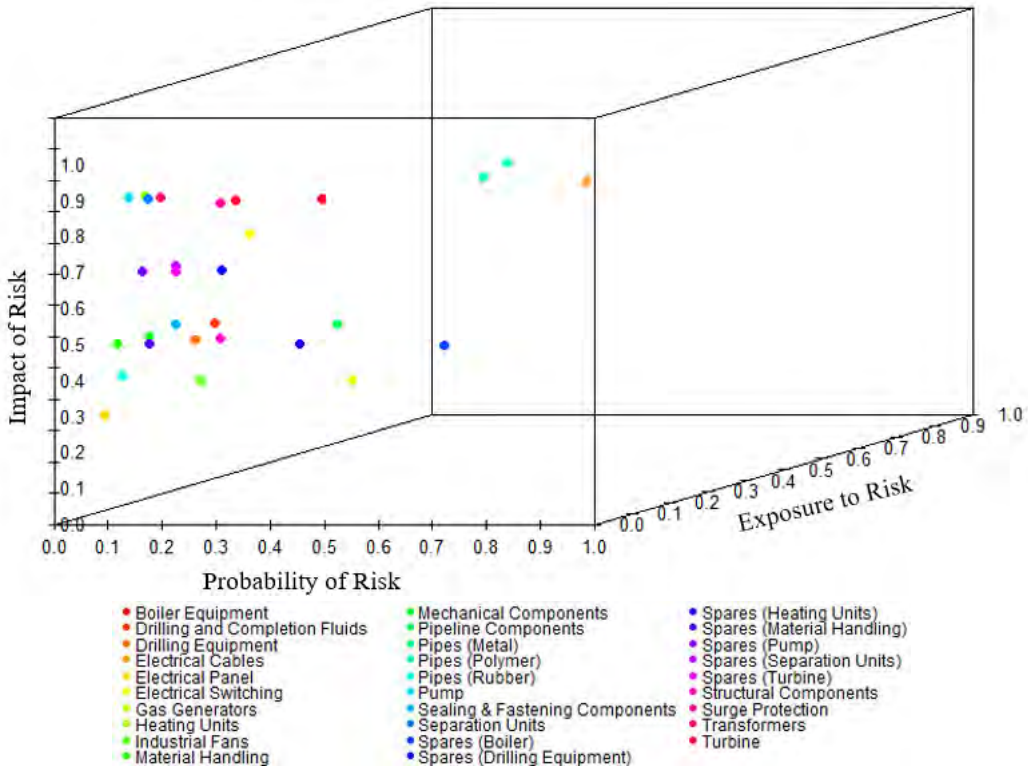


Figure 1. Risk of Critical Import Categories

Table 3. Risk Characteristics of Critical Import Categories

Probability	Exposure	Impact	Import Category
Low	Low	Low	Drilling & Completion fluid, Drilling Equipment, Electrical Panel, Material Handling, Mechanical Component, Pipes (Rubber), Sealing & Fastening Components, Spares (Material Handling)
Low	Low	High	Heating Units, Pumps, Separation Units, Spares (Separation Units), Spares (Pumps), Spares (Turbine), Transformer
Low	High	Low	Pipeline components
Low	High	High	Electrical Switching, Surge Protection, Pipes (Metal), Pipes (Polymer)
High	Low	Low	Gas Generators, Industrial Fans, Structural Components, Spares (Heating Units), Spares (Boiler)
High	Low	High	Boiler, Electrical Cables, Turbine, Spares (Drilling Equipment)

Table 4. Classification of Risk Characteristics

Dimension	Indicator	Low	High
Probability	Herfindahl–Hirschman Index	≤ 0.25	> 0.25

Exposure	Volume of Imports (normalized)	≤ 0.20	> 0.21
Impact	Degradation of system performance	≤ 0.60	> 0.60

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Macroeconomic Impacts of Single and Multi-Hazards across European regions

Surender Raj Vanniya Perumal [1], Mark Thissen [2, 3], Marleen de Ruiter [1], and Elco E. Koks [1]

1 Institute for Environmental Studies (IVM), Vrije University Amsterdam, Amsterdam, The Netherlands;

2 Spatial Economics, Vrije Universiteit Amsterdam, The Netherlands;

3 Netherlands Environmental Assessment Agency (PBL), The Hague, The Netherlands.

Abstract

Disasters frequently disrupt supply chains, generating cascading effects that propagate across regions and sectors. In this study, we develop a Dynamic Multi-Regional Impact Assessment (DMRIA) model to estimate the temporal evolution of disaster-induced macroeconomic impacts. The DMRIA model builds upon the MRIA model developed by Koks & Thissen (2016) and later extended by Raj et al. (2025). While the MRIA model incorporates regional substitution subject to sectoral production capacities and interregional logistical capacities available, it is formulated as a static model and therefore does not represent the dynamic adjustment of capacities. DMRIA addresses this limitation by taking into account the evolution of production and logistical capacities endogenously, thereby providing a dynamic representation of the macroeconomic consequences.

Using the DMRIA model, we perform a spatial criticality analysis of disaster impacts across NUTS-1 regions of Europe. In this analysis, supply shocks are imposed on individual regions, and the resulting macroeconomic impacts are quantified. The analysis is further extended to multi-hazard scenarios, where shocks to two regions are imposed simultaneously to capture the amplified impacts. Finally, the model will be used to evaluate the effectiveness of economic resilience measures including increased production extension capacities, trade flexibility between regions, inventory capacity, and interregional participation in mitigating the disaster impacts. We believe the results will provide an evidence base for EU policymakers to identify regions of less redundancy, prioritize capacity-building, and design targeted resilience strategies to strengthen regional economic systems.

Keywords: disasters, macroeconomic impacts, economic resilience, input–output analysis, multi-hazard

Introduction

With climate change intensifying, the frequency and severity of natural hazards are expected to rise. The hazard impacts often extend beyond directly affected areas, cascading through interconnected global supply chains. For instance, tropical cyclones disrupt microchip production in Taiwan and triggering global ripple effects in the electronics sector (Allianz Research, 2024). To capture such multi-regional effects, macroeconomic models such as the Multi-Regional Impact Assessment (MRIA) model are increasingly important (Koks & Thissen , 2016). In this study, we develop an updated Dynamic MRIA model that accounts for the time-dependent evolution of regional substitution capacities. We then apply the model to European regions to assess the impacts to single and simultaneous hazards by inducing supply shocks, and also evaluate how resilience measures, such as inventories and inter-regional substitution can mitigate economic losses.

Methods

Figure 1 illustrates the conceptual framework through which disaster impacts can be mitigated via regional substitution. Consider the case where Region 1 experiences a supply shock of magnitude *s%*. In the absence of interregional trade (Case 1), recovery is solely dependent on Region 1's endogenous capacity restoration, resulting in prolonged demand shortages. In contrast, when Region 2 possesses the ability to expand production and export to Region 1, demand shortages can be reduced rapidly. However, the rate of recovery depends on the rate of production extension and the available logistical capacity in Region 2.

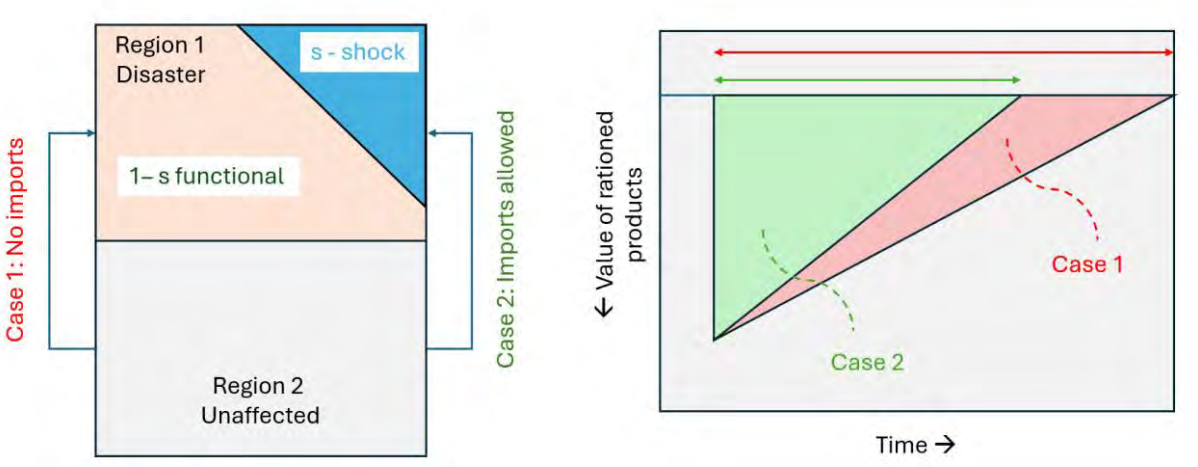


Figure 1. Effect of regional substitution in mitigating macroeconomic impacts of disaster

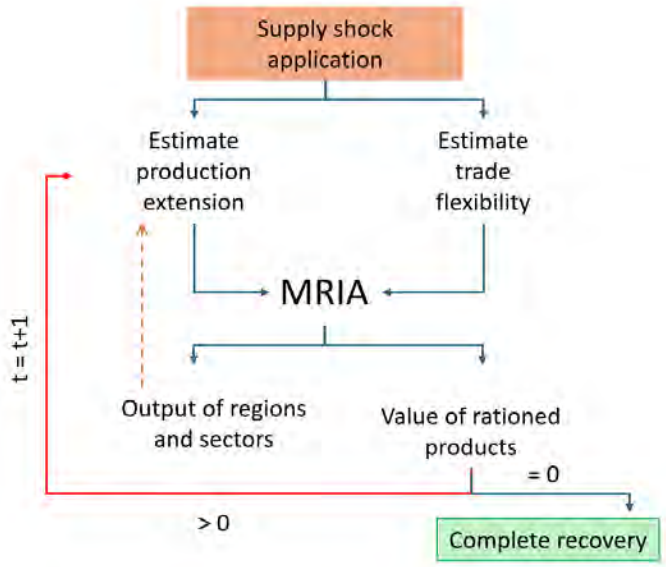


Figure 2. DMRIA workflow

Figure 2 illustrates the workflow of the DMRIA model. The analysis begins by introducing a supply shock in the region of interest. Subsequently, the sectoral production extension and interregional trade flexibility of unaffected regions are computed according to the equations summarized in Table 1. These adjusted capacities are then incorporated into the MRIA framework to quantify the residual unmet demand. The iterative process continues until all regional demands are fully satisfied.

Table 1. DMRIA model equations[1].

Equations	Symbols	Description
If r is disaster struck,	γ_d	Production extension rate – *intra regional resilience*
$\bar{X}^{t+1}_{r,s} = \min\left(X^{base}, X^{t}_{r,s} \times \gamma_d\right)$	γ_u	Production extension rate – *inter regional resilience*
else	γ_t	Trade flexibility extension rate
$\bar{X}^{t+1}_{r,s} = \min\left(\delta^{\max} \times X^{base}{}_{r,s}, X^{t}{}_{r,s} \times \left\lfloor \frac{\gamma_u}{e^{-\theta}} \right\rfloor\right)$	$\bar{X}$	Upper bound for sectoral output X
	θ	Decay parameter defining regional participation
	$\delta^{\max}$	Permissible production extension
$\phi^{t+1}{}_{r1,r2,p} = \left(\phi^{t}{}_{r1,r2,p} \times \gamma_t\right) + \phi_{\min}$	$\Phi_{r1,r2,p}$	Trade flexibility between regions *r1,r2* for the product *p*

Preliminary results[2]

Figures 3a and 3b present the relative change in regional output across the EU in response to a 5% supply disruption in West Netherlands (NL3), under scenarios of zero and enhanced substitution capacities (with 1% production extension and 10% trade flexibility extension per week), respectively. In the absence of interregional flexibilities, all regions experience persistent negative impacts throughout the time period. By contrast, when substitution mechanisms are enabled, neighboring trading partners exhibit positive output effects, reflecting compensatory and redistributed production to mitigate the initial disruption.

[1] The equations relevant solely to the dynamics of the model is presented here. For complete set of equations defining the model refer Raj et al. (2025)

[2] The work is currently under preparation and the results are outcomes of the preliminary test runs.

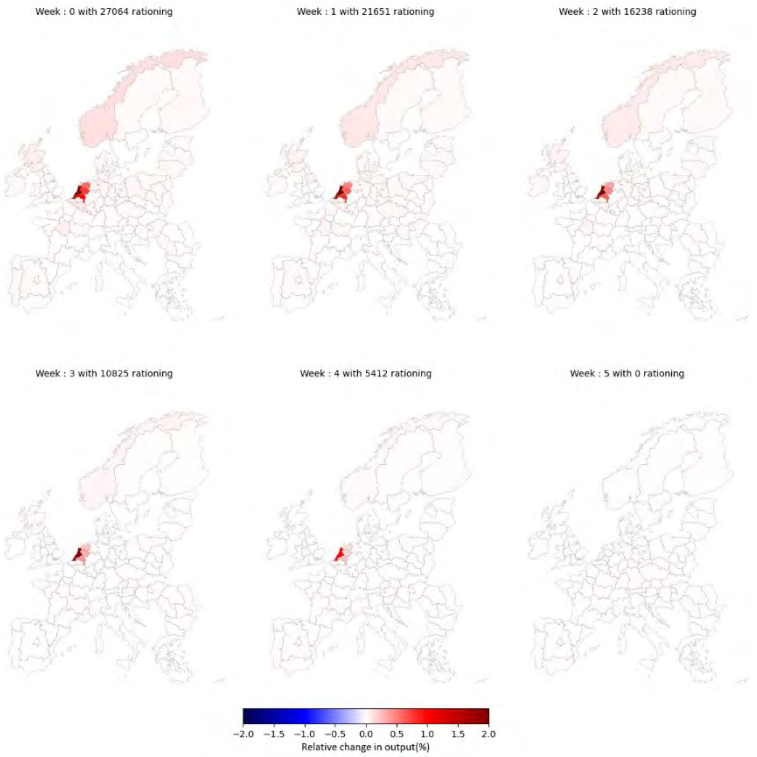


Figure 3a. Relative change in regional outputs to 5% disruption to West-Netherlands (NL3) under zero production extension and trade flexibility capacities

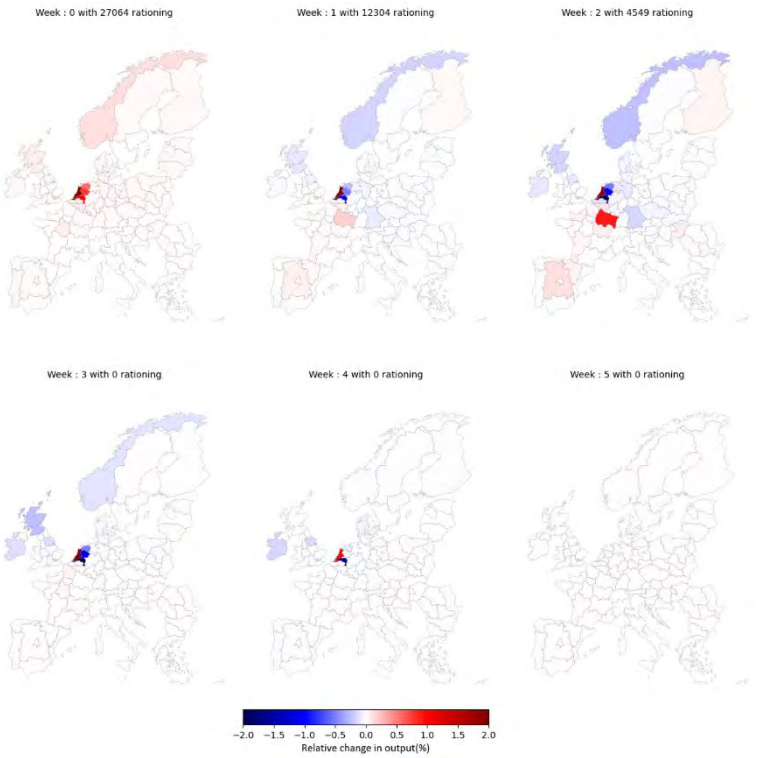
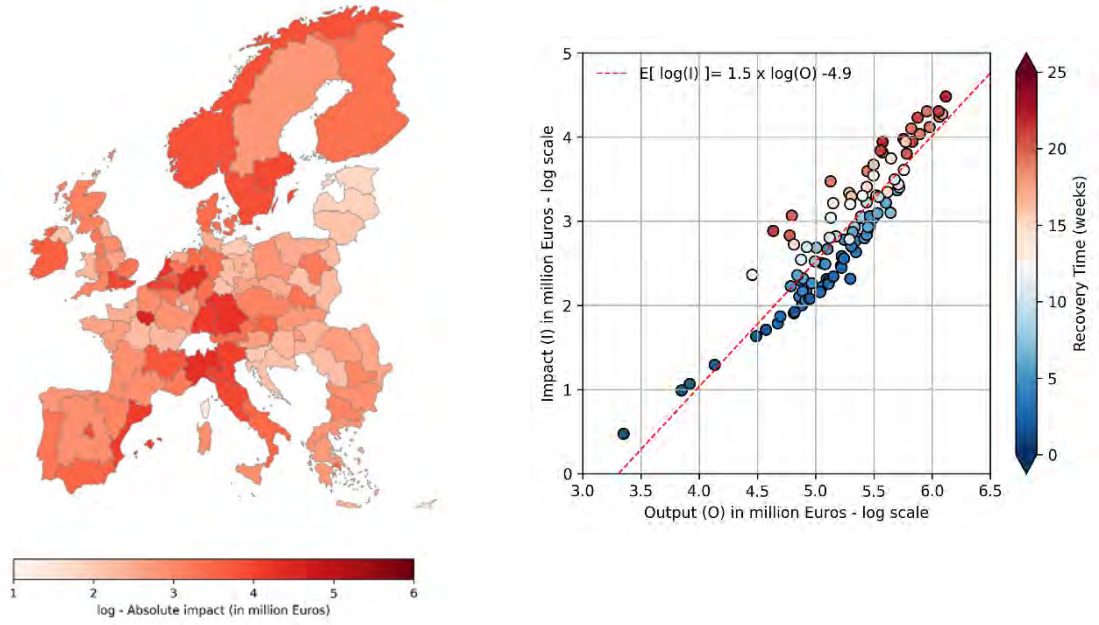


Figure 3b. Relative change in regional outputs to 5% disruption to West-Netherlands (NL3) with 1% production extension and 10% trade flexibility extension per week



(a) (b)

Figure 4. a) Impact across EU regions b) Regional economic output Vs the Observed macroeconomic impact

Figure 4a illustrates the absolute economic impacts across all EU regions under a 5% supply disruption. The impacts exhibit substantial regional heterogeneity, with major economies experiencing relatively higher absolute losses. Figure 4b compares regional economic output with the corresponding observed impacts, revealing an approximately linear relationship. However, smaller regions with limited trade connectivity can experience impacts equivalent to the impacts observed in major economies (of 5–8 times higher output), highlighting their vulnerability to supply shocks. In subsequent analyses, we will assess the effectiveness of various economic resilience measures and examine regional responses to these interventions.

Conclusion

This study introduces a Dynamic Multi-Regional Impact Assessment (MRIA) model to analyze the macroeconomic consequences of disasters across EU regions. Preliminary results show that regional substitution can significantly reduce impacts, while regional responses vary by both its size and trade connectivity. The role of economic resilience measures will also be explored.

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Abstract

High-tech solutions are increasingly promoted as transformative instruments for food systems; however, their economic implications and effects on resilience are not adequately scrutinized. This paper conducts a systematic literature review to examine economic performance and engineering resilience within a high-tech, data-driven fruits and vegetables (F&V) food system. The analysis concentrates on economic indicators such as profitability, productivity, and cost, and engineering resilience attributes, including stability, predictive capacity, and responsiveness to disruptions. Based on predefined inclusion criteria, the review encompasses high-tech interventions spanning artificial intelligence (AI), the Internet of Things (IoT), machine learning (ML), sensor technologies, and decision support systems. Evidence indicates that such applications can improve coordination and demand forecasting, thus potentially enhancing operational efficiency. However, the realization and distribution of these benefits depend on factors such as governance arrangements, and incentive mechanisms. This study contributes to current debates on the digitalization of food systems by providing a structured assessment of how high-tech adoption may shape economic viability and system stability, while simultaneously cautioning against techno-optimistic narratives that overlook contextual and structural constraints.

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National Resilience for Critical Mineral Value Chains

Feiya CHEN[1], Benjamin Sprecher[2], Shauhrat S. CHOPRA[1],

1School of Energy and Environment, City University of Hong Kong, Tat Chee Avenue, Hong Kong SAR, China, feiychen3-c@my.cityu.edu.hk

2Faculty of Industrial Design Engineering, TU Delft, Landbergstraat 15, 2628 CE Delft, The Netherlands,b.sprecher@tudelft.nl 1School of Energy and Environment, City University of Hong Kong, Tat Chee Avenue, Hong Kong SAR, China, sschopra@cityu.edu.hk

Abstract

Amid rising geopolitical tensions and climate shocks, ensuring the resilience of critical mineral value chains has become a paramount concern for national security. Conventional analysis frameworks are increasingly inadequate, as they typically rely on static trade data, fail to capture the dynamics of the entire value chain from mine to market, and overlook nations' adjustable capacities to reconfigure supply routes during a crisis. To address these shortcomings, this study introduces a dynamic, multi-stage resilience assessment framework that provides a more holistic view of national vulnerability.

Our framework integrates production capacity analysis, spatial infrastructure diagnostics using GIS, and dynamic trade simulations based on complex network theory. We apply this methodology to a critical case study: China's copper supply chain, due to its role as the world's largest consumer and copper's foundational importance for industrialization and the green energy transition. The analysis evaluates resilience across three distinct phases: preparedness, robustness, and recovery.

The findings reveal multiple, stage-specific vulnerabilities. In the preparedness phase, we identify high spatial concentration in China's domestic copper infrastructure, with Gini coefficients of approximately 0.68 indicating significant exposure to localized disruptions. During the robustness phase, a simulated 100% mining disruption in a key trade partner, Chile, is shown to trigger a severe 35.06% shortfall in China’s refined copper supply. Finally, in the recovery phase, a disruption in domestic smelting capacity highlights cascading failures, resulting in a 33.48% consumption demand deficit that cannot be fully offset by compensatory imports.

By pinpointing distinct bottlenecks, from geographic concentration to import dependencies and domestic processing limitations, this framework moves beyond static resilience assessment. It provides policymakers with a tool to develop more reliable, "safe-to-fail" strategies, enhancing national mineral security in an era of compounding global uncertainty.

Keywords: Critical Minerals; Value Chain Resilience; Complex Network Theory

2. Infrastructure Utilities And Economic Systems

Enhancing transport system resilience during mass participation events

Dr. Kristina Wolf *[1], Dr. Matt Burke[1], Dr. Peter Helm[1], Prof. Phil Blythe[1], Rose Bunker[1]

*corresponding author: Kristina.Wolf@newcastle.ac.uk
[1]School of Engineering, Newcastle University, Newcastle upon Tyne, UK

Abstract

Extreme weather events, including flooding and heatwaves, are projected to become more frequent and intense in the future, posing significant challenges to urban infrastructure, the environment and society. Mass participation events, such as sports fixtures, are particularly at risk, as large crowds of participants and spectators are exposed to challenging outdoor conditions. This case study examines the impacts of the heatwave followed by extreme rainfall during the 2023 Great North Run, the world's largest half-marathon held in North East England. Integrating near-time weather and transport data with insights from a participant's survey, this case study provides insights into the impacts of extreme weather on participants' return travel, travel options, and travel delays. We anticipate that these findings will help authorities and organisers enhance the resilience of similar future events.

Keywords: extreme weather; mass participation events; Great North Run; extreme rainfall; stakeholder engagement

Introduction

The UK Met Office predicts warmer and wetter winters, hotter and drier summers, and an increase in more intense rainfall (Met Office, 2025), which can directly impact urban infrastructure, including road surface damage and transport service failures (Markolf et al., 2019).

The UK Met Office (2024) assessed the impact of future climate conditions on British sporting events, including the world's largest half-marathon, the Great North Run (GNR), which could experience temperatures 2.5°C above current averages by the 2050s. The 2024 Olympics and the 2024 UEFA Euro Cup have already highlighted the impact of extreme weather on athletes' health and performance, as well as on transport services due to capacity challenges. Compared to large-scale events featuring professional athletes, literature highlights the need to understand the implications of extreme weather for regional events (Werner, 2024), which present unique logistical challenges at the community level.

This case study aims to assess the impact of extreme weather on transport systems and participants' travel during the 2023 GNR event, which was marked by a heatwave and followed by heavy rainfall, resulting in flooded metro stations and service disruptions. Findings will include practical ideas for more resilient travel and infrastructure that can improve public safety and mitigate pressure on emergency services during future mass participation events.

Methodology

This case study employed a mixed-methods approach, incorporating near-real-time weather and transport data from the Met Office, Newcastle Urban Observatory, and the Tyne and Wear Urban Traffic Management and Control Centre, and drawing on regional stakeholder discussions.

Further data stems from a participants' survey, featuring 319 participants with a 90% confidence level and a 5% margin of error, with questions on participants' locations, the impact on their travel, health, future participation, and recommendations for future events.

Time-series weather and transport data extraction, transformation and analysis are performed in the Jupyter Notebook development environment using core Python libraries, and the results are visualised in ArcGIS Pro 3.0. Thematic mapping of qualitative data was performed using NVivo.

Results and discussion

Following temperatures of up to 24 degrees, while the average ranges from 10 to 15 degrees in September, thunderstorms produced heavy rainfall (ranging from 15mm to 41 mm) from 2 pm, resulting in direct damage to the South Shields metro station infrastructure, including doors and lifts. As a result, participants diverted to the nearby ferry station. While the ferry continued to operate, it ran at full capacity, indirectly impacting travel times due to long queues until late in the evening. Flooding at Tyne Dock metro station disrupted the metro service to Bede metro station. **Figure 1** visualises incidents, impacted metro stations and roads with the highest increase in travel time.

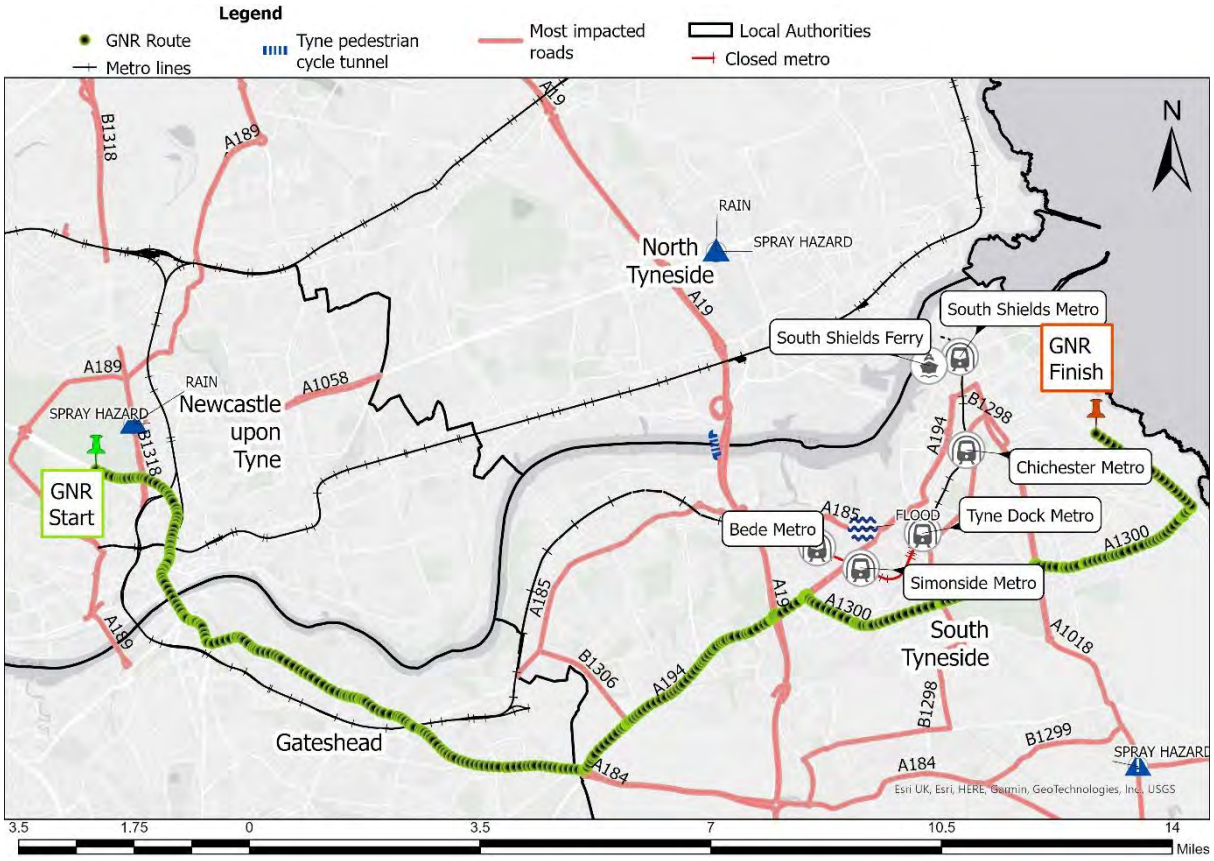


Figure 1: Impacts of extreme weather on transport systems during the 2023 GNR.

30% (96 participants) reported changing travel plans and transport modes. 95 people reported that it was due to the major or moderate impact of rainfall. 52 people attributed their change in travel plans to a major or moderate impact of temperature. When comparing planned and actual usage of transport modes, the metro usage decreased (-35%), mainly due to service disruptions during the event, while the uptake of cars, buses and ferries has increased. The highest increase was in walking (+106%), as participants walked longer distances to locations unaffected by flooding to get a lift or walked entirely home, noting distances of up to 13 miles and the impact on their well-being, due to fatigue and the extreme weather.

To enhance resilience, it is suggested to prepare alternative routes, such as safe walking, cycling, and road routes, to activate if primary routes are compromised. While the Tyne Pedestrian Tunnel could serve as an option, not all alternatives are equally practical, accessible or safe for everyone due to individual needs, such as limited mobility. Another aspect is to explore additional, underused, lesser-known routes. Adaptive transport solutions, such as repurposing available vehicles and using baggage coaches, can transport participants. Deploying express shuttle routes between key locations and providing alternative destinations to major transport hubs are subject to feasibility and existing road closures.

Conclusion

Using the example of the 2023 GNR, the world's largest half-marathon, this study assessed the impact of extreme weather on mass participation events. Quantitative data analysis, participant survey and stakeholder discussions helped identify practical ideas for enhancing resilient travel

and infrastructure. As a next step, this case study aims to develop contingency plans that incorporate measures to enhance transport networks around the GNR area and provide recommendations for future events.

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A rapid decision-support tool to assess flood-induced accessibility disruptions

Shadi Shirazian*[1], Elco Koks[2], Alexander Fekete[3], Julie Rozenberg[4]

1 Research Associate, Departments of Water and Climate Risk, Vrije University Amsterdam, Netherlands* **2** Associate professor, Departments of Water and Climate Risk, Vrije University Amsterdam, Netherlands **3** Professor, Institute of Rescue Engineering and Civil Protection, TH Köln – University of Applied Sciences, Cologne, Germany **4** Senior Economist, World Bank, Washington D.C., United States

Abstract

Ensuring a functional road network during disasters, one that is robust and redundant enough to maintain connectivity in urgent situations, particularly to hospitals, is crucial for minimizing societal disruptions and protecting community wellbeing. In this study, we present an automated and scalable decision-support tool to identify critical road segments in terms of accessibility and connectivity to essential public services and infrastructure. To exemplify our approach, we evaluate population accessibility to healthcare facilities via the road network under nationwide flood scenarios in Georgia. The results provide valuable insights for policymakers on the impact of hazards on road network accessibility from a community vulnerability perspective, rather than focusing solely on economic impacts. These insights are essential to better guide budget allocation and prioritization from an equity perspective.

Keywords: accessibility; road network; flood impact; decision-support tool

Introduction

Timely and equitable access to some critical destinations is a fundamental social right, as delays can lead to severe consequences (Al-Worafi, 2023). This issue becomes even more critical during natural hazard events, when disruptions to mobility exacerbate existing vulnerabilities and restrict access to hospitals, shelters, evacuation routes and other vital social infrastructure (Balomenos et al., 2019). Recent studies highlight the importance of quantifying healthcare accessibility (Weiss et al., 2020) and its disruption under hazard scenarios (Tariverdi et al., 2023; Petricola et al., 2022).

In this study, we present a decision-support tool to assess the impact of potential hazards on access to essential destinations and the resulting non-financial losses. This approach helps policymakers to evaluate hazard impacts from a societal perspective. The workflow enables a rapid yet robust assessment of access vulnerabilities under hazard conditions, producing results that are clear and actionable for decision-making. To exemplify the workflow, we analyze the impact of floods on vehicle access from population areas to hospitals in Georgia.

Methodology

The scalable decision-support tool that is developed here automates data acquisition for the country of interest, including road networks, population distribution, and destination points (e.g., healthcare facilities, airports or ports), then cleans the data, models transportation

networks as a diagraph. Simulates flood scenarios, and an adjustable threshold water level is applied to identify road segments blocked by inundation. For each simulated event, the affected road segments are removed, and network analysis is performed on the damaged system. The resulting loss metric, defined as travel time under free-flow conditions, is computed using the Dijkstra algorithm (Dijkstra, 1959). Changes in accessibility are then quantified by comparing disrupted travel times with baseline conditions. The tool is designed and developed as Python code that will be publicly available on GitHub.

Population data are collected from WorldPop, a global open-source initiative providing high resolution population distribution datasets. Road network data and the destination data points are sourced from the OpenStreetMap (OSM) database, a collaborative mapping platform that offers detailed geospatial data for roads and infrastructure.

To demonstrate the application of this workflow, here we present the assessment of vehicle accessibility of population to the health facilities in Georgia under several flood scenarios. Georgia is a country located at the intersection of Eastern Europe and Western Asia, with a population of approximately 3.8 million. Health facility data (hospitals and clinics) are derived from OSM. To represent disruptions, single-hazard event sets are created using basin and subnational geometries from the HydroSHEDS project (Lehner et al., 2013). Flood depths for these basins are derived from the latest Fathom flood hazard maps (Fathom Global, 2022), The threshold for water level is set to 25 cm due to the average height of air inlets of regular vehicles and falls within a commutable range studied by Pregnolato et al. (2017). Considering there is no standard 'golden time' applicable to all situations, different policymakers might have different requirements, we present the results of the loss in access time as curves. This curve is plotted versus time thresholds to make the results interpretable and adaptable for diverse needs.

Results and discussion

In figure 1, panel A shows the healthcare access time under normal conditions. Panel B shows the total affected population in each basin, where each basin represents the location of a fluvial flood event. Panel C shows the critical road segments impacted by the top ten flood events in terms of the number of affected people.

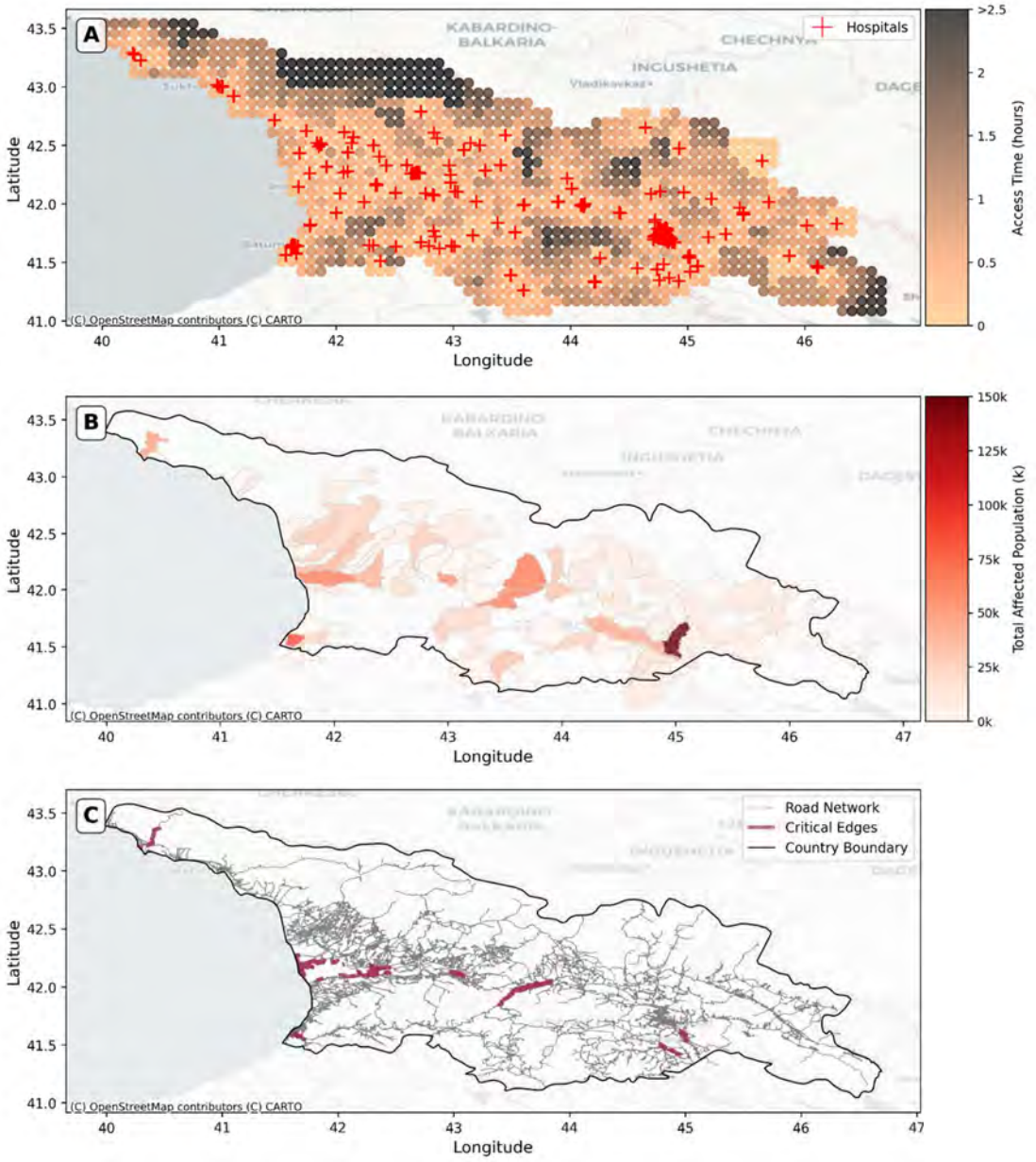


Figure 1. A) The access time to the closest health facilities under normal conditions B) The total affected population by each created flood event. C) the critical road segments damaged by flood events that led to the highest number of affected populations.

Figure 2 shows an example of loss modeling and the results for one of the fluvial flood events of this study. The total affected population by this event is about 75,000 people. Panel A shows the damaged road segments by the flood and Panel B illustrates the states of access to healthcare in the pre- and post-event conditions. In this event, a portion of the population completely lost access without an alternative route; therefore, the curve for the post-event condition will not reach 100% of the population until the road blockages are restored.

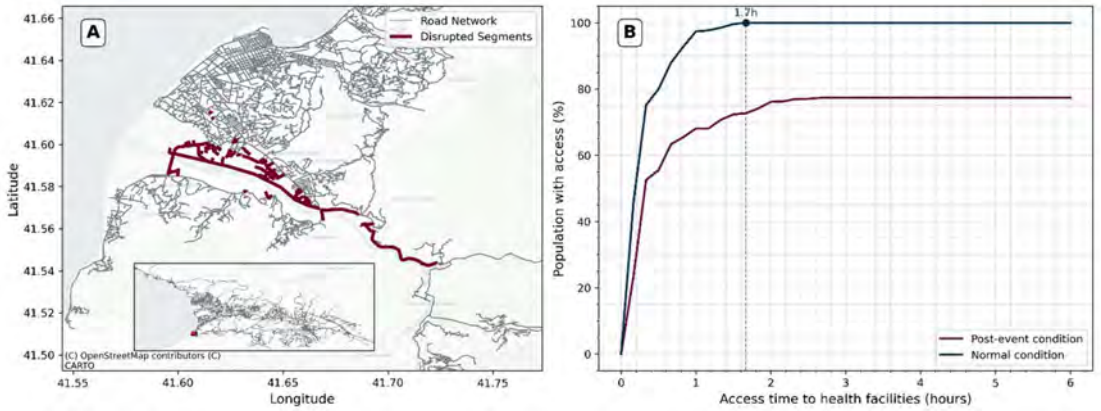


Figure 2. A) The road segments impacted by a flood event. B) The access curve shows the percentage of the population who could reach the health center within several time thresholds under normal and flooded conditions. It highlights what percentage of the population, within any defined time threshold (golden time), has access to their closest health facilities.

Conclusions

This paper presented a sample application of the developed scalable automated decision support tool, focusing on vehicle access to health facilities in Georgia. By using publicly available databases, the workflow is applicable even in data-scarce areas. The loss modeling results provide a general but clear overview of vulnerabilities in access to important destinations under flood conditions, highlighting critical road segments based on their social impact and the number of affected populations rather than just economic impact. These insights are valuable for policymakers in allocating and prioritizing budgets for developing effective risk mitigation strategies.

Acknowledgements

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Critical Infrastructure failure escalates the macroeconomic impacts of disasters

Surender Raj Vanniya Perumal[1], Elco E. Koks[1], Marleen de Ruiter[1] and Mark Thissen[2,3]

1 Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam, Amsterdam, The Netherlands;
2 Spatial Economics, Vrije Universiteit Amsterdam, The Netherlands;
3 Netherlands Environmental Assessment Agency (PBL), The Hague, The Netherlands.

Abstract

Critical infrastructures (CIs), such as power systems, are vulnerable to disaster-induced disruptions, often resulting in industrial shutdowns and production losses. These disruptions cascade through interregional supply chains, amplifying the economic consequences. Conventional macroeconomic disaster impact assessments often overlook production downtimes caused by CI failures and fail to account for the spatial interdependencies between CIs and different sectors of the economy. This study presents a spatially explicit methodology to quantify the macroeconomic impacts of CI failures, demonstrated using power disruptions induced by flood events. Our analysis shows that CI failures can amplify macroeconomic impacts by 30% to 360%, depending on the degree of interregional substitution (i.e., economic resilience) available and the robustness of CI assets. Our results underscore the importance of incorporating CI disruptions into macroeconomic risk assessments Additionally, the findings suggest that CI adaptation decisions solely based on maximum damage assessments may be ineffective. A more systemic approach that targets the adaptation of CI assets serving crucial and less redundant economic sectors proves to be more efficient. Furthermore, the proposed approach provides a basis for transitioning from traditional damage-based adaptation decisions to a more holistic, system-level framework for climate adaptation of CIs.

Keywords:disasters, critical infrastructure, power outage, climate adaptation, input – output analysis

Introduction

Recent substation failure events at Heathrow Airport (NESO, 2025) and the Europoort area of Rotterdam (Meijer et al., 2024) led to widespread disruptions in passenger transit and refinery operations, respectively, underscoring strong dependencies between CI services and the socio-economic functioning. The likelihood of CI failures increases during natural hazard events, where multiple critical assets may be damaged simultaneously (Guikema et al., 2010; Li et al., 2022). The consequences of such failures extend beyond physical damages, as the lack of CI services will force the downtime of its dependent industries resulting in production losses. The affected industries are an integral part of supply chains, resulting in broader multi-regional

macroeconomic impacts (see Figure 1). In this study, we develop a modelling framework to estimate the macroeconomic impacts of disasters, explicitly incorporating disruptions resulting from CI failures. The framework is applied to a case study in Zuid-Holland—the region with the highest economic output in the Netherlands, subjected to hypothetical flood scenarios and associated power disruptions. By comparing macroeconomic impacts with and without CI failures, we highlight the significance of accounting for CI disruptions. Subsequently, this framework is used to identify CI prioritization strategies for adaptation, differing with conventional damage-based approaches e.g., Chang & Hossain (2024) ; Karagiannakis et al. (2025) . This study offers an early contribution toward incorporating system-level economic impacts into the decision-making process for CI adaptation planning.

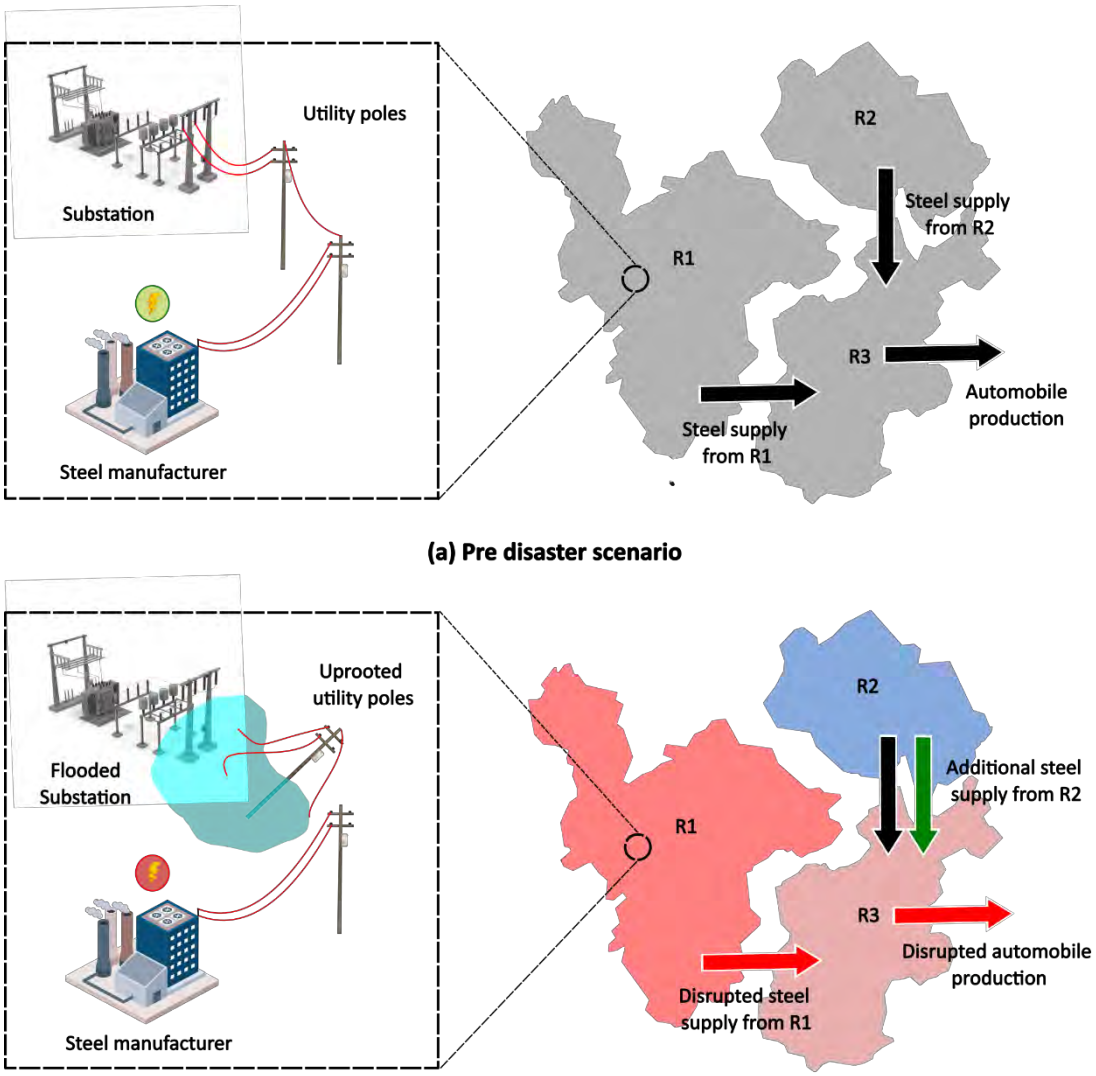


Figure 1. An example to illustrate the macroeconomic consequences of CI failure. The black, red, and green arrows indicate business-as-usual, reduced, and increased trade flows, respectively.

Methods

Figure 1a illustrates a representative pre-disaster scenario highlighting the role of CI services in enabling the normal functioning of supply chains. Figure 1b presents the multi-regional macroeconomic consequences of CI failure following a flood event. Assume a flood event occurs in the region R1. The substation is flooded, and the utility poles are uprooted. Subsequently, the steel manufacturer is forced to shut down the plant due to a power shortage. Knowing this and to satisfy the market demand for steel, the steel manufacturer of R2 extends its steel production to a certain extent and supplies it to R3. Despite this compensatory adjustment, region R3 still receives less steel relative to the business-as-usual scenario, leading to a reduction in automobile production. This sequential failure propagation is taken into account in this study.

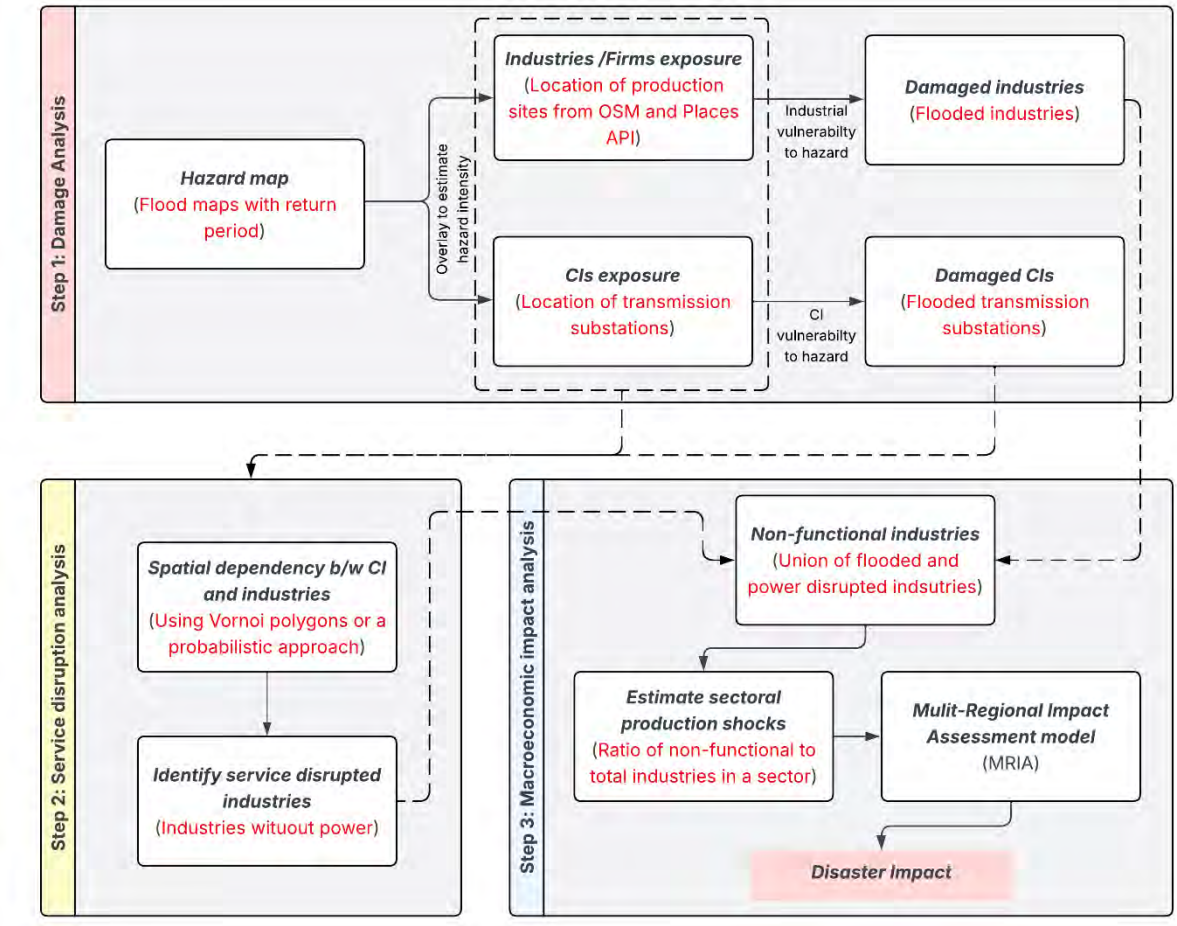


Figure 2. Flowchart outlining the steps involved in estimating the macroeconomic impacts of disasters, with consideration of service disruptions from critical infrastructures. Steps shown in bold represent a generic methodology applicable across various CIs and hazards, while the red text in parentheses highlights the specific steps to the case study presented.

Figure 2 outlines the sequential steps of the proposed framework for estimating the macroeconomic impacts of disasters, explicitly accounting for service disruptions resulting from CI failures. The first step involves identifying the damaged CI and industrial assets. Subsequently, the industries experiencing service disruptions from CI failure is also identified. This combined information is then fed into a multi-regional impact assessment model MRIA (Koks & Thissen (2016) and Raj et al. (2025)) to estimate the multi-regional macroeconomic impacts.

Results

Critical infrastructure failure and its macroeconomic impact during disasters

The exceedance probability (EP) curves associated with the sectoral production shocks—(a) incorporating power service disruptions and (b) excluding power service disruptions are presented in Figure 3a. The Expected Annual Impact (EAI), computed as the area under the EP curve in accordance with Equation 5, is estimated at €3.53 million for case (a) and €2.38 million for case (b), indicating that 32.4 % of EAI is attributable to power service disruption. Fig 3b presents the results of sensitivity analysis of varying economic and CI resilience parameters.

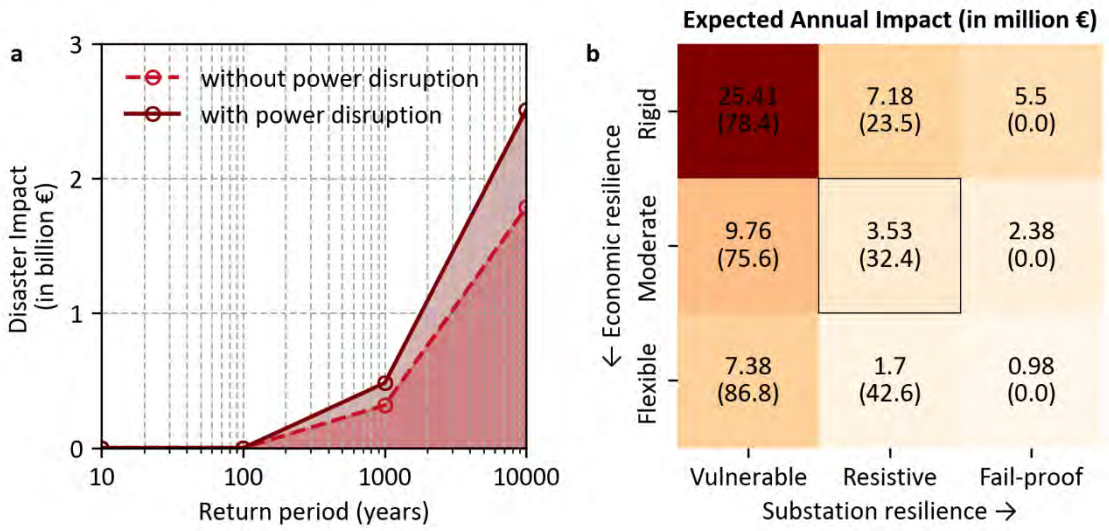


Figure 3. (a) Exceedance Probability (EP) curves depicting macroeconomic impacts with and without the inclusion of power service disruptions. (b) Expected Annual Impact (EAI) estimates under varying economic system configurations (rigid, moderate, and flexible) and substation resilience levels (vulnerable, resistive, and fail-proof). Values in parentheses indicate the power disruption attribution ratio (in %) (i.e., the relative contribution of power disruptions to overall economic impact). Boxed values correspond to the baseline scenario, in which substations remain operational up to a flood depth of 1 meter, with a 1% production extension and 25% trade flexibility.

Critical infrastructure adaptation - a macroeconomic perspective on impact reduction and prioritization

Infrastructure operators face financial constraints for adaptation, making it essential to prioritize investments based on substation criticality. An effective prioritization strategy should aim to maximize impact reduction with minimal investment. In this study, we examine the effectiveness of three different prioritisation strategies. The first strategy ranks substations according to inundation depth under a 10,000-year return period event, with higher inundation depths indicating greater criticality. The second strategy prioritizes substations based on the total area of industrial sites they serve across all sectors. The third strategy ranks substations based on the area of industrial areas they serve associated with the Oil and Petrochemicals (C19) and Chemicals (C20) sectors only. These sectors are considered critical due to their substantial contribution to economic output and, additionally in the case of C19, the absence of spatial substitution possibilities from other regions in the Netherlands (Raj et al., 2025). Fig 5 presents the results of the analysis.

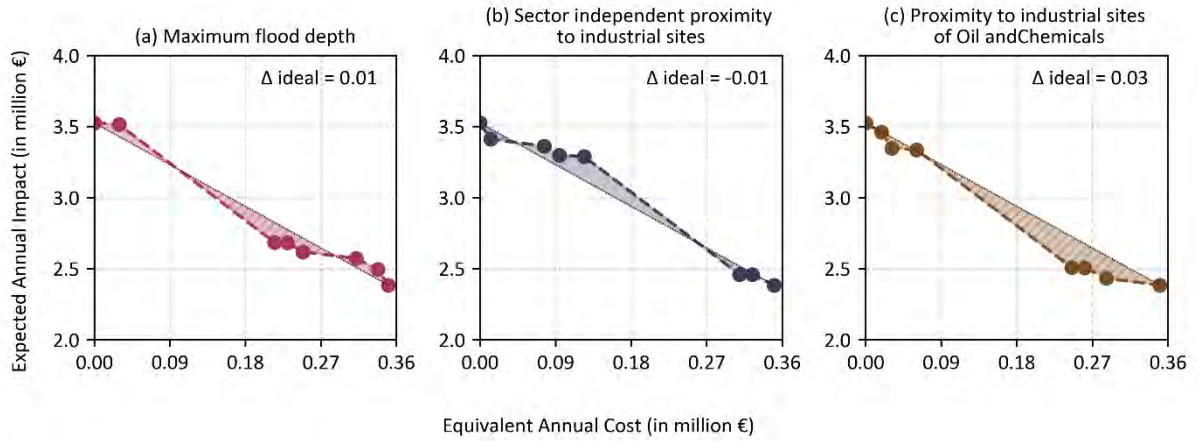


Figure 4. Expected Annual Impact (EAI) and Equivalent Annual Cost (EAC) of investment under sequential adaptation of substations following three prioritization schemes: a) maximum flood depth b) proximity to industrial sites (sector independent), and c) proximity to industrial sites of Oil and Petrochemicals (C19) and Chemicals (C20) sector

To evaluate the performance of the prioritization strategies, we introduce a hypothetical ideal reference line representing a linear proportional relationship between annual investment and expected reduction in economic impacts, as shown in Figure 5. Deviations below this line (hatched area) indicate favourable outcomes—i.e., greater impact reduction achieved with lower investment and vice versa. For each of the three prioritization schemes, substations are sequentially adapted cumulatively, and the corresponding EAI and EAC are plotted. The net area between the ideal line and the observed performance curve, $\Delta ideal$ (expressed in sq.

million Euros) is used as a metric to compare the effectiveness of strategies. Among the schemes considered, prioritising substations that serves higher areas of C19 and C20 sectors yields favourable outcomes with Δ*ideal* = 0.03. This is followed by prioritization based on maximum flood depth (Δideal = 0.01), and lastly, prioritization based on area of industrial sites served irrespective of the sector (Δideal = -0.01). Although strategies that prioritize hazard intensities may be effective in mitigating physical damage, they do not necessarily perform better when the goal is to reduce macroeconomic impacts (as measured by EAI in this case).

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Pan-European Analysis of Flood-Induced Supply Chain Disruptions

***Fernandez-Perez, A[1]; Pant, R[1] ; Li, Y[1]; Raj, S[2]; Koks, E.E[2]; Hall, J[1]**
***alberto.fernandezperez@ouce.ox.ac.uk**
1. Environmental Change Institute, University of Oxford
2. Instituut voor Milieuvraagstukken (IVM) – Vrije University of Amsterdam

Abstract

Flooding is among the most disruptive natural hazards in Europe, not only damaging physical infrastructure but also triggering cascading disruptions across industrial supply chains. While existing research has largely focused on direct impacts on assets, the indirect consequences for interconnected production and trade systems remain underexplored. This study develops a Europe-wide assessment of flood-induced disruptions to industrial supply chains by integrating industrial output localization, transport lifeline connections, and commodity flow mapping. Using Eurostat Supply-Use Tables, facility-scale industrial data, and multi-modal freight network modeling, we construct a geospatially explicit representation of production and trade dependencies across Europe. Flood hazard maps from the Joint Research Centre are then overlaid to evaluate damages under baseline and future climate scenarios (SSP2-4.5 and SSP5-8.5). Initial results highlight significant damages to rail assets from river flooding in the central European countries.

Keywords: Flooding disruptions, Supply chain, multi-modal transport.

Introduction

Floods are among the most frequent and costly natural hazards in Europe, causing billions of euros in damages each year and severely disrupting communities, businesses, and national economies (Paprotny et al. 2018). Recent events such as the 2021 Central European floods and recurrent flooding of river basins like the Danube, Rhine, and Po have demonstrated that flooding not only damages infrastructure but also disrupts critical services and industrial production across wide regions (Koks et al. 2021).

While existing research has provided valuable insights into flood risk for physical assets (van Ginkel et al. 2021), less attention has been devoted to the indirect and cascading effects of flooding on industrial supply chains. Industrial clusters, transport lifelines, and commodity flows are tightly interconnected; localized flooding of ports, rail junctions, or inland waterways can ripple across national borders and trigger systemic impacts.

This work develops a Europe-wide analysis of flood-induced disruptions to industrial supply chains by mapping: (1) the localization of industrial output, (2) lifeline connections to ports, airports, and rail stations, and (3) commodity flows across Europe by transport mode.

By using flood maps for present and future scenarios, and their disruption to transport infrastructure, we estimate cascading impacts on industrial continuity. The analysis highlights critical bottlenecks and systemic vulnerabilities, providing insights into how resilience strategies may be designed to protect Europe's economy from flood-related risks.

Methodology

The study adopts a three-step methodology tailored to flood impacts:

Localization of industrial output

Industrial production (in tonnes/year) mapped at the NUTS-2 level using Eurostat Supply-Use tables (SUT) (García-Rodríguez et al., 2025) provides the baseline of industrial activity across Europe. This is downscaled to geolocated industrial locations using EPRTS (European Pollutant Release and Transfer Register) footprint maps, enabling industrial input and output flows from regional to facility level. Industrial activity is categorized into key industry/commodity groups: metals, chemicals, intensive livestock, food, and paper/wood, commercial and mining.

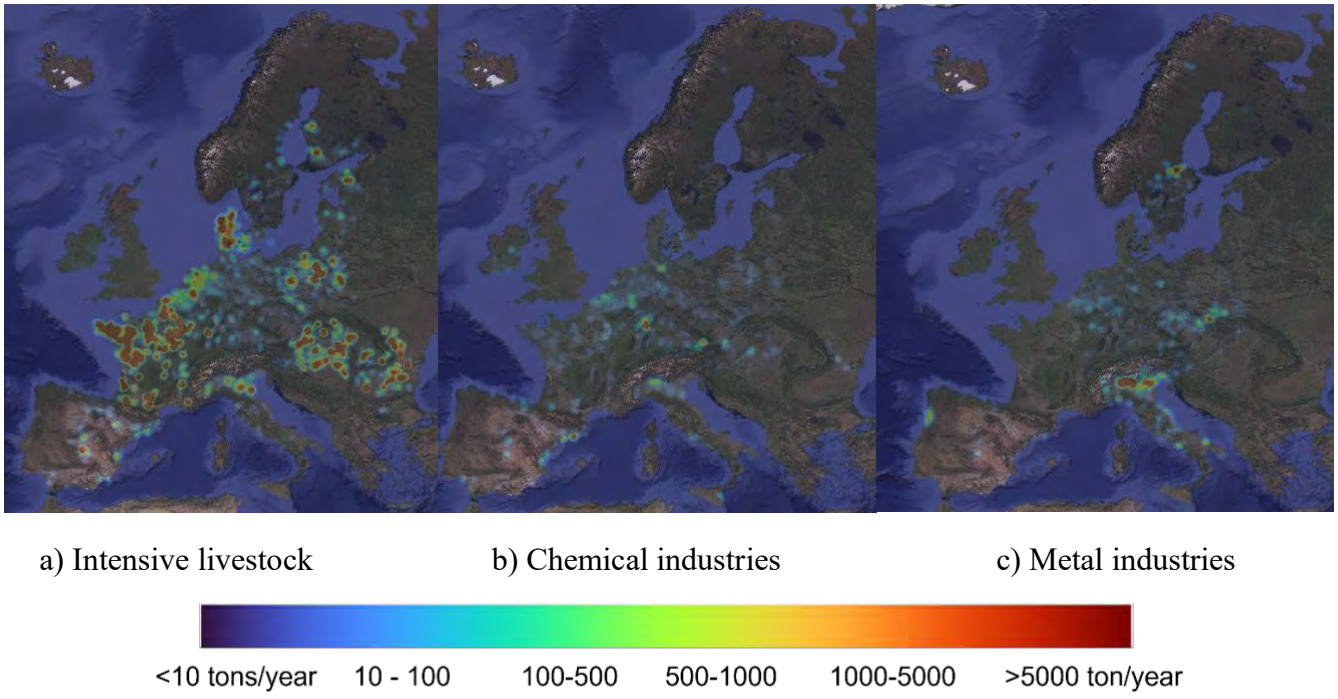


Figure 1. Localization of industrial output at pan-European scale for three different commodity types.

Trade flow downscaling and lifelines analysis

The location specific downscaling of the SUT helps to generate a geospatially explicit network of inter-sectorial trade at the facility level. Then, each facility is linked to its nearest ports, airports, rail stations and road junctions. Downscaled commodity trade flows between industrial locations are assigned to air, maritime, rail and road connections between the facilities, using Eurostat statistics for port, airport and inland waterways as capacity constraints of the flows. Thus, the multi-modal Origin-Destination matrices are created at pan European scale, which are then fed into a flow allocation model (Li et al., 2025). The left panel of Figure 2 provides a representation of the multi-modal transport flow allocation.

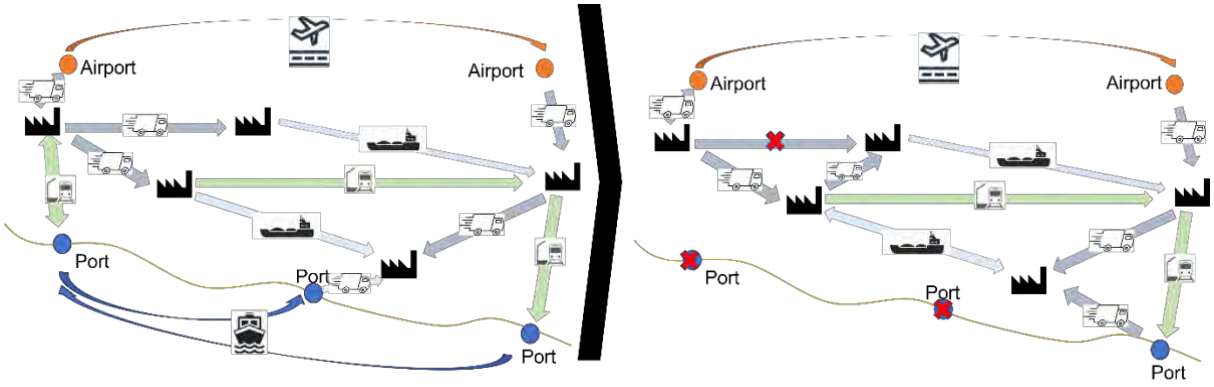


Figure 2. Assumed supply chain structure and disruption-rerouting analysis

Flood disruption analysis

Flood hazard return period maps from the JRC (Baugh et al., 2024) are overlaid to identify exposed and disrupted transport assets and estimate potential service interruptions in transportation networks (see Figure 2 right panel). A baseline scenario plus two future ones (SSP2 4.5 and SSP5 8.5) are considered for mid and end of century. Then, commodity flows are re-computed based on the multi-modal network flow re-routing costs (Li et al., 2025). Thus, disruptions from flood-exposed assets enable to trace cascading impacts through industrial supply chains. Both direct effects (damages on assets) and indirect effects (lost connectivity of commodity flows) are quantified.

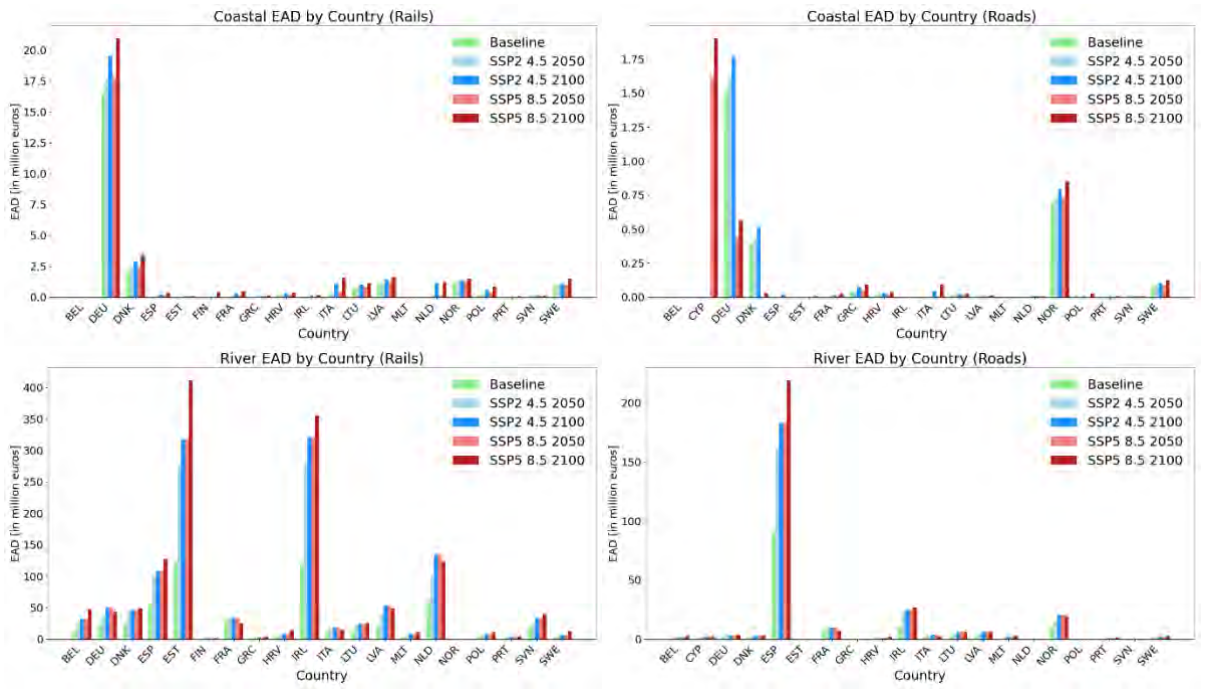


Figure 3. Expected Annual Damage from direct damages caused coastal and river flooding for baseline and future scenarios

In Figure 3, preliminary results of the Expected Annual Damage (EAD) due to coastal and river flooding events are highlighted for each European country. The results show the increase in

disruptions on transportation assets due to Sea Level Rise and the changes in the extreme events patterns. These effects are more prominent when evaluating river flooding, specially affecting central European railways.

Conclusion

This study aims to demonstrate that both coastal and river flooding in Europe have the potential to generate widespread and cascading disruptions far beyond the directly affected areas. Preliminary analysis shows that these effects, which are presently significant for the European transport assets, will further increase in frequency and intensity of extreme floods.

By combining industrial production data, facility-level footprints, and multi-modal freight flow modeling with present and future flood scenarios, we aim to identify critical vulnerabilities in Europe's industrial and transport networks. In next steps of the work, we aim to show the critical linkages across flood-exposed transport networks whose failures can trigger cascading impacts on industrial continuity and cross-border supply chains. Such disruptions compound the direct damages to physical assets, amplifying economic losses and threatening the stability of key sectors across Europe.

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Cascading economic impacts of critical infrastructure failures on supply chains

Elisa G.L. Nobile[1,2], Celian Colon[2], Marcello Arosio[1], Alessandro Caiani[1]
1 University School for Advanced Studies - IUSS Pavia, Pavia, 27100, Italy, elisa.nobile@iusspavia.it
2 International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

Abstract

This study presents a comprehensive framework for evaluating the cascading effects of the disruptions to transportation networks on supply chains. This is achieved by combining standard risk assessment approaches with the novel DisruptSC model, a spatially explicit agent-based model, that integrates dynamic behaviour of firms in terms of selecting transport routes, increasing logistics costs, and forcing firms to adapt by changing suppliers or reducing production. In particular, this framework, given its spatially explicit nature, is particularly suitable to analyze the economic impacts of spatially and temporally compounding hazards. This approach is applied in Italy and Cambodia, which demonstrate its broad applicability across different economic and climatic contexts. This work aims to bridge the gap in current economic impact studies by merging direct and indirect damage assessment, assessing the cascading impacts of transport disruptions. The results offer valuable insights for policymakers contributing to the development of more integrated risk assessment strategies that strengthen systemic resilience in the face of climate-related hazards.

Keywords: floods, compound events, critical infrastructures, supply chains, agent-based models

Introduction

Transportation networks, such as roads and bridges, have a fundamental role in the daily economic and social activities, enabling the access to jobs, goods delivery, and social services. However, due to their interconnected nature, these infrastructures are particularly vulnerable to external shocks, especially natural hazards, and therefore it is essential to assess their risk through a systemic approach (Mühlhofer et al., 2024). Yet, traditional risk assessment methods typically focus only on direct physical damage to infrastructure, often overlooking the cascading effects, especially how this affects firms and households, a crucial limitation for understanding the large-scale economic costs of extreme weather events (Willner et al., 2018). In particular, given that climate change is increasing the magnitude and frequency of extreme events, it is very important to quantify these systemic risks and indirect impacts in order to guide investments and policy interventions (IPCC, 2023). Moreover, when multiple hazards or drivers happen at the same time, like storm surge and heavy precipitation, compound events can result in significantly higher damages than when these hazards happen separately (Wahl et al., 2015). The co-occurrence of these meteorological drivers is increasing due to climate change (Bevacqua et al., 2020), which in turn is increasing the frequency of these compound events (Ridder et al., 2022). However, although there is growing interest in this topic, most studies focus on analyzing the statistical relationships between different drivers, with limited attention on quantifying the associated

economic losses. In order to address these gaps, we present a comprehensive framework that integrates the novel DisruptSC model (Colon et al., 2021), a spatially explicit agent-based model that captures the propagation of infrastructure through supply chains, resulting in shortages and price increases, with standard direct impact modeling approaches. Both direct infrastructure damage and the ripple effects that spread through interconnected economic systems can be quantified thanks to this integrated approach.

Case study

The aim of this work is not only on quantifying the indirect impacts of critical infrastructure failures but also the effects of sequential or spatially distributed cascading hazards on supply chains. To do this, we apply our integrated framework to two flood events: the 2023 wet-season floods in Cambodia and the 2023 flood in Emilia-Romagna, Italy. These two case studies allow us to test the methodology across different locations with distinct characteristics including climatic patterns (tropical vs. mediterranean), economic structures (developing vs. developed economy) and infrastructure exposure. In Cambodia, extended heavy rainfall during the wet season lead to multiple flooding phenomena occurring in close succession during September-October. Instead, Emilia-Romagna experienced not only intense precipitation in early May that caused flooding before the main flood event, but also antecedent conditions that contributed to worsening the impacts.

Methods

Direct impacts

We simulate direct flood damage to road networks by combining the three key components: hazard, exposure, and vulnerability. In the case of Cambodia, we apply the River Flood Inundation method (Riedel et al., 2024), using GloFAS river discharge forecasts and the flood hazard maps developed by JRC. We calculate return periods for the daily maximum discharge and then those are spatially interpolated to generate flood depth maps. While for Italy we adopt the flood hazard maps developed by the Copernicus Emergency Service developed from Sentinel-1 images. For exposure, we use OpenStreetMap data, applying network topology simplification algorithms to remove isolated edges and degree-2 nodes while preserving connectivity. For vulnerability, we adopt standard vulnerability curves, such as Huizinga et al. (2017) depth-damage functions, classifying road edges exceeding a 50% damage threshold as disrupted and removing them during the indirect impact simulation.

Indirect impacts

The DisruptSC model adopts an agent-based approach that connects three different levels of analysis. At the firm level, the model generates synthetic firms and households on maps, where each agent makes decisions about production, inventory, and supplier relationships based on real economic data. At the network level, the model represents transport infrastructure including roads, railways, and ports, calculating costs based on distance and route information. At the macro level, the model ensures that all firm behaviors match national economic data through input-output tables. The model generates synthetic supply chains by adopting a gravity model, connecting firms based on proximity and size, creating a network of supplier-buyer relationships mapped onto the transport system. When flooding

occurs, the model simulates two types of disruptions: firms must use more expensive alternative routes, which increases costs throughout supply chains, or transport links are completely blocked, causing shortages and production delays that spread through connected firms.

Results

This work analyzes both direct infrastructure damage and indirect economic losses. Results show how transport disruptions cascade through supply chains, with impacts varying across regions and sectors. The model quantifies two types of indirect impacts: price increases from costly rerouting and shortages from complete blockages. Indirect losses often exceed direct infrastructure damage, depending on disruption duration and infrastructure criticality. The temporal component is crucial as inventories initially buffer impacts but deplete over time, leading to non-linear increases in economic losses. The model identifies critical roads and disruption thresholds that trigger exponential economic impacts.

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The Fiscal Implications of Probabilistic Disaster Risks to Infrastructure

Puranasamriddhi, Akaraseth[1],*, Ranger, Nicola[1,2], Hall, Jim[1]

1 Environmental Change Institute, University of Oxford, Oxford, United Kingdom

2 Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science, London, United Kingdom

Abstract

The increasing frequency and intensity of extreme weather events pose significant threats to countries and their economies. Not only these events directly damage essential assets and networks, but they can also severely disrupt economic activities required for productivity, resulting in both acute and long-term effects on fiscal stability. Governments are central in preparing for and responding to these disaster risks, yet there is relatively a limited body of literature directly examining the fiscal implications of disaster risks to infrastructure. The research therefore aims to quantify the fiscal implications of probabilistic disaster risks to infrastructure. This is examined through a cross-country analysis across low- and middle-income countries using a dynamic general equilibrium model to observe a range of damages across different economies. The research focuses on eight countries in sub-Saharan Africa, Southeast Asia, and the Caribbean focusing on floods and earthquakes from 1-in-10 to 1-in-5000 return period scenarios. The results demonstrate that the fiscal impacts are non-linear, and that each type of disaster exhibit distinct fiscal impacts across short- and long-term due to the differences in damages, country's economic conditions, and ex-post public investment. These findings will inform governments, policymakers, insurance, and other relevant authorities on disaster-fiscal relationships and support these actors in integrating these risks into their risk assessments. By improving disaster risk management strategies, governments would be more resilient and less susceptible to fiscal shocks and therefore can invest more resources into economic growth, social development, and climate resilience.

Keywords: Probabilistic disaster risks; Public infrastructure; Public finances.

Introduction

Physical disaster risks are increasing as climate change leads to changes in both the frequency and intensity of extreme weather events (IPCC, 2021). The disaster risks from these events pose significant threats to countries and their economies at a systemic level (Stern, 2006). Not only these extreme events directly damage essential physical infrastructure assets and networks, but they can also severely disrupt economic activities, resulting in a destabilised economy and acute and long-term effects on fiscal stability (Hall et al., 2019; Ranger et al., 2021). Governments are critical in preparing for and responding to these risks due to them either owning the assets themselves or having moral, legal, and financial obligations to support firms and households. The rising expenditure costs and reducing tax revenues can simultaneously compromise the country's fiscal capacity to invest in economic growth, social development, and climate resilience (Beirne et al., 2021; Buhr et al., 2018). As a result, disaster risks can have adverse impacts on governments and their balance sheets, thereby undermining the sustainability of public finances.

While there is a rich body of literature on the macroeconomic impacts of climate change (e.g., Battiston et al. (2021), Cantelmo et al. (2023), Feyen et al. (2020), Kahn et al. (2021)), the research on the fiscal implications of disaster risks is still in its nascent stage, as consistently highlight by Boehm (2021) and Koetsier (2017). Moreover, as outlined by Feyen et al. (2020) and Koks et al. (2019), most studies underestimate the economic costs and do not accurately represent the spatial representation and essential role of infrastructure in terms of its impact across the economy. Recent studies (e.g., Hickford et al. (2023), Kesete et al. (2021), Oh et al. (2019)) have emerged to address this gap to capture the system-wide impacts of infrastructure asset damage and disruption, yet they do not further quantify how the macroeconomic impacts might lead to fiscal impacts, and which channels are important.

Using a dynamic general equilibrium model with probabilistic data on impacts from disasters, the research therefore aims to quantify the fiscal implications of disaster risks to infrastructure. This is examined through a cross-country analysis across low- and middle-income countries to observe a range of damages across different economies and recognise patterns that are most influential in enhancing fiscal resilience.

Methodology

The research applies the dynamic general equilibrium model that has been extensively used by the IMF to assess the macroeconomic and fiscal impacts of a disaster in low- and middle-income countries (Marto et al., 2018). The model contains three blocks representing firms, governments, and households. Furthermore, it focuses on five transmission channels in which disasters can affect the economy: (1) permanent damages to public infrastructure, (2) permanent damages to private capital, (3) temporary losses in productivity, (4) damages in the sovereign's creditworthiness, and (5) a decline in public investment efficiency for reconstruction.

The research also constructs multiple disaster shock scenarios based on the occurrence of probability, ranging from 1-in-10 to 1-in-5000 year event. The scenarios are drawn from the Global Infrastructure Risk Model and Resilience Index (GIRI), a publicly available model that estimates the economic values of risks to infrastructure assets with respect to hazards. The damages are derived from three levels of assessments: (1) hazard assessment, representing hazard scenarios according to intensity and spatial distribution, (2) exposure assessment, specifying the level of exposed assets, and (3) vulnerability assessment, linking assets to vulnerability functions.

Lastly, the country selection is based on the differences in public debt sustainability-related components, as well as considering the diversity in terms of geography, sovereign credit ratings, and public infrastructure investment level. It is assumed that debt financing is the preferred financing option for the government for all countries to cover the fiscal gap for reconstruction and economy recovery.

Simulation Results

The research focuses on eight economies across sub-Saharan Africa, Southeast Asia, and the Caribbean focusing on impacts from floods and earthquakes. The initial findings underline the non-linear impacts on real GDP and public debt across scenarios, and that both types of disasters display distinct fiscal impacts in both acute and long-term due to their differences in spatial distribution of the disaster impact, types of infrastructure sectors affected, and damage levels to infrastructure assets. In particular, the impacts from a disaster in some scenarios can sharply increase public debt and further contribute to the increasing servicing costs. Figure 1 presents the range of the public debt servicing costs (as a percentage of GDP), assuming that the average interest rate remains constant, from baseline to across 1-10 to 1-5000 year scenarios. The figure indicates that the range between the scenarios is limited for flood scenarios across countries, from 0% in Rwanda to 0.19% in Bangladesh, when compared to the same set of scenarios for earthquakes, which are from 0.01% in Cameroon to 1.05% in Jamaica. The results demonstrate the differences of the potential additional fiscal pressure on the government budgets. This could also lead to implications in terms of public interventions post-disaster to address the fiscal imbalances, for example raising taxes for revenues or redirecting the funds from other essential public expenditures such as health and education which can pause the country's development trajectories.

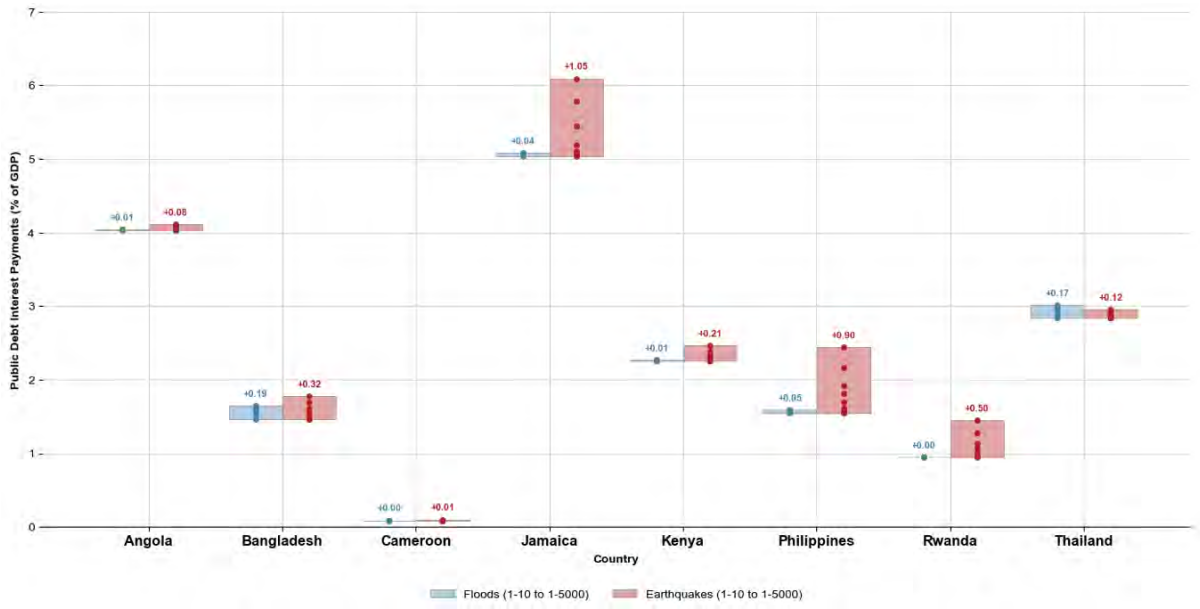


Figure 1. Public debt interest payments from the impacts of a disaster across 1-10 to 1-5000 return period scenarios.

Conclusion

The research estimates the fiscal implications of disaster risks to infrastructure using data on probabilistic risks disaster impacts in countries across low and middle-income countries. It connects forward-looking disaster scenarios with fiscal risk assessments in order to provide a more comprehensive view of the potential damages on different economies and fiscal budgets. These findings will inform governments, policymakers, and other relevant authorities on the relationship between extreme events and the economy and public finances and encourage these actors to strengthen their fiscal risk assessments. By incorporating a wider range of scenarios

to improve disaster risk management strategies, governments would be less susceptible to fiscal shocks and therefore can invest more resources into economic growth, social development, and climate resilience.

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Estimating (contingent) business interruption losses for insurance pricing.

Tan Phan[1], Marcello Arosio[2]

1 Scuola Universitaria Superiore IUSS Pavia, Italy, tan.phan@iusspavia.it

2 Scuola Universitaria Superiore IUSS Pavia, Italy, marcello.arosio@iusspavia.it

Abstract

Business interruption (BI) insurance covers direct financial losses from physical damage to a company's own operations, while contingent business interruption (CBI) insurance covers indirect losses from disruptions to third-party suppliers or customers. However, the insurance industry faces pricing challenges due to the lack of methodologies that explicitly separate these loss types, particularly in insurance catastrophe models that produce granular physical damage estimations. This study develops a novel framework to distinguish BI from CBI losses and enhance catastrophe modeling capabilities using the 2023 Emilia-Romagna flood as a case study. We integrate CORINE Land Use and Land Cover data with a modified dynamic inoperability input-output model to quantify physical damage impacts and cascading supply chain disruptions. Our methodology prevents double-counting through conditional logic that separates BI and CBI components while providing granular loss estimations.

Keywords: Business interruption, Contingent business interruption, Cascading effect, Insurance

1. Introduction

Business interruption (BI) insurance has long been a core offering in the insurance industry, providing coverage for financial losses resulting from direct disruptions to a company's operations. However, contingent business interruption (CBI) has only recently gained prominence, driven by the increasing complexity and interdependence of global supply chains. Unlike traditional business interruption, CBI covers losses from disruptions to third-party suppliers, customers, or partners. Due to its complexity, CBI has been understudied in existing literature. To address this gap, our research aims to separately estimate BI and CBI losses using the 2023 Emilia-Romagna flood as a case study. We employ land use and land cover (LULC) data and a dynamic inoperability input-output model to quantify direct and indirect economic impacts. Results show total economic losses of €5.5 billion regionally and €6.0 billion nationally, with ICT, industry, and agriculture sectors most affected by cascading effects.

2. Methodology

2.1. Mapping economic activities and LULC data

The CORINE Land Use and Land Cover (LULC) (European Environment Agency, 2019) data has been adopted as the foundational dataset for the analysis (Fig.1). Each LULC class is systematically assigned to one or more economic sectors based on its characteristics and relevance.

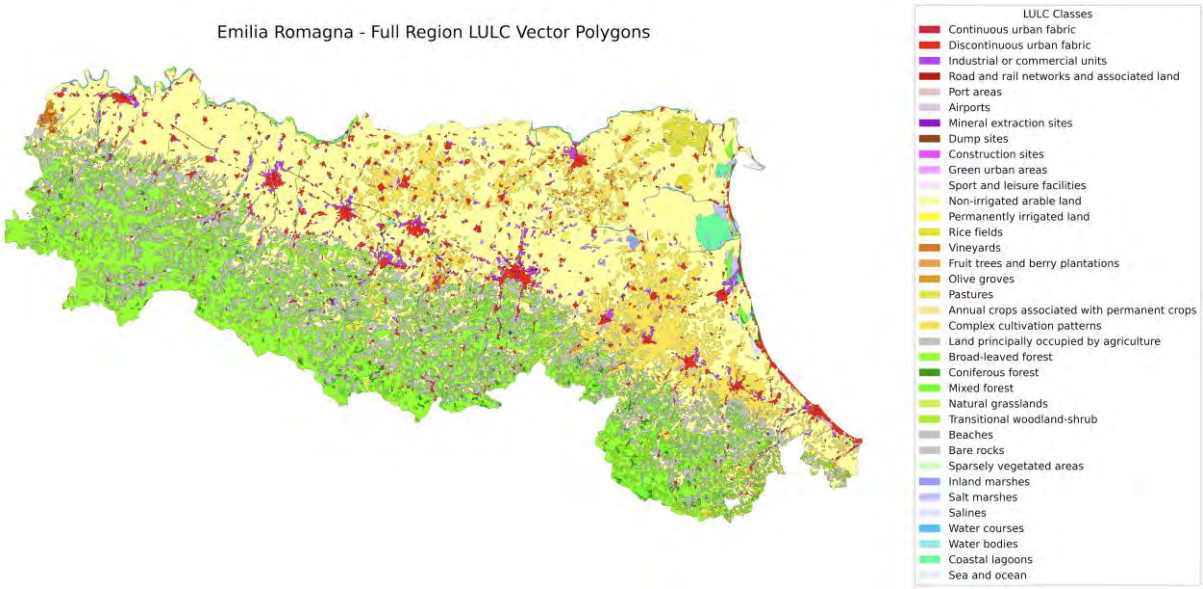


Figure 1. Emilia-Romagna LULC map

2.2. Estimating BI losses

The estimation of BI losses is conducted through a systematic approach. First, a hazard map is overlaid onto the LULC map to delineate the flooded areas corresponding to each LULC class. The intensity of the hazard is then utilized to extract the damage factor from JRC-established vulnerability curves (Huizinga et al., 2017), facilitating the quantification of physical damage within the inundated regions.

Subsequently, BI losses for each economic sector are assumed to be directly proportional to the physical damage sustained by the associated LULC class. To enhance the accuracy of the physical damage estimation, an occupancy type is assigned to each sector-LULC combination. Each occupancy type is characterized by a distinct vulnerability profile, ensuring that the estimation process accounts for the specific susceptibility of different sector-LULC pairings.

The restoration time for physical damage (and the associated BI losses) is derived from HAZUS and Di Noia et al., (2025). In the frameworks proposed by HAZUS and Di Noia et al., (2025) production is assumed to cease entirely during the restoration period. However, in our model, we adopt a dynamic approach by assuming that production recovers gradually on a weekly basis. The total BI losses are then calculated as the cumulative weekly losses over the restoration period.

2.3. Estimating CBI losses

To estimate the CBI losses, we utilized the dynamic inoperability input-output model (DIIM). However, the original DIIM framework and its applications to date have not distinguished between BI and CBI losses, instead calculating the overall economic losses collectively. To address this limitation, our model incorporates an additional step to explicitly separate BI and CBI losses, enabling a more detailed and nuanced analysis of economic disruptions.

Consider the general equation of the DIIM (Orsi & Santos, 2010; Santos et al., 2014):

$$\boldsymbol{q}(t+1) = \boldsymbol{q}(t) + \boldsymbol{K}[\boldsymbol{A}^*\boldsymbol{q}(t) + \boldsymbol{c}^*(t) - \boldsymbol{q}(t)]$$

Where:

- $q(t)$ – inoperability vector (0-1) at time *t*, in which 0 means there is no, and 1 means the production is totally inoperable
- K – resilience matrix (0-1), represents the ability of the system to recover from some initial level to a final level of inoperability in each period
- A^* – interdependency matrix represents the pairwise relationship across sectors
- $c^*(t)$ – perturbation vector at time *t* represents the drop in demand

At the initial time step, BI losses serve as the baseline for quantifying inoperability propagation. At each subsequent time step, an inoperability adjustment is introduced. Within this flooded region, sectors directly impacted by physical damage experienced BI and CBI losses. To prevent double-counting, a conditional approach is applied: if BI losses exceed CBI losses at a given time step *t*, only the BI losses are considered. Conversely, if supply chain disruptions surpass the impact of flood damage, the additional disruption is classified as CBI loss.

3. Case study & Preliminary results

We conducted a case study for the flood in the Emilia-Romagna region in 2023. We employ a multi-regional input-output table (MRIO) which contains the material flows between 272 NUTS2 regions and 10 aggregated sectors (Huang & Koutroumpis, 2023). The hazard map of the event is provided by Copernicus (Fig. 2) (*EMSN154 | Copernicus EMS On Demand Mapping*, n.d.).

The total economic losses resulting from the flood are estimated at €5,500 million within the flooded region and €6,038 million at the national scale (Fig. 3 & Fig. 4). Within the Emilia-Romagna region, CBI losses are notably more minor compared to those observed at the national level. Among the sectors, ICT, industry, and primary (agriculture) are identified as the most affected due to the cascading effects, as evidenced by their significant CBI losses (Fig. 5).

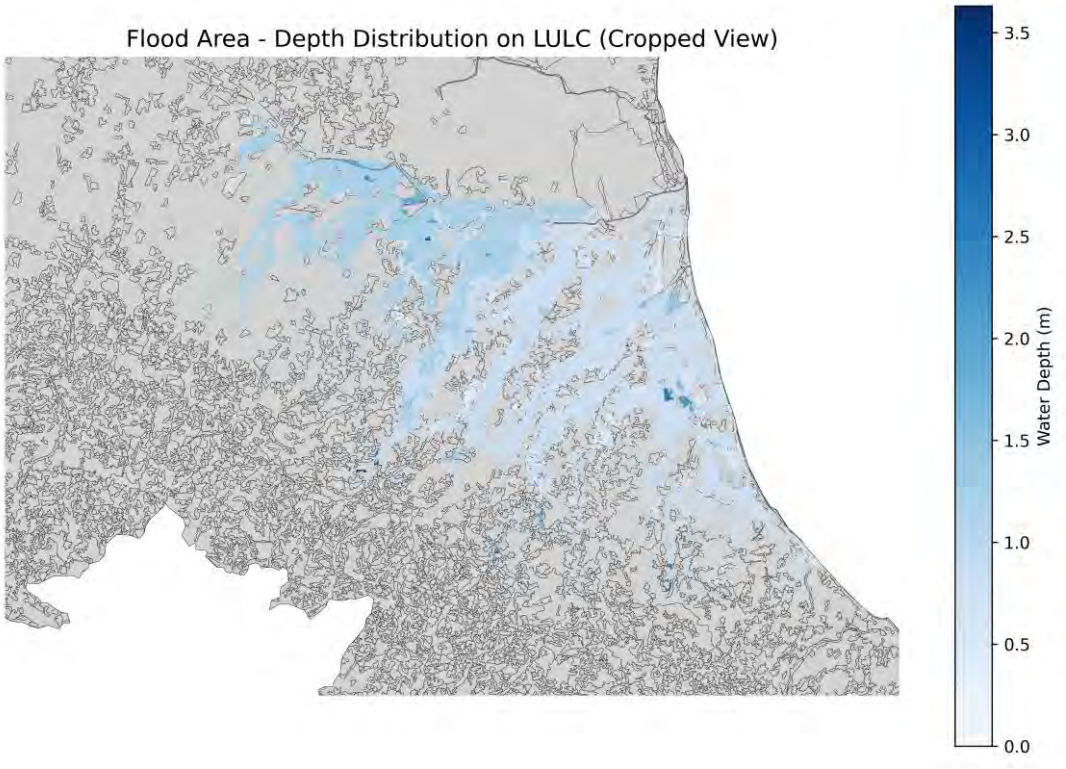


Figure 2. Emilia-Romagna flood 2023 hazard map

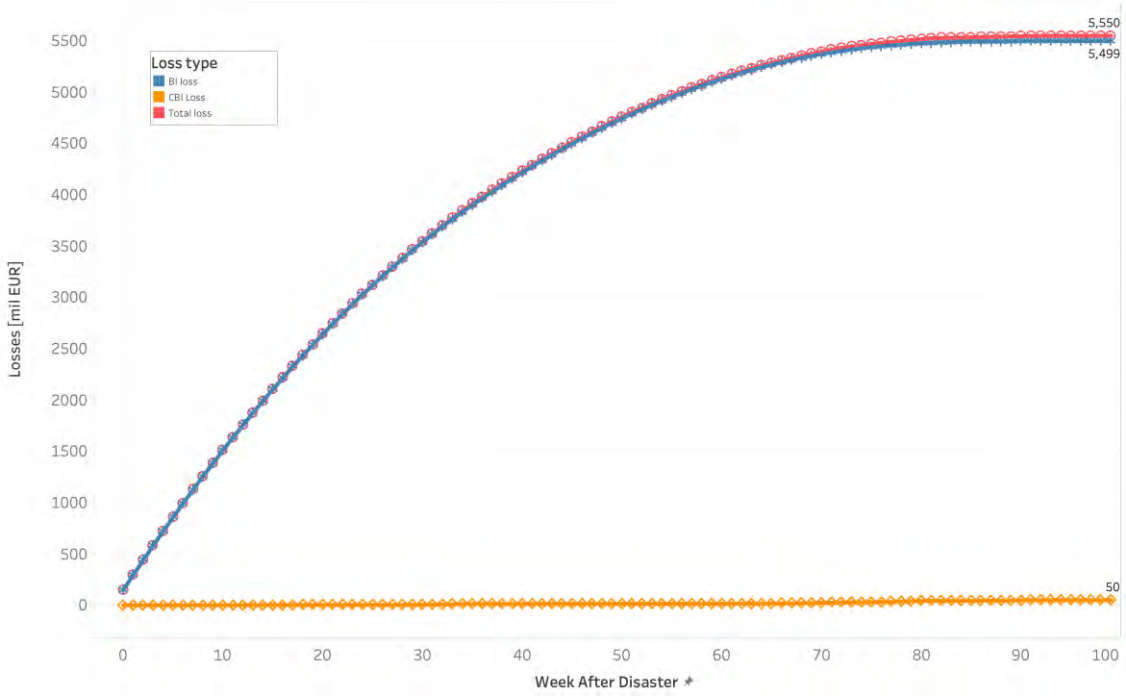


Figure 3. Emilia-Romagna regional economic losses

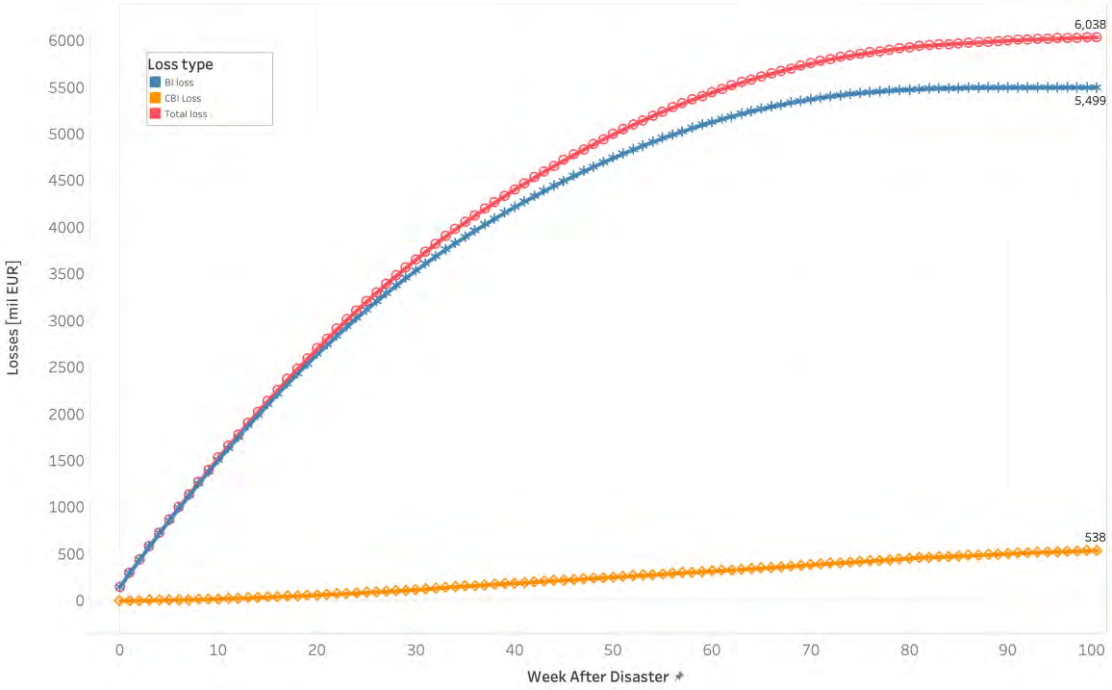


Figure 4. Italy's national economic losses

4. Discussion and conclusion

The results are evidently influenced by the assignment of LULC classes and areas to economic sectors. Currently, economic output is exclusively used as the weighting factor. However, in the forthcoming version, the weighting factor will be derived from firm locations provided by Di Noia et al., (2025) and a building footprint dataset, ensuring a more precise and spatially informed analysis.

Despite the limitation, we emphasize that this model is, to the best of our knowledge, the first to explicitly differentiate between BI and CBI losses caused by natural disasters on a large scale. Therefore, this approach provides valuable applications for insurance pricing and claims and is a straightforward and effective tool for systemic risk management.

Region Name	Sector Name: Primary	Industry	Construction	Distribution	ICT	Financial Services	Real Estate Activities	Professional Services	Public Services	Other Services	Grand Total
Piemonte	0.7	0.2	1.3	0.0	1.0	1.3	0.6	6.3	0.0	0.0	11.4
Valle d'Aosta	0.1	0.0	0.6	1.9	1.7	0.1	0.0	0.0	0.0	0.4	4.8
Liguria	0.0	0.1	0.1	0.7	0.0	1.5	0.3	0.4	0.0	0.0	3.1
Lombardia	0.0	0.1	2.8	0.3	0.0	1.8	0.0	0.0	0.5	0.2	5.6
Abruzzo	0.3	0.0	0.1	9.0	2.2	0.0	1.4	0.0	0.2	0.2	13.3
Molise	0.3	0.0	0.2	0.1	0.1	0.2	0.3	0.7	0.0	0.0	1.9
Campania	45.1	2.8	7.9	8.0	0.0	17.9	0.2	0.6	48.9	17.2	148.7
Puglia	5.9	0.0	0.0	0.1	0.3	0.1	18.5	2.0	0.9	0.0	27.9
Basilicata	0.6	46.4	0.0	0.0	0.5	0.3	1.6	0.4	0.2	0.5	50.5
Calabria	0.1	0.0	0.4	3.9	0.0	0.2	0.1	1.4	0.0	0.1	6.2
Sicilia	1.2	2.5	0.0	0.2	20.5	1.8	5.7	0.2	0.0	0.2	32.4
Sardegna	0.0	0.0	0.0	17.3	3.8	0.0	0.0	0.0	0.0	2.8	24.1
Bolzano/Bozen	0.0	0.1	0.5	0.0	0.0	0.8	4.4	0.5	0.0	0.0	6.3
Trento	0.0	0.1	0.4	1.4	0.0	0.3	0.0	2.8	0.1	0.1	5.3
Veneto	0.0	0.0	3.3	0.2	20.0	0.0	13.6	0.0	0.0	0.1	37.3
Friuli-Venezia Giulia	0.2	1.0	1.4	0.0	0.7	0.1	9.1	0.2	0.0	0.2	13.1
Emilia-Romagna (Flooded)	1.3	8.3	3.8	2.1	14.1	0.9	0.9	8.2	2.9	7.7	50.1
Toscana	11.3	0.0	0.0	0.0	0.3	0.1	0.5	10.0	0.0	0.0	22.4
Umbria	1.7	6.2	0.0	0.0	0.0	1.3	0.4	0.7	0.2	5.5	16.0
Marche	0.0	0.0	4.2	0.1	25.6	1.9	0.1	4.2	0.0	0.0	36.2
Lazio	10.8	0.0	0.3	1.0	1.9	6.3	0.8	0.1	0.0	0.3	21.5
Grand Total	79.8	68.0	27.3	46.3	92.8	36.9	58.4	38.9	54.0	35.6	538.1

Figure 5. Region-Sector CBI losses

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3. Resilience Of Infrastructure Systems

Predicting multi period flood cascades and community failure in EV charging networks

Yunshan Wan[1], Rong Xia[1], Paolo Vincenzo Genovese[1]
1.College of Civil Engineering and Architecture, Zhejiang University, Hangzhou, China

Abstract

Most infrastructure-network risk assessments rest on static, component-level resilience, neglecting both the need for asset-specific strategies within a shared network and the spatiotemporal cascades from dynamic interdependencies that govern system-wide risk. To bridge this gap, we develop a spatiotemporal framework for infrastructure networks that maps structural risk within and between regions, quantifies risk transfer and failure linkages across historical and projected seasons, and prescribes community-specific risk mitigation. Remote-sensing–informed FLEXTH with BiLSTM bias correction and forecasting yields UK-wide floodextent and depth for 2020, 2022, 2024 and projected 2026, 2028, 2030 in dry and wet seasons. For each period, a UK-wide risk network was constructed from 43,162 charging points using a road-skeleton–constrained kNN–MST hybrid. The 12-region graph encodes node features (asset importance, environmental exposure, flood probability and depth) and edge features (service dependence, hydrologic propagation, and road propagation). The resulting failure probabilities feed into a static–dynamic non-homogeneous Markov model, producing multi-period trajectories of node and edge failure. A non-homogeneous Markov random-walk flow analysed with Infomap then yields approximately 632–688 risk communities per scenario. We find: (1) In a network with coupled nodes and edges, station failure is governed by network-level propagation, showing co-amplification in wet seasons and edge-dominated, topology-driven behavior in dry seasons. Edge risk explains node failure more than the reverse; cross-regional links are more fragile than intra-regional links. Hotspots persist or recur, yet by 2030 both node and edge failure rates converge to lower levels; (2) Under dynamic conditions, the regional risk network exhibits a dual-core structure (London and Scotland), a small-world pattern, and backbone dominance. Node failure is most strongly associated with degree, k-core, Katz, and strength (Spearman !≈0.18–0.34, p<0.01); edge failure is driven by endpoint scale, with degree product positively correlated with failure probability (Spearman ! ≈0.12-0.23, p<0.01) ; (3)Six risk-propagation archetypes are identified: source-driven, corridor-amplifying, vulnerable-absorbing, bidirectionally coupled, isolated-robust, and neutral-steady. Under future scenarios, network risk shifts from concentration in a few large communities to dispersion across many smaller ones, with the high-risk burden more widely distributed. This decision-grade framework links flood hazards to multi-period system and community failure, targets resilience investment at risk communities and regional backbones for maximal system benefit, and generalizes across infrastructures for climate-ready governance.

Keywords: infrastructure networks; failure probability; risk transfer; Nonhomogeneous Markov model; Infomap community detection

Flash Flood Damage Analysis of the Rail Road Infrastructure

Eva-Lotte Schriewer 1

1 Institute of Hydraulic Engineering and Water Resources Management, RWTH Aachen University, Germany, schriewer@iww.rwth-aachen.de

Abstract

The rail road infrastructure plays an important role in the daily transport of people and goods. However, its fixed location to railroad tracks with almost no alternative routes makes this transport system highly vulnerable to disruptions and closures leading to extended travel times, delay of goods or even losses of businesses as a further consequence. Disruptions to the rail road traffic system can be caused by natural hazards like heavy rainfall. These events are characterized by small catchments which makes it difficult to predict the affected areas reliably highlighting its potential appearance in every region. Moreover, heavy rainfall can result in flash floods with a high damage potential in consequence of high-velocity flows and high shear stresses, especially in regions with pronounced topography. Recent heavy rainfall events exemplified by the flood in July 2021 in Germany and other parts of Europe caused significant damages to infrastructures including the rail road infrastructure. Rail road tracks or bridge piers were washed-out and debris was deposited on tracks.

The predicted increase in frequency and intensity of extreme events due to climate change highlight the importance to develop a more resilient rail road infrastructure. To tackle these challenges from a technical perspective, knowledge about critical elements and highly vulnerable track sections is needed. Therefore, a detailed analysis of the rail road infrastructure was conducted using flood hazard and flash flood hazard maps as well as the distance to rivers as indicators. The analysis shows that this approach is easily applicable with QGIS tools and potentially affected rail road tracks can be identified. Furthermore, a detailed damage analysis of affected rail road sections caused by the event in July 2021 identified vulnerable rail road elements of the rail road infrastructure in the case study area.

Overall, the results from this study provide a fundamental basis to develop measures and concepts that mitigate the effects of damage induced by heavy rainfall and flash floods and to further increase the resilience of the rail road infrastructure. Additional analysis of flash floods damages to the rail road infrastructure can enhance the understanding of damage potentials in different areas.

Keywords: flash flood damage; rail road infrastructure; heavy rain

Impact of Diversity on Energy System Resilience

Ann Kathrin Seyfried[1], Paul Runte[2]
1: Fraunhofer-Institut für Chemische Technologie (ICT), Germany, ann.kathrin.seyfried@ict.fraunhofer.de
2: University of Bremen, Germany, runte@iat.uni-bremen.de

Abstract

Diversity is widely regarded as enhancing energy system resilience. However, most existing metrics emphasize only variety and balance, while largely ignoring disparity, yielding unclear links to resilience. First, the composition of diversity is performed by capturing variety, balance, and disparity. Second, the diversity of energy systems is analyzed to assess their resilience. Stirling's diversity heuristic is then implemented in a sector-coupled energy system including electricity, heat, and hydrogen. Disparity is quantified from sector-specific attributes such as import dependence, CO_2 intensity, and weather dependency. Existing diversity indices – including the Shannon-Wiener and Herfindahl-Hirschman measures – are evaluated, and a sensitivity analysis of the Stirling heuristic is carried out. This analysis enables informed, cross-sector decisions for resilient, cost-aware energy system design.

Keywords: Diversity, Disparity, Sector coupling, Energy System

Introduction

Resilience in energy systems is of high and growing interest, as our modern societies are increasingly dependent on reliable, affordable, and efficient energy supply (Ahmadi et al., 2021). This dependence creates systemic risk, with recent events highlighting potential consequences, such as the blackout in Spain in April 2025.

Diversity is widely advocated as a resilience-enhancing property in energy systems (Wyss et al., 2018). However, a recent review by Shafiei et al. (2025) on resilience in energy systems did not systematically address diversity. Nevertheless, it has received greater attention and application in various studies (Grubb et al., 2006; Kharrazi et al., 2015; Molyneaux et al., 2014). The studies deploy a range of indicators to measure diversity, and no single metric has become standard. Consequently, it remains unclear which indicator(s) are most suitable for diversity quantification. Moreover, although diversity is generally associated with resilience, the actual levels of diversity in real systems and their impact on resilience remain insufficiently understood (Kharrazi et al., 2015; Thier & Pot d'or, 2020; Wyss et al., 2018).

Based on these gaps, two research questions guide this study:

1. How can energy system diversity be measured in a way that captures all salient properties of the system?

2. What levels and compositions of diversity are most favorable for energy system resilience?

Diversity

Diversity is generally described by its three properties: variety, balance, and disparity. Variety is the number of categories within the system. Balance describes the distribution of shares across those categories. Disparity measures how different categories are from each other (Stirling, 1998).

A range of indicators for these properties and their combinations exist in literature:

Table 1: Selected existing diversity indicators (Stirling, 2010)

Property	**Name**	**Form**
Variety	Category Count (Mc Arthur 1965)	N
Balance	Shannon Evenness (Pielou 1969)	$E = (-\Sigma_i\, p_i \ln p_i)/\ln N$
Disparity	Solow and Polasky (1994)	$D_i = f\,(d_{ij})$
Variety/ Balance	Shannon-Wiener Index (1962)	SWI $= -\Sigma_i\, p_i \ln p_i$
	Herfindahl-Hirschmann (1949)	HHI $= \Sigma_i\, p_i^2$
Variety / Balance / Disparity	Stirling's diversity (2007)	$D = \Sigma_{ij}\, d_{ij} p_i p_j$
	Stirling's heuristic (2007, 2010)	$\Delta = \Sigma_{ij}\, d_{ij}^{\alpha}\, (p_i p_j)^{\beta}$
N p_i, p_j $f\,(d_{ij})$ α, β	Number of categories of energy options Proportion of energy system option category *i*, *j* Function of disparity distance between categories *i* and *j* Parameters governing relative weightings on variety, balance, and disparity	

Most applications in the energy literature emphasize variety and/or balance, e.g., the Shannon–Wiener Index (SWI) (Kharrazi et al., 2015), the Gini Diversity Index (Molyneaux et al., 2012), or combinations such as SWI with Herfindahl-Hirschmann (HHI) (Grubb et al., 2006). The International Energy Agency notes that HHI is often used to quantify concentration, which is most appropriate for market structure assessments (IEA, 2020, see also Kruyt et al., 2009). However, focusing only on variety and balance neglects the crucial property of disparity, i.e., how different options are (Stirling, 2010), exemplary illustrated in Figure 1.

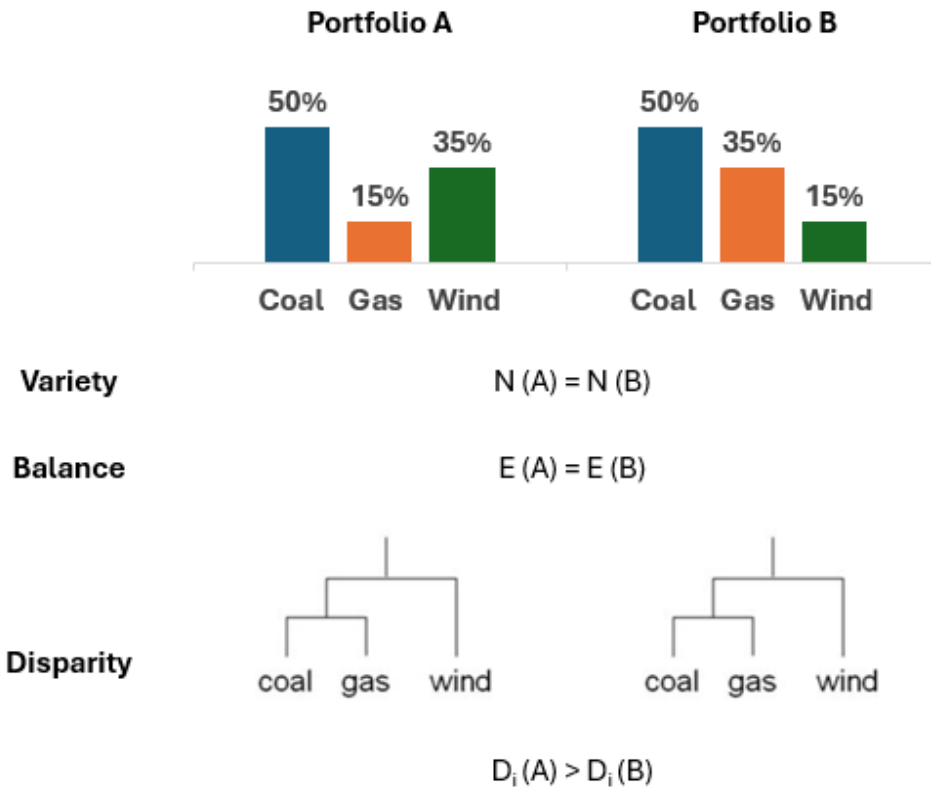


Figure 1: Example of diversity properties of two portfolios (modified after (Stirling, 2010)

The variation in coal, gas, and wind across portfolios A and B will not affect the variety and balance indicators, see Figure 1. Because wind differs from coal to a greater extent than gas does—particularly in terms of fuel dependence, operational characteristics, and geographic constraints (Stirling, 2010). These differences matter for resilience especially when facing multiple uncertain shocks.

Stirling's diversity framework (Stirling, 2007, 2010) formalizes a general diversity framework that integrates all three properties: variety, balance, and disparity. The non-parametric form is $D = \Sigma_{ij} d_{ij} p_i p_j$, where p_i and p_j are category shares (balance) and d_{ij} are pairwise disparities. Variety is implicitly included as the sum runs over all pairs of options with non-zero shares. To flexibly reweight the contribution of disparity and balance, Stirling proposes the parametric "heuristic": $\Delta = \Sigma_{ij}\, d_{ij}^{\alpha}\, (p_i p_j)^{\beta}$:

- α controls the emphasis on disparity distances: higher α amplifies the influence of more distant (more different) option pairs, while α = 0 collapses disparity to a constant (effectively ignoring it).
- β controls sensitivity to balance: higher β places more weight on evenly distributed portfolios, while β = 0 reduces the role of shares and focuses on the presence/absence and distances (i.e., variety-weighted disparity).

Disparity

By including disparity in diversity quantification a central challenge is how to determine disparity objectively (Stirling, 2010). Kruyt et al. (2009) argue that disparity assessment is opinion-driven. Without a well-founded disparity measure, no disparity measure can be considered theoretically valid. A practical approach is to compute disparity as distances in a normalized multi-attribute space that captures salient differences among technologies (Stirling, 2007).

Wyss et al. (2018) propose such an approach for renewable technologies, incorporating attributes like conversion efficiency, CO_2 intensity, weather dependency, and other disparity attributes. More recently, Runte et al. (2024) applied this approach specifically for power systems on plant- and grid level.
Based on Wyss et al. (2018), disparity is assessed at the system and sector levels, with an expanded technology scope covering the electricity, heat, and hydrogen sectors. This enables a transparent and reproducible disparity assessment for these sectors based on attributes such as:

- Import dependency
- CO_2 intensity
- Weather dependency

Attributes are normalized, weighted (with sensitivity analysis), and combined to compute disparity. This allows Δ to reflect technological differences that are salient to resilience, rather than only the number (variety) or evenness (balance) of options.

Outlook

To address Research Question 1 – how to quantify diversity – by operationalizing a disparity-aware metric and benchmarking it against commonly used indicators. This work applies Stirling's D and Δ to a sector-coupled energy system (electricity, heat, hydrogen) and evaluates them against established variety/balance indices (SWI and HHI) that omit disparity. We construct a disparity matrix based on (Wyss et al., 2018) and extending, adding technologies across the three sectors and disparity attributes. We then compare rankings and sensitivities across D, Δ (with varied α and β), SWI, and HHI. Research Question 2 – what level of diversity is favorable – is addressed by exploring how different α and β values, portfolio compositions, and attribute weightings relate to resilience and costs. The results aim to enhance resilience and maintain economic feasibility.

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Integrative Infrastructure Management for Municipality's Climate Resilience

Yirang Lim[1], Angela Ordóñez Llancce[2], Johan Ninan[3]
1. Faculty of Civil Engineering and Geoscience, TU Delft, Netherlands, y.lim@tudelft.nl
2. Royal Haskoning DHV, Netherlands, aordonezll@hotmail.com
3. Faculty of Civil Engineering and Geoscience, TU Delft, Netherlands, j.ninan@tudelft.nl

Abstract

Climate change increases the chances of extreme weather, while public agencies struggle with constrained budgets, and ageing infrastructure assets require renewal. Building resilient infrastructure involves not only technical solutions but also significant institutional and managerial efforts. As climate-induced disruptions grow in frequency and intensity, municipalities face urgent pressure to reconfigure how infrastructure is designed, delivered, and maintained. This paper investigates how integrative infrastructure management can be operationalised at the municipality level to enhance climate resilience, drawing from in-depth empirical research in the city of Rotterdam, Netherlands. The data were collected through by 16 semi-structured interviews at various levels and departments related to infrastructure management in the municipality. Based on thematic analysis, this research found that challenges stem from fragmentation and path-dependency in the infrastructure system, which leads to temporal misalignment and delayed alignment between infrastructure projects that hinder system thinking and opportunities for integration. We also identified pilot projects as enablers of organisational learning and the importance of motivated agents and institutional support to keep them. This research offers insights bridging climate resilience, infrastructure governance, and project management and practical guidance for municipalities on how to enhance their climate resilience in infrastructure management.

Keywords: climate-resilient infrastructure; integrated infrastructure management; collaborative governance; municipality

1. Introduction

Climate change-induced extreme weather events have caused significant damage to lives and assets across many countries. For example, UK and Western Europe were struck by Storm Eunice in 2022, causing significant structural damage, power outages, fatalities, and an estimated €500 million in damages[1]. The significant socio-economic impacts of climate change highlight the urgent need for more resilient planning, designing and managing of infrastructure

[1] https://www.knmi.nl/over-het-knmi/nieuws/drielingstorm-dudley-eunice-en-franklin

systems (Brown et al., 2018). Infrastructure systems are interdependent in material, data and information, locations, and administration (Haggag et al., 2020; Rinaldi et al., 2001). However, current infrastructure systems are focused on project-based management by disciplines such as water, transport, energy and information and communication technologies (ICT) (Teisman et al., 2013). Moreover, it is challenging to facilitate systematic change due to the inherent uncertainty of climate and societal change (Meerow et al., 2016) and complexity in decision-making (Gay & Sinha, 2013; Haggag et al., 2020).

To deal with complexity and interdependency in infrastructure management, integration at the local level is desirable (Derrible, 2017). An integrative approach that encompasses various disciplines can contribute to enhancing resilience and sustainability in infrastructure management (Mohebbi et al., 2020). An integrative approach inherently requires collaboration between actors to generate new ideas, out-of-the-box thinking, while overcoming the limitation of domain-specific knowledge. However, the integrative approach is sporadically implemented, rather than program-wide implementation, not aligned with the budgeting and governance structure of the local governments (Ordóñez Llancce et al., 2025). System-wide transition is needed, yet how to facilitate this transition remains a challenge. In this regard, this research investigates following research question: what is needed to facilitate integrated infrastructure management at municipal level for climate-resilient infrastructure delivery? We especially focus on early cross-sector collaboration, lifecycle design, and adaptive management, as a strategy for integrated infrastructure management.

Using Rotterdam as a case study, we investigate how integrative infrastructure management is being implemented in practice. Rotterdam, located in the Dutch delta region and home to critical national assets such as the Port of Rotterdam and major energy and transport networks, faces acute climate risks. Simultaneously, it has become a frontrunner in adaptive urban strategies, including multifunctional water plazas, blue-green networks, and pilot-based innovations. The research is based on 16 expert interviews conducted with municipal staff across departments including water, energy, circularity, climate adaptation, and urban planning. Using thematic analysis, we explored how climate-resilient infrastructure is understood, what enablers and barriers shape integrated practices, and how pilot projects and organizational roles contribute to transition pathways.

2. Literature Review

2.1. Adaptive governance and System thinking for Climate-Resilient Infrastructure

Conventionally, infrastructure resilience has been framed through the lens of robustness and redundancy, with an emphasis on physical performance and technical durability. Infrastructure resilience was based on a "fail-safe" approach, which emphasises designing systems to withstand known risks within established thresholds (Ahern, 2011). However, the unpredictability of climate change has necessitated a shift toward "safe-to-fail" and adaptive strategies, where flexibility and learning are prioritised (Miller et al., 2018). In the resilience lens, infrastructure is a dynamic system that must absorb, adapt, and transform in response to stressors (Folke, 2006).

Recent work distinguishes between different levels of resilience: asset-level (reducing life cycle costs), network-level (ensuring continuous service), and user-level (protecting community well-being) (Hallegatte et al., 2019). These levels provide a holistic approach of understanding resilience of infrastructure system. However, strengthening resilience at the asset, network, and user levels is not only a technical challenge but also an institutional and governance one. Achieving coherence across these levels requires coordination among diverse stakeholders, whose actions are often fragmented across sectors and administrative boundaries. This makes governance frameworks particularly important in guiding how resilience is operationalized in infrastructure systems

Theoretical frameworks such as Collaborative Governance Theory (Ansell & Gash, 2008) and Policy Integration Theory (Candel & Biesbroek, 2016) provide insight into how public agencies can overcome these silos. Collaborative governance emphasises the need for coordinated action among governmental and non-governmental actors, especially under conditions of interdependence and uncertainty (Ansell & Gash, 2008; Head & Alford, 2013). Policy integration, meanwhile, assesses the extent to which policies across sectors are aligned, a prerequisite for effective infrastructure management in the face of complex challenges like climate change (Candel & Biesbroek, 2016). Adaptive governance (Pahl-Wostl, 2009; Folke et al., 2005) further emphasises flexible, learning-based structures capable of responding to complex environmental challenges. These concepts are especially relevant for municipalities like Rotterdam, where high climate risk intersects with national economic interests (Bucx et al., 2014). There is a need for an integrated approach for lifecycle thinking for climate adaptation and also to enable systemic coordination.

2.2. Integrated Infrastructure Management

Urban infrastructure systems such as water, energy, green space, transport, and ICT are deeply interdependent, yet their management is often fragmented across departmental, disciplinary, and governance boundaries (Teisman et al., 2013; Haggag et al., 2020). This fragmentation leads to inefficiencies, misaligned goals, and tensions among stakeholders, particularly at the municipal level, where the responsibility for daily management, adaptation, and service delivery is most acute (Eidelman et al., 2022; Ordóñez Llancce et al., 2025).

However, growing complexity and interdependence in urban infrastructure systems call for a broader understanding that integrates governance, organisational learning, and collaborative project delivery. In this context, integrated infrastructure management emerges as a potential enabler of resilience, functioning not merely as a project delivery tool but as a governance mechanism capable of coordinating diverse interests, timelines, and goals throughout the infrastructure lifecycle. Integrated infrastructure management emphasizes early interdisciplinary coordination, lifecycle thinking, and systemic design in public infrastructure (Winch, 2010; Lenferink et al., 2013).

Despite recognition of the need for integration, implementation remains sporadic and often misaligned with municipal budgeting and governance structures (Ordóñez Llancce et al., 2025). Intersectoral collaboration can generate innovative solutions and overcome the limitations of domain-specific knowledge (Mohebbi et al., 2020) but requires significant organizational change and capacity building within local governments.

Derrible (2017) proposed a framework to understand integration in urban infrastructure system with two standards: integrated vs. separated infrastructure structure and centralized vs. decentralized by the location. This framework maps infrastructures by physical design and control structure (e.g., centralized water treatment, decentralized microgrids). However, even a physically centralized system can be governed in an integrative or siloed way, depending on how projects are planned, financed, and delivered. Therefore, we need to add governance dimension (fragmented →systematic) to further advance in process integration. The difference between integration and governance dimensions is that the former focuses on day-to-day practice, tools, and methods through which infrastructure projects are designed, planned, and delivered in a coordinated way, while the latter focuses on the formal structure, roles, and rules that determine who has authority, how responsibilities are divided and how decisions are made. Governance dimension focuses on institutions, mandates, decision rights, accountability and finance, while integration dimension focuses on project management processes, design routines, co-creation methods and tools.

3. Methodology

The methodology of this research is qualitative methods to investigate holistic and in-depth knowledge on participant's experience and perception on integrative approach at local level to enhance climate resilience (Bansal et al., 2018; Owen, 2014). We use the context of Rotterdam municipality for this student given they have an ambition to be resilient city and have taken numerous effects towards it. The data is collected by expert interviews at the Rotterdam municipality at various levels: strategic managers, program managers, and project managers. The experts were from various disciplines including urban design, climate resilience, energy transition, water management, and circularity see (Table 1). The language of interviews was English; durations of interview were between 30~60 minutes. The transcriptions were made and anonymized and used for in-depth analysis.

Table 1 List of interviewees

Code	Role	Interview	Duration
EXP1	Urban water advisor	Semi-Structured	47
EXP2	Infrastructure design advisor	Semi-Structured	80
EXP3	Urban water advisor	Semi-Structured	45
EXP4	Urban design advisor	Semi-Structured	54
EXP5	Underground Design advisor	Unstructured	45
EXP6	Circularity advisor	Unstructured	53
EXP7	Energy advisor	Semi-Structured	49
EXP8	Landscape Designer	Semi-Structured	57
EXP9	Landscape Designer	Semi-Structured	57
EXP10	Strategic Advisor	Semi-Structured	43
EXP11	Project Manager	Semi-Structured	54
EXP12	Integral Manager	Semi-Structured	53
EXP13	Program Manager	Semi-Structured	59
EXP14	Project Manager	Semi-Structured	55
EXP15	Program Manager	Semi-Structured	54

Semi-structured interviews were conducted to understand challenges and drivers of implementing integrated approach for enhancing climate resilience. First, we asked interviewee's role in the municipality then key questions were asked such as perception on climate resilient infrastructure, barriers and drivers of climate resilient infrastructure in design phase, barriers and drivers of integrated approach, and recommendations for implementing integrated approach in other infrastructure projects. In total, seventeen interviews were conducted.

Thematic analysis can provide comprehensive perspective of an issue based on open coding (Clarke & Braun, 2017). Using ATLAS.ti 24.0.0 for Windows as program, the coding process started by familiarizing with the transcriptions, assigning preliminary codes. As the coding progressed, some codes were merged or change to more suitable codes. It is an iterative process to identify key themes on barriers and drivers of integrative approach for climate resilient infrastructure. The following table summarizes codes identified in challenges and enablers of integrated infrastructure management.

Table 2. Challenges and Enablers of Integrated Infrastructure Management.

Framework dimension	Challenges	Enablers
Governance (Institution)	Fragmented roles and criteria	Integrative roles & leadership
	Misaligned timing	Strategic alignment and metrics
	Rigid process	Cross-functional teams
	Dependence on informal network	Formal collaboration mechanism
	Path dependency	Consensus-based decision making
	Unclear authority	Adaptive finance and process innovation
Integration (Process)	Collaboration difficulty	Digital tools & visualization
	Integration overload	Knowledge and transparency platforms
	Lack of shared understanding	Early co-design, stakeholder mapping
	Interdependency blind spots	Multi-functionality
	Tension of priorities	System perspective
Location	Local specificity	Area-based approach
	Scale mismatch	
Crosscutting	Awareness and motivation gaps	Culture & attitude
	Information gaps	Boundary spanning skills
	Skills gap	Capacity building and learning

*Challenges and enablers are simple list, not in a corresponding order.

4. Preliminary findings

a) Fragmentation and Path-Dependence

Current infrastructure governance is tightly siloed. Departments responsible for sewage, transport, utilities, and maintenance operate based on legacy responsibilities, leading to path-dependent institutional behaviour. Existing design-procurement systems reinforce sequential, discipline-specific work, limiting systems thinking and innovation in renewal projects.

In Rotterdam, the City development, City maintenance, and Design departments have their own boundaries and perspectives on specific sectors. Within the design department, there are specialised people who focus on sewage water, rain and storm water. Specialisation is necessary to provide up-to-date technological knowledge and know-how, but it makes broad system thinking difficult. When designing a new city development, each department and disciplines only focus on its tasks, often overlooking opportunities for synergies or an integrated system.

The current design process is first making a design for each discipline (e.g., water, electricity, telecommunication, transport, etc.), then combining those plans. The limitation of this approach is when there is limited space to incorporate all these claims and difficult decisions need to be made. "*Well, it's a difficult situation because the more people you involve, the more difficulties you make, and processes are slower and more time-consuming (DR1_SS)"*

Path dependency occurs not only at the policy level but also at the individual worker's level. In this structure, people often keep doing what they were doing. "*I guess the tendency of people and organisations is to do what they have already done. (DR4_SS)"*

Despite awareness and commitment, implementation of integrated approaches remains sporadic. Fragmentation persists in organisational structures, with responsibilities divided among departments based on disciplinary expertise (e.g., water, traffic, public space), leading to siloed planning and missed opportunities for synergies.

b) Temporal Misalignment and Delayed Alignment

Temporal misalignment between project cycles, department schedules, and strategic plans emerged as a key challenge. Integration is often undermined when departments work on different timelines or define project scopes without cross-sectoral alignment. This is particularly acute when project scopes are locked early in the process, limiting flexibility for later integration.

Discrepancies in project pace among teams generate coordination breakdowns. For example, design teams ready to advance circularity interventions encounter municipal stakeholders still engaged in strategic planning. Without synchronised timelines, opportunities for integrated design are lost.

c) Pilot Projects as Enablers of Learning

Pilot initiatives, such as multi-functional public squares doubling as stormwater reservoirs, emerge as micro-laboratories of integrated infrastructure planning. These small-scale, bounded experiments allow for failure, learning, co-creation, and potential scaling, under relative protection from institutional risk aversion. Pilots such as multi-functional water plaza (public space + water reservoir) allow for experimentation, learning, and stakeholder engagement in a relatively low-risk environment. Successful pilots, when followed by iterative rounds, can lead

to routinised practices and broader organisational learning. "*Pilot projects lead to scalable solutions […], and that's why we need a certain […] rounds of pilots (DR6_NS)"*
Moreover, existing governance procedures prioritise risk-aversion and financial accountability—constraining experimentation and collaboration. Public servants often face the dilemma of adhering to strict protocols while also needing to innovate within rigid structures.

d) Role of Motivated Agents and the Need for Institutional Support

Individuals with high intrinsic motivation (e.g. "integral managers") have been critical in brokering collaboration. While these efforts are commendable, they remain vulnerable without institutional embedding. Their efforts remain fragile without formal roles, routine processes, and organizational capacity-building. This underscores the need for Institutionalized Integrated Design Readiness across departments. *"We need people who want to take up the challenge as a society to give form to the necessary change. (DR2_SS)"*

Across interviews, there was consensus that climate change necessitates a shift in design paradigms and professional practices. Experts emphasised that climate-resilient infrastructure must be flexible, adaptive, robust, and people-centric—able to accommodate evolving societal and environmental needs. Notably, infrastructure is no longer seen as static physical systems but as part of dynamic socio-technical landscapes shaped by governance choices, user needs, and long-term risks.
A recurring insight was the need to move from isolated renewal efforts to lifecycle-oriented and area-based design. Maintenance cycles, for instance, were viewed as critical entry points for embedding climate adaptation goals, transforming renewal from routine replacement into strategic reinvention. "*You make it[infrastructure] in a way that it […] would last forever or […] much longer lifespan. […] Cities are ever evolving and changing, and so in a way, it's good that every couple of decades you get an opportunity to adapt or renovate with the needs of that time. So, in that sense, maybe the strategy is not to build things that last forever, but for a shorter lifespan by using completely local and naturally sourced materials. (DR4_SS)"*
Digital tools and visual communication (e.g., 3D models, Neighbourhood Atlas) were recognised as valuable in fostering shared understanding among departments and external actors. Visualisation helped translate abstract goals into tangible designs, enabling collaborative planning.

5. Discussion and Conclusion

This study underscores that building climate-resilient infrastructure is not only a technical challenge but also a deeply institutional and managerial one. Integrated project management provides a viable framework for municipalities to break silos, align goals, and deliver sustainable infrastructure systems. Rotterdam's experience offers both cautionary lessons and inspiring practices, showing that climate resilience can be pursued through pragmatic, adaptive, and collaborative processes.
This study contributes to multiple theoretical domains. Drawing from adaptive and collaborative governance, we highlight how integrative practices require flexible, learning-oriented institutions that can navigate uncertainty. Drawing from transition studies, we position

integrated infrastructure management as a transition pathway—where niche innovations such as pilot projects, new roles, and cross-sectoral routines gradually reshape the dominant governance regime.

For municipalities seeking to build climate resilience, the following actions are recommended:

- Institutionalise integrative roles such as integral managers to coordinate across disciplines and manage trade-offs in early design phases
- Leverage maintenance and renewal cycles as opportunities for integrated, future-oriented planning
- Invest in internal capacity building, combining training with interdepartmental learning platforms
- Use pilot projects as iterative learning spaces—focusing on specific themes, evaluating outcomes, and scaling successful elements
- Align budgeting and governance structures to support lifecycle and area-based planning approaches

As climate change imposes ever-more complex stresses on ageing urban infrastructure, the need for more than technical adaptation becomes imperative. This study argues that Integrated Infrastructure Management can enable sustainable transitions in infrastructure delivery with formal capacity and informed by experimental governance.

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Meaningful boundaries that enhance flood resilience: a comparative study of three integrated flood risk management projects

Max de Vries

Abstract

Climate change and urbanisation exacerbate flood risks, stressing the need for more integrated flood risk management (FRM) that enhances flood resilience by diversifying FRM strategies. However, implementation of integrated FRM is often hampered by increased complexity, sectoral responsibilities and short-term decision-making. Addressing this complexity requires the rethinking of boundary judgements, i.e. implicit and explicit decisions that actors make about who and what is relevant to include. Drawing boundaries is a balancing act: boundaries that exclude certain domains can reduce complexity but too narrow boundaries can also have a negative impact on flood resilience. This study therefore asks: *What boundaries should be drawn in flood risk management decision-making processes to enhance flood resilience?* We develop a framework to examine how boundary judgements influenced assessment processes and decisions in three successfully implemented integrated FRM projects. Our comparative case study research sheds light on meaningful boundaries, thereby providing guidance for practitioners and decision-makers who engage in integrated FRM to enhance flood resilience.

Keywords: Integrated flood risk management; Flood resilience; Boundary judgements; Policy implementation;

Introduction

Climate change increasingly impacts urban deltas, where intensifying extreme weather events and urbanisation increases flood risks. Traditionally, flood risk management (FRM) has relied on engineered structures to manage flood risks (Tempels & Hartmann, 2014; Verweij et al., 2021). However, prioritizing one FRM strategy, e.g. relying on engineered structures, is unlikely to enhance flood resilience in the future given the projected increase in both flood frequency and intensity (IPCC, 2023; van Buuren et al., 2016). Around the world, policies reflect a growing awareness of the need for more integrated, holistic and nature-based (or ecosystem-based) solutions (Vinke-de Kruijf et al., 2024b). This shift towards integrated FRM, also referred to as the diversification of FRM strategies, enhances flood resilience not only by resisting to floods, but also by enabling the capacity to absorb, recover, transform and adapt to floods (Hegger et al., 2016).

Despite international and national policies, the implementation of integrated FRM – which would generally enhance resilience – remains challenging (Bosoni et al., 2023; Hartmann & Spit, 2016). An underlying factor is the complexity of integrated FRM projects. Compared to engineering-oriented projects, actors face more challenges related to the need for cross-sectoral alignment (Willems et al., 2022). Another factor is the absence of a long-term perspective in decision-making (Pot et al., 2019). Finally, frameworks to assess and compare solutions tend to be sector-specific and overemphasise short-term priorities, causing decision-makers to overlook more integrated solutions (Beceiro et al., 2022; Dumitru et al., 2020). Thus, both the inherent complexity of integrated FRM and how decisions are made hamper its implementation.

This contribution draws attention to one aspect of decision-making, i.e. boundary judgements: explicit and implicit decisions about who and what to include when making decisions (De Loë & Patterson, 2017; Vinke-de Kruijf et al., 2024a). Boundaries that are too tight hamper cross-sectoral collaboration, while wide boundaries risk 'paralysis by analysis' through the inclusion of a vast range of factors (ibid.). Therefore, this study asks: *What boundaries should be drawn in flood risk management decision-making processes to enhance flood resilience?* We develop a framework that we apply to analyse and compare three integrated FRM projects in the Netherlands. We identify how system boundaries shaped the assessment and decision-making within these projects. As such, this study offers guidance on meaningful boundaries that are supportive of flood resilience.

Boundary judgements

For decades, FRM has been predominantly techno-centric (van Buuren et al., 2016). However, interdependent climate and spatial challenges emphasise the need for a more holistic perspective on flood infrastructure (Markolf et al., 2018). This perspective understands flood infrastructure as an interdependent social, ecological and technological system (SETS) (ibid.), and inherently involves more diverse sectors and actors than traditional FRM.

To manage complexity, actors need to draw boundaries (Helfgott, 2018). Yet, such boundaries are in the water sector often rather "water-centric" (De Loë & Patterson, 2017). This is also the case in the Netherlands where water authorities – accustomed to make decisions independently – tend to draw boundaries too tight, hampering cross-sectoral collaboration (Vinke-de Kruijf et al., 2024a). These boundaries may concern various project dimensions including a project's scale and time horizon (*substantive*), which actors are involved, how and when (*participation*) and how roles and responsibilities are distributed and dealt with *(planning and decision*) (ibid).

Previous studies analysed how boundary judgements influenced adaptive practices in water governance (van Meerkerk et al., 2013), or diversification-oriented projects (Vinke-de Kruijf et al., 2024a). Building on these frameworks and the importance of boundary judgements, we define *meaningful boundaries* as those that are drawn in integrated FRM projects and enhance flood resilience. We expand current frameworks that categorise boundary judgements (van Meerkerk et al., 2013; Vinke-de Kruijf et al., 2024a) with theory on forward-looking decision-making to address the lack of long-term perspective in decision-making (Pot et al., 2018). We further draw on Doornkamp et al. (2024), who emphasised the role of FRM projects in

enhancing flood resilience. Our framework enables us to identify what boundaries are meaningful in FRM decision-making processes to enhance resilience.

Method

To answer our research question, we employ qualitative case study research. We analyse three successfully implemented integrated FRM projects in the Netherlands, each involving multiple domains and a larger geographical scale than traditional FRM (Figure 1):

1. Koehool-Lauwersmeer is an integrated dike protection project combining flood safety, nature and spatial quality (Rijksoverheid, 2023).
2. Kampen Bypass is part of the Room for the River program, integrating flood safety and spatial quality (Verweij et al., 2021).
3. Noordwaard Depoldering is also a Room for the River project with similar integration objectives (ibid.)

Data are collected through document analysis and semi-structured interviews with key actors and includes data that were collected in previous research focusing on Koehool-Lauwersmeer (Hanning, 2023), and the Noordwaard (Bralts, 2024). Guided by our theoretical framework, we empirically identify which system boundaries were drawn and how these influenced decision-making processes and outcomes. We compare these findings with boundaries that are desirable in theory to draw conclusions on boundaries that are meaningful in practice.



Figure 1: Case locations of successful implemented integrated FRM projects in the Netherlands. 1) Koehool-Lauwersmeer, 2) Kampen Bypass and 3) Noordwaard Depoldering.

Expected results

Based on the Noordwaard Depoldering case, we expect relatively wide participation boundaries. As that project clearly focused on two objectives, i.e. flood safety and spatial quality, a diverse set of actors were involved (Bralts, 2024). While the double objective contributed to a wide substantive scope in terms of scale, only flood safety was considered as a long-term challenge, neglecting other interdependent challenges (ibid.). This indicates a wide substantive boundary in terms of scale, but depending on the issue at hand a very wide (flood safety) or a very tight (spatial challenges) boundary judgement in terms of time horizon.

In the remainder of our study, we further explore the three case studies to identify what boundaries should be drawn to enhance flood resilience. We aim to provide an improved understanding of how boundary judgements influence decision-making processes of integrated FRM projects. This research contributes to the broader governance challenges on integrated projects by clarifying which boundaries are meaningful, thereby providing guidance for practitioners and decision-makers who engage in integrated FRM to enhance flood resilience.

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Assessing Local Capacity in Alabama, US, to Plan for Climate-Resilient Infrastructure

Megan Heim-LaFrombois and John C. Morris, Auburn University, USA

Introduction

The impacts of climate change are experienced first-hand in Alabama, located in the Southeast portion of the US. For example, coastal communities along the Gulf of Mexico in Alabama and across the Southeast are regularly impacted by extreme hydrological events, such as tropical storms and hurricanes, coupled with fast urbanization in some areas. With varying degrees of success, cities' codes and plans across the state have adopted green infrastructure practices that help manage stormwater (Heim LaFrombois et al. 2023). Yet these approaches have limited ability to help with issues linked to flash flooding (Mattos et al. 2021). While flooding is a primary concern, a diversity of severe weather events, exasperated by climate change, are experienced across the state, including drought, extreme temperatures, and tornadoes. The effects of climate change, and a heightened awareness of its disparate impacts, have put tremendous stress on our existing water infrastructure and how we govern and manage these systems. Water infrastructure remains critical to the health, welfare, and safety of Alabamians, and a reliable supply of water suitable to meet household, agricultural, and industrial needs is necessary to ensure long-term social and economic health.

Against this backdrop, Alabama remains one of the least resilient states in the US in terms of the ability of its water infrastructure to resist the frank effects of severe weather events. This is important because most infrastructure decisions originate at the local level of government, and a lack of knowledge, understanding, or awareness of the need – along with the necessary resources – for climate resilient infrastructure can lead to decisions that can undermine human and economic well-being. Given the lack of state or national policies to address climate change or resilience to severe weather events, the burden for resilience falls squarely to local government officials.

This interdisciplinary-based, mixed-methods paper assesses the barriers experienced by communities in Alabama as they seek to protect their vital water infrastructure from severe weather events. From an operational perspective, this paper assesses the best practices and tools available to local government officials to build resilience for water infrastructure that is effective, cost-efficient, climate resilient, and viable in the long term. These tools can be regulatory/legal in nature; involve physical infrastructure; can be administrative or technical in nature; or involve intergovernmental or community partnerships. Our research includes a statewide survey of local government officials, coupled with site visits and interviews with communities, and examines resiliency through the social, ecological, and technical (SETS) framework, with an emphasis on the socio-political factors that affect climate resilient water infrastructure.

Literature Review

The concept of resilience, from a community planning perspective, can be understood as "the capacity of a city's systems, businesses, institutions, communities, and individuals to survive, adapt, and thrive, no matter what chronic stresses and acute shocks they experience" (Resilient Cities Network 2023). Resilience planning thus refers to building and maintaining a community's capacity to withstand, adapt, and improve their quality of life, regardless of stresses or shocks to the community, including climate change-related events. This capacity building/strengthening

happens at all levels – systems, institutions, infrastructure, communities, and individuals (APA 2023). Planning scholars and practitioners tend to focus on the comprehensive planning process and the resulting locally adopted document, along with the implementation of it, to determine how resilient a community is via plan evaluation scores. In examining green infrastructure's specific role in planning resilient communities, Heim LaFrombois et al. (2023) found that the comprehensive plans for nine coastal cities in Alabama and Mississippi scored well in terms of overall plan quality, but there are barriers and constraints in practice, namely around implementation, evaluation, and stakeholder engagement.

Morley (2023) focuses on whether a state has defined 'resilience' and how it is codified; if the state has resilience offices and staff, and how it is administratively situated; and whether there is a statewide interagency coordinating entity tasked with resilience governance. In the case of Alabama, the state has not defined 'resilience,' nor does it have resilience offices or staff. While there is an interagency coordination body (the Alabama Resilience Council) Alabama does not have a statewide resilience plan (ARC 2023; Office of Alabama Governor 2023).

The extant literature in public works and infrastructure has recognized the criticality of climate change resilience (see Morris, et al. 2021; Morris and Little 2019; Fisk 2019; Morris, et al. 2019), but there is little work that seeks to conduct comparative research on infrastructure resilience and climate change. Existing work has focused on adapting resilience concepts to public works management (Brown 2019), the role of the insurance industry in climate resilience policy (McShane and Yusuf 2019), resilient communications infrastructure (Comfort and Haase 2006), adapting infrastructure to flood risk (Heikkila and Huang 2014; Zevenbergen, van Herk, and Rijke 2017), the administrative and managerial frameworks necessary for successful resilience (Fisk, et al. 2023), or even broader questions of appropriate national policy choices to address infrastructure resilience (Morris and Little 2019). This research contributes to the scholarship by examining local governments explicitly and how their tools to enhance resiliency are shaped by social – especially political –, ecological, and technological factors (Pineda-Pinto et al. 2021; Markolf, et al. 2018).

Findings

This interdisciplinary study consists of a statewide survey of local government officials in Alabama, coupled with in-person interviews conducted in communities around the state. Our research reveals a surprising array of best practices and tools available to local officials to build resilience, despite many constraints. The most common types of tools cluster around administrative/technical tools, coupled with intergovernmental or community partnerships. The regulatory/legal options available to communities are limited and are driven by a combination of clashes over property rights and political resistance to discussions around climate change. Depending on the community, common examples include subdivision regulations, zoning ordinances, building regulations, and city ordinances (laws). Several respondents report that they employ nature-based/green infrastructure, albeit on a limited scale. Such solutions include requirements for permeable surfaces, the construction of retention ponds, and other low impact development (LID) solutions.

The administrative/technical tools available include updated stormwater plans, infrastructure maintenance plans, GIS inventories and mapping; updated emergency response plans; fostering cross-departmental cooperation; and initiating regularized interactions between city departments. Intergovernmental partnerships include mutual aid agreements; the formation and use of regional organizations/planning districts; and public education programs. Despite clear social vulnerabilities, few Alabama communities take into account the socioeconomic conditions

of their jurisdictions when making infrastructure resilience decisions. Our findings highlight how local governments' actions fit within the SETS framework; however, we draw attention to the importance of socio-political factors and how they affect community resilience.

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Equitable Resilience for Social Sustainable Urban Infrastructure

Feiya CHEN, Shauhrat S. CHOPRA
School of Energy and Environment, City University of Hong Kong, Tat Chee Avenue, Hong Kong SAR, China, feiychen3-c@my.cityu.edu.hk School of Energy and Environment, City University of Hong Kong, Tat Chee Avenue, Hong Kong SAR, China, sschopra@cityu.edu.hk

Abstract

Understanding the resilience of urban infrastructure is crucial for reducing the adverse impacts of disruptions, given its vital role in contemporary society. Prevailing approaches to resilience assessment, however, often presuppose that all users experience uniform levels of resilience, effectively treating them as a monolithic group. The implication of this assumption is that infrastructure disruptions impact every user in the same manner. To challenge this view, we propose the integration of equity factors into the analysis, enabling policymakers to develop customized strategies for different demographic segments. In contrast to traditional 'one-size-fits-all' risk analyses centered on fail-safe measures, our approach advocates for a shift towards safe-to-fail principles that acknowledge the distinct needs of various social groups. This fosters a more inclusive mode of resilience analysis where flexible solutions are prioritized over uniform ones.

Our study utilizes a multi-stage analytical framework to evaluate the socio-demographic, temporal, and spatial factors that influence resilience. By examining resilience through three distinct stages—preparedness, robustness, and recovery—the framework facilitates a detailed evaluation for each specific social group. This research is contextualized through a case study of Hong Kong's Mass Transit Railway (MTR) system. Applying complex network theory to data from the Travel Characteristic Survey, we conduct statistical tests to identify significant variations in disruption impacts among different sub-populations.

Our findings reveal variations in performance among social groups across the distinct stages of resilience. Notably, older populations demonstrate greater preparedness and robustness against both random disruptions and targeted attacks, yet they exhibit diminished recovery capabilities. Their higher preparedness can be partially attributed to more diverse daily usage patterns, which differ from the typical peak-hour commuting habits of working-age individuals. The reduced recovery capacity in elderly groups is likely linked to their more limited maximum walking abilities, highlighting the need for accommodations tailored to diverse demographic requirements. Young males show lower evening preparedness, a consequence of their engagement in activities concentrated within specific areas, such as the northern shore of Hong Kong Island. Accordingly, targeted station management strategies could include queue management systems with wait time displays, brightly colored

queue lines, and better real-time information via interactive signage or mobile applications.

This framework facilitates a transition from utilitarian perspectives to one that incorporates deontological principles, placing emphasis on social justice and social sustainability. It assists stakeholders in pinpointing stations that require upgrades to serve diverse social needs and combines resilience-by-design (RbD) with resilience-by-intervention (RbI) strategies to strengthen both internal system capabilities and external emergency measures.

Keywords: Equitable Resilience; Social Sustainability; Networked-urban Infrastructure

Consumer Impact on Resilience of Water Distribution Systems

Kevin T. Logan [1] Peter F. Pelz [2]
1 Chair of Fluid Systems, Technische Universität Darmstadt, Germany, kevin.logan@tu-darmstadt.de
2 Chair of Fluid Systems, Technische Universität Darmstadt, Germany, peter.pelz@tu-darmstadt.de

Abstract

Water distribution systems are socio-technical systems. However, the social and technical aspects are rarely studied simultaneously. The presented work proposes considering consumers in WDSs as active parts of a sociotechnical system and presents two approaches for investigating the impact consumers can have on WDS resilience. The first approach is experimental and utilizes a physical test rig that represents a WDS with generalised consumer behaviour implemented via actuators. The second approach discusses a novel methodology for modelling consumer behaviour in agent-models: the major-minor-mean-field control (M3FC) framework. First results from M3FC indicate improved system performance in case of proactive, cooperative consumers participating in WDS control.

Keywords: water distribution systems; resilient sociotechnical systems; experiment; multi-agent systems; reinforcement learning

Introduction

Water distribution systems (WDSs) are vital infrastructure in cities, delivering drinking water to urban populations. They face major challenges due to the impact of climate change and progressing urbanisation. In consequence, the resilience of WDSs has been widely studied regarding network design (e.g.,Alperovits and Shamir (1977), Todini (2000), Yazdani et al. (2011), Ulusoy et al. (2020)), and considering the impact of disruptions (e.g., Farahmandfar et al. (2017), Han et al. (2020), Hernandez Hernandez and Ormsbee (2021), Hou et al. (2021)). Though the interdependence between an infrastructure system and the social system of the community it serves has been noted (Gay & Sinha, 2013), research has generally focused on the impact of infrastructure disruptions on the consumers. The fact that consumers can play an active role in the resilience of the inherently socio-technical WDS has been understudied.
The presented work explores this issue, proposing two approaches to modelling the consumers, allowing them, alongside the system operator, to play an active role in system stability. We first show how the question can be studied experimentally, and then discuss the novel method of Major-Minor-Mean-Field Control (M3FC) (Cui et al., 2024), which allows studying the consumer behaviour at the scale of an urban WDS.

Experimental method for studying consumer impact on WDS resilience

Test rig

The test rig, shown in Figure 1, represents a WDS with gravity supply supported by pumping (cf. Figure 3.48 in Trifunović (2006)). Two pumps deliver water to two tanks each of which has an outlet connected to a separate pipe. Both outlet pipes are fitted with a flow meter and a valve. These valves represent the consumers. The function of a WDS is to deliver water volume flow at a required pressure to the consumers. Accordingly, the system function of the test rig

is to maintain a given pressure in the tanks, which allows an outflow through the consumer valves.

Consumer Types
Four different cases of consumer behaviour are considered. The baseline case is implemented by consumer valves with constant opening, with consumed volume flow depending directly on tank pressure. The second case represents habitual consumers, implemented by the valve opening changing periodically to emulate a daily consumption routine. The third case assumes fully egoistic consumers, who aim to fulfil their own demand regardless of the system state. This case is implemented by equipping the consumer valves with controllers that maintain constant outflow. The fourth case assumes fully cooperative consumers, who prioritise system stability over their own consumption.

Topologic Configurations
Two topologic configurations are considered: decentralised and coupled (c.f. **Error! Reference source not found.**). In both configurations, one pump separately feeds each of the tanks and controls the tank pressure $p_i(t)$ by manipulating the pump speed $n_i(p_i)$. The two subsystems 1 and 2 are fully separated in the decentralised configuration, whereas in the coupled configuration, a valve between the two tanks may be opened to equalise pressure in the pipes feeding the consumers.

Control Strategies
The pumps are operated using four control strategies. The first, baseline strategy uses a PID controller for each of the pumps. Three further control strategies are applied. These strategies constitute enhanced resilience control strategies, implementing the four resilience functions according to Hollnagel (2011): monitor, react, learn, anticipate. The three strategies are: (i) signal-based, (ii) based on analytical modelling, and (iii) based on statistical modelling.

Disruptions
The test rig allows applying various disruptions. Three disruptions are considered: (i) a pump failure of limited duration, (ii) a blockage disruption in the shape of a harmonic oscillation implemented by the blockage valve, (iii) a leakage with gradual onset and long-term duration.

Resilience Assessment
The framework described by Cassottana et al. (2021) is used for resilience assessment, as it allows assessing *integral service loss*, *maximum service loss*, and *time to recovery*, along with *performance loss behaviour* and *recovery behaviour*. Furthermore, the *total energy consumption* is used to illustrate the effort required from the system for fulfilling its functionality. This gives a comprehensive overview of the resilience of the system in general, and allows quantifying the specific impact of consumer behaviour.

Major-Minor-Mean-Field Control as a method for studying consumer impact

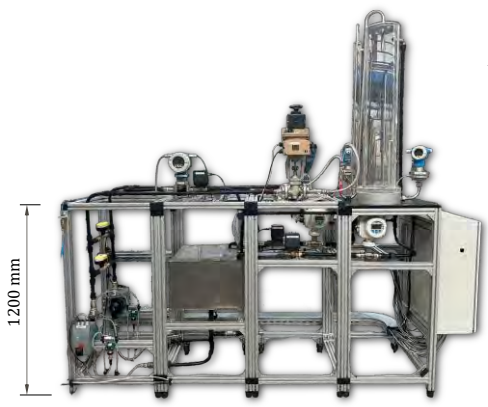
While the experimental study has the advantage of using a physical system, it is limited in scale and granularity of consumer behaviour. In contrast, the M3FC framework offers a modelling approach with which both the system operator with significant impact on the system (major agent) and the individual consumers with small individual impact but large overall influence

(minor agents) can be represented, while maintaining tractability of the multi-agent reinforcement learning (MARL) problem. This novel framework has been applied to WDS in a recent study by the authors.

The study distinguishes between habitual consumers and fully cooperative consumers. The system operator agent receives aggregated information on the consumer demand and aims to minimise energy consumption while meeting the demand. Habitual consumers follow a recurring daily demand pattern, whereas cooperative consumers pursue, with strategic actions based on aggregated information, the same control objective as the operator: fulfilling their demand while minimising the energy required for WDS operation. In this way, consumers become an active part of the WDS control problem. The policies of all agents were trained using MARL. The results show that, in the event of pump failure, the cooperative agents coordinated their consumption so as to allow downstream consumers to also fulfil their demand. This results in more equitable water distribution, quantified by a reduction of water Gini coefficient of 57% compared to habitual consumers.

Conclusion

The presented work explores the question of consumer impact on WDS resilience. Two approaches are proposed. The first uses a physical test rig representing a generic WDS and implementing various types of consumer behaviour by means of available actuators. The second is based on multi-agent systems, using the M3FC framework and MARL. While experimental results from the test rig are pending, the study using the M3FC framework indicates that resilience gains can be achieved by incorporating active, cooperative consumers into the control problem of WDS operation.



TECHNICAL DETAILS

Actuators
- Pump 1
  - heat circulation pump Wilo Stratos 25/1-10
  - rated power: 140 W
- Pump 2
  - heat circulation pump Wilo Stratos 25/1-6
  - rated power: 65 W
- 6 electrically actuated proportional control valves
- 2 electrically actuated ball valves

Sensors
- 3 piezoresistive differential pressure sensors
- 2 piezoresistive liquid level sensors
- 3 magnetic inductive flowmeters
- 2 active power sensors
- 1 PT-100 temperature sensor

Figure 1. Test rig with scale including technical specification.

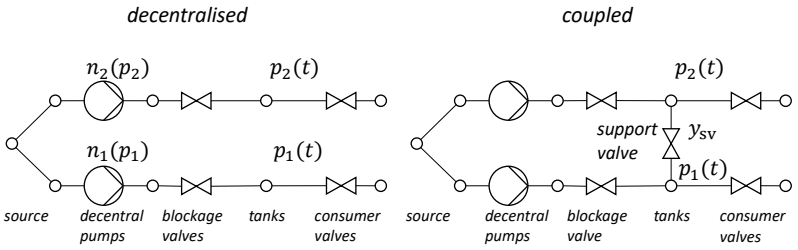


Figure 2. Considered topological configurations

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4. Resilience Of Coupled Energy And Transport Systems Under Deep Decarbonization

Framework for Climate-Resilient Low-Carbon Transport:Application to Spain

Manuel Pérez-Bravo[1], Sonia Yeh[2], Antonio Francisco Rodriguez-Matas[1], Pedro Linares[134]

[1] Universidad Pontificia Comillas, ICAI, Instituto de Investigación Tecnológica (IIT), 28015, Madrid, Spain

[2] Department of Space, Earth and Environment, Chalmers University of Technology, Gothenburg, Sweden

[3] Center for Energy and Environmental Policy Research, Massachusetts Institute of Technology (MIT), E40-435, 77 Massachusetts Ave., Cambridge, MA 02139 USA

[4] Energy Policy Research Group, University of Cambridge, Cambridge, UK

Abstract

Transport decarbonisation, especially through electrification, increases the interdependence with the wider energy system, thereby amplifying climate vulnerability. We propose a framework that represents the interactions of energy and transport in an optimization model (openMASTER) and applies robust optimization to design alternative investment strategies. This evaluates resilience through: demand-fulfillment ratio (DFR), total system cost, and GHG emissions. In a case study for Spain, increasing the robustness of the energy-transport system substantially reduces disruption-driven unmet demand and closes the cost gap, leading to a stable system cost while keeping emissions unchanged.

Keywords: Transport Resilience; Decarbonization; Alternative fuels; Climate Change Adaptation; Robust Optimization

Introduction

The transport sector faces the dual challenge of reducing greenhouse gas (GHG) emissions while adapting to growing climate risks. The EU targets 90% transport emission reductions by 2050 (European Commission 2019), while climate hazards such as floods, heatwaves, snowstorms, and wildfires are increasingly disrupting both transport and energy infrastructures (IPCC 2023).

Electrifying on-road transport, including hydrogen and synthetic fuels, provides significant opportunities for emission reductions. However, electrification increases the interdependence of transport and energy systems, as transport becomes reliant on multiple energy carriers and infrastructures, while energy systems increasingly depend on transport system for flexibility and demand management to enhance generation and grid stability (European Commission et al. 2022; Knezović et al. 2017; Rezkalla, Pertl, and Marinelli 2018). This interdependence also creates new vulnerabilities, requiring a system-wide resilience perspective.

The Multi System Dynamics (MSD) framework captures this interdependence by conceptualizing transport as a system of systems embedded in wider sociotechnical infrastructures (Yeh et al. 2024). In this paper, we represent the MSD framework with an energy systems model which includes a detailed characterization of the transport system and its interactions. We then simulate several disruptions and assess their impact on energy-transport systems designed through robust optimization (RO), using indicators of reliability, affordability, and sustainability. This allows us to identify designs that remain functional and cost-effective across a wide range of stress scenarios.

Methods

Conceptual framework for resilience

Here, we operationalize robustness as the ability of the energy-transport system to maintain required service levels under a range of adverse but plausible conditions (pre-disruption performance), and resilience as the capacity to withstand disturbances and then either restore performance or transition to a new, steady state (a "new normal") (Amoaning-Yankson and Amekudzi-Kennedy 2017)**.**

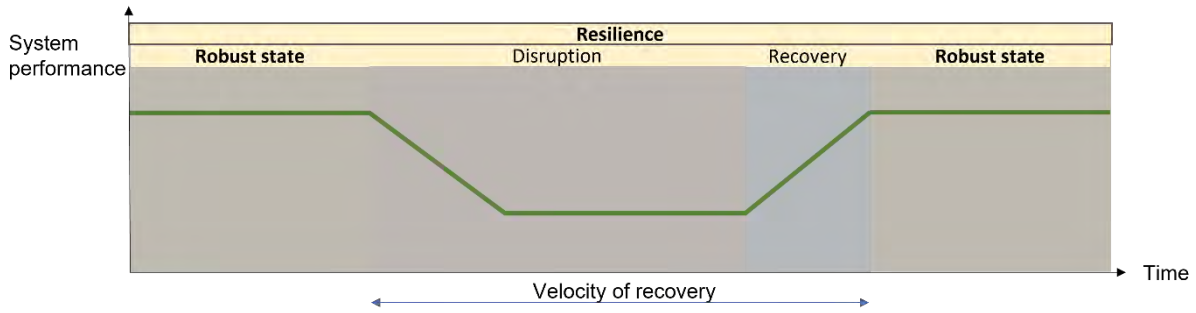


Figure 1. An illustration of robustness vs. resilience.

A Multi System Dynamic Approach to Transport Resilience

Sector-specific resilience assessments can undermine infrastructure planning and limit the effectiveness of mitigation strategies. The MSD framework instead emphasizes system interdependences (Yeh et al. 2025). Building on this systems perspective, we operationalize resilience by stress-testing different energy–transport system configurations against a set of stylized disruption events. We identify nine stylized disruption events across the energy-transport chain (Figure 2). System performance is assessed through three indicators: (i) demand-fulfillment ratio (DFR), i.e., the share of passenger/tonne-km delivered during shocks; (ii) total system cost; and (iii) GHG emissions.

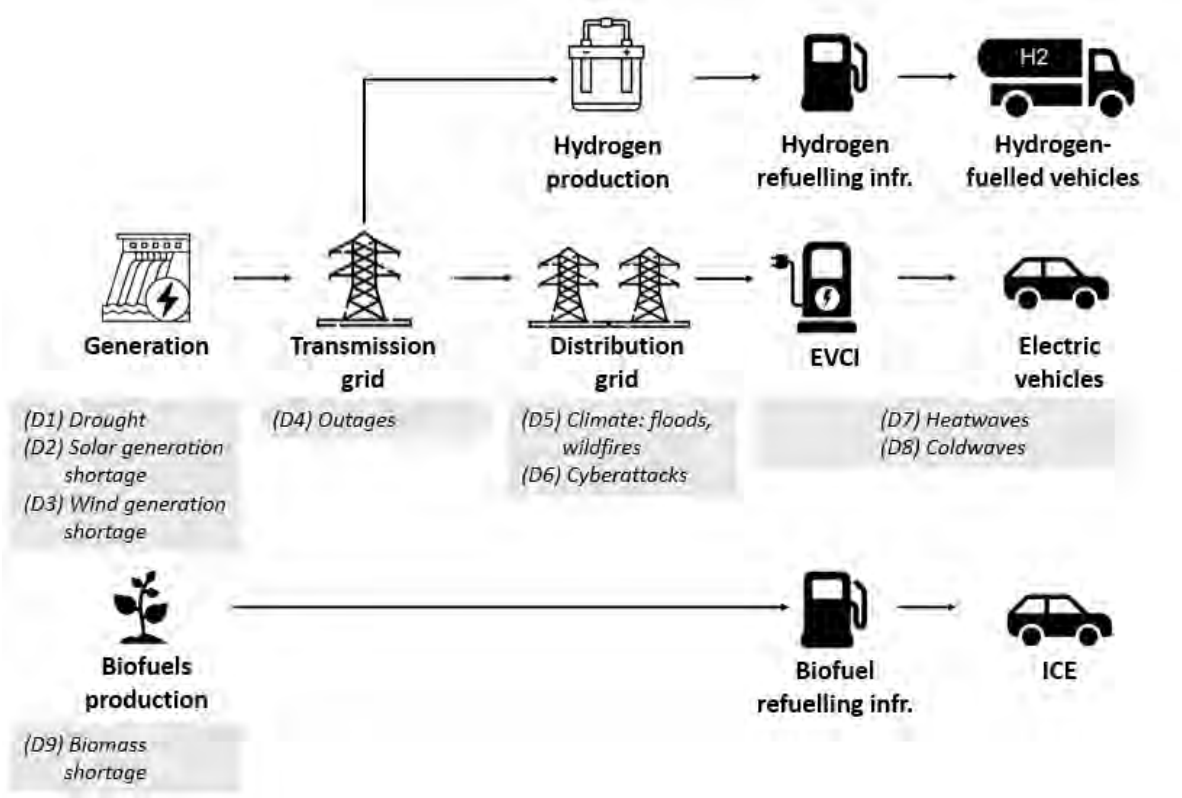


Figure 2. Energy-transport supply chain and stylized disruption events (bullet points) considered in the modeling framework.

Modeling Framework and Workflow

The workflow has two stages: (i) generate decarbonization strategies; (ii) evaluate their performance under the disruptions using the three indicators. Strategies are created with an energy-transport modeling framework. We apply openMASTER (Rodriguez-Matas et al. 2024), an open-source model with detailed technology and behavioral representation.

We establish a baseline scenario aligned with European and national targets, representing the default decarbonization strategy. Then, we build increasingly robust strategies with Robust Optimization (Bertsimas and Sim 2004), increasing the degree of protection of those strategies against uncertain disruptions. For that we introduce a tunable level of conservatism through a protection parameter, denoted as τ. This formulation enables the explicit representation of trade-offs between system performance and protection against uncertainty: increasing τ progressively introduces more severe uncertainty outcomes in the energy supply system, yielding increasingly conservative system designs. This gradual activation mirrors the real-world progression of climate stressors and provides a flexible mechanism for modeling system responses under deep uncertainty:

$$C_i \cdot \left(\overline{a_{i,t}} - \tau \cdot w_{i,t} - p_{i,t}\right) \geq x_{i,t}, \qquad \forall i \in I, \forall t \in T \tag{1}$$

$$w_{i,t} + p_{i,t} \geq \Delta a_{i,t}, \quad \forall i \in I, \forall t \in T \tag{2}$$

where C_i is installed capacity, $\overline{a_{i,t}}$ the nominal availability factor, $w_{i,t}$ and $p_{i,t}$ auxiliary variables capturing, respectively, the uncertainty budget and residual protection, τ the protection parameter, $x_{i,t}$ the required output, and $\Delta a_{i,t}$ deviation of $\overline{a_{i,t}}$ under disruption.

Finally, we assess all strategies by fixing investment decisions and testing performance under the disruption set, evaluating the reliability, affordability, and sustainability of the different solutions.

Data

The disruption assumptions applied to this modelling framework[1] span renewable generation, energy networks, and end-use systems. For renewables, we model reductions in energy output: 30% for hydro (D1) and wind (D3), 2% for solar (D2), and 30% for biomass-derived fuels (D9), reflecting seasonal shortages or supply chain disruptions (Freitas et al. 2021; Gernaat et al. 2021; de Jong et al. 2019; Kheshgi, Prince, and Marland 2000). For the electricity grid (D4), we represent up to 8.8 hours of unmet demand per year (ENTSOG and ENTSO-E 2022). At the distribution level, failures are modeled as either an 85% loss of capacity (D5) or a 20% reduction due to cyberattacks (D6) (ACER 2024).

On the demand side, we capture performance losses in electric vehicles and charging stations, with output reduced by 20% during heatwaves and by 30% during coldwaves (D7, D8) (Lindgren and Lund 2016; Parker et al. 2025).

Results and Discussion

Spain targets 90% GHG reduction by 2050, with 98% transport emission cuts from 2020 levels (MITECO 2020). The PNIEC sets intermediate milestones (MITERD 2024). The modeled baseline strategy aligns with these objectives: by 2050 road and rail are almost entirely electrified, while aviation and maritime rely on RFNBOs and biofuels. Renewable generation exceeds 80% by 2030 and becomes dominant after 2040.

[1] All model details are available in the openMASTER repository: https://github.com/IIT-EnergySystemModels/openMASTER

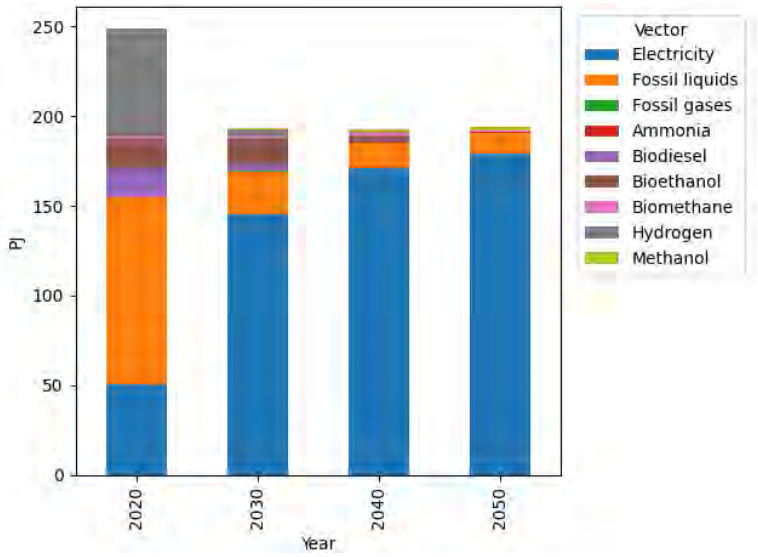


Figure 3. Spain's transport final energy consumption per year consistent with Spain's Long-Term Strategy (Nominal case).

At the baseline level $\tau = 0$, disruptions increase total system cost by about 11.9% compared to the pre-shock levels. But, with $\tau \geq 1$ costs remain unaffected by disruptions. Achieving this robustness in costs comes with a modest trade-off. The overall system cost increases by 5.6% when moving from $\tau = 0$ to $\tau \geq 1$. In other words, the strategy pays a predictable 5-6% premium to eliminate a 12% disruption penalty.

For $\tau \geq 1$, both costs and emissions remain stable, while unmet demand (DFR losses) is minimized at $\tau = 5$ On this basis, we adopt $\tau = 5$ as the robust strategy.

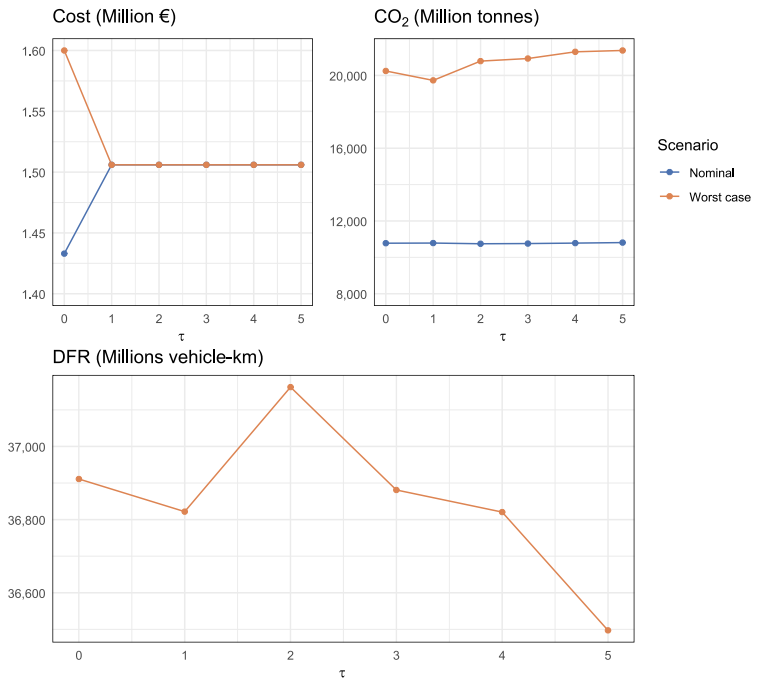


Figure 4. Performance indicators of two scenarios (nominal versus disrupted) under RO protection levels τ: (a) Cost (M EUR), (b) CO2 (Mt), and demand fulfillment ratio (DFR) (million vehicle-km).

Conclusions

This study shows how resilience is embedded in Spanish decarbonization: stress-testing shows small planning adjustments can eliminate disruption-driven cost penalties, and reduce unmet demand with only a small increase in emissions.

The results underline a broader lesson: resilience indicators developed for fossil-fuel systems are no longer sufficient in today's electrified, multi-carrier context. Fair comparison requires assessing resilience within an MSD framework encompassing disruptions and energy–transport interactions.

Framing resilience in this way highlights the importance of "no-regret" measures, design choices that safeguard performance across disruption scenarios while supporting long-term decarbonization. Building such strategies means budgeting not only for capacity, but also for reliability and flexibility, so that future energy-transport systems remain robust amid disruption.

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Assessing the Robustness of the Urban Transport–Energy Nexus: Evidence from the Glasgow City Region

Si Chen[1], Benoit Couraud[1], Wei Bi[2], Jamie Blanche[1], Merlinda Andoni[1], Kristen MacAskill[2], David Flynn[1]

1 University of Glasgow, United Kingdom, Si.Chen@glasgow.ac.uk, benoit.couraud@glasgow.ac.uk, jamie.blanche@glasgow.ac.uk, merlinda.andoni@glasgow.ac.uk, david.flynn@glasgow.ac.uk

2 University of Cambridge, United Kingdom, wb316@cam.ac.uk, kam71@cam.ac.uk

Abstract

Rapid electrification of transport and the integration of renewable resources pose new stresses on urban electricity distribution networks. Understanding these risks is vital for developing advanced methodologies that support adoption of electric vehicles (EVs), adaptation to climate risks, and resilience of the transport–energy nexus. Existing research has explored renewable integration and smart grid solutions, but less attention has been given to how distribution network faults interact with emerging EV charging demand in dense urban settings. This paper addresses this gap through a case study of Glasgow City. Using power flow analysis, the study shows that climate events resulting in faults on the grid could considerably impact the grid supply points, whereas the voltage levels in a urban environment will stay within boundaries.

Keywords: urban resilience; transport-energy nexus; urban energy system

Introduction

Urban electricity networks are facing several challenges that include the electrification of heat and transport, but also widespread distributed generation and an increase of climate-related disturbances (Wang, Yang, Fang, Wang, & Wu, 2023). This results in highly complex systems, where weather dependent variables influence the whole energy system (Shi, Liu, Zeng, Hui, & Li, 2022), and can impact its stability (Shi, et al., 2021) (Barnes, Nagarajan, Yamangil, Bent, & Backhaus, 2019).

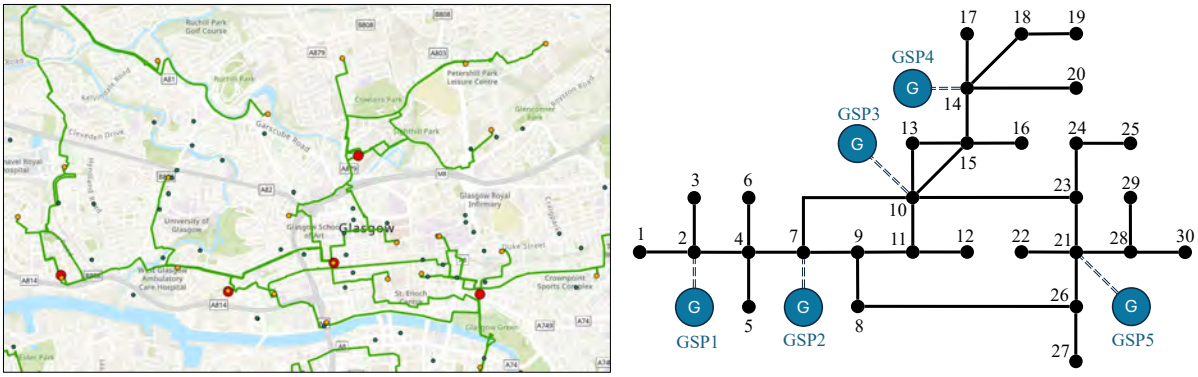
In this study, we explore the resilience challenges of urban electricity networks with high penetration of EVs, through an analysis of Glasgow's 33 kV distribution network. Using a digital model of this network, we assess how Grid Supply Point (GSP) failures can impact the normal operation of the network even in scenarios with high penetration of EVs, underscoring the importance of intelligent coordination strategies across transport–energy (T–E) networks to strengthen resilience.

Methodology

The study simulates the behaviour of an urban electrical grid in the case of future scenarios involving high EV penetration and climate events. Three aspects were considered.

A. Modelling the 33 kV Distribution Network

The 33 kV electric distribution network of Glasgow was modelled as a multi-node feeder network of 30 nodes as shown in Figure 1.



(a) (b)

Figure 1. Distribution network (33 kV) of Glasgow urban area. (a) Network map with public EV charger locations in ArcGIS, (b) Simplified 30-node feeder diagram.

Network data were obtained from the local distribution network operator (SP Energy Networks, 2025). Figure 1 shows the modelled network, represented by 5 Grid Supply Points (GSPs) that are well interconnected to enhance resilience during faults.

B. EV Charging Demand under Transport Electrification

In addition to the real network model, we incorporated historical load data from primary substations and integrated real public EV charger locations and consumption data (Charge Place Scotland, 2025). To assess the impact of transport electrification, we generated synthetic charging load profiles for higher penetration scenarios ranging from 1.4%, current EV penetration rate (Consumer Scotland, August 2024), to 84%. The total load at each substation thus comprises both residential/commercial demand and EV charging demand.

C. Integration of Climate Events

Finally, we assessed network resilience to climate-related events by simulating fault scenarios on GSPs to evaluate the system's response when the total load remains unchanged. Historical fault records indicate that over 90% of incidents are attributed to cable failures, with falling trees during high windstorms and flooding being particularly significant contributors (SP Energy Networks, 2024).

By running power flow simulations with these three aspects, we can assess the network status in future scenarios with high EV penetration and faults from GSPs due to climate events.

Results

Simulations have shown that climate events that would lead to GSPs faults have two main impacts on the network: firstly, they affect adjacent GSPs by requesting more power from them, and secondly, they modify the network voltage profiles.

A. Impact on Electricity Supply Points

Due to the meshed nature of the distribution network, GSPs can support each other during a fault. When one GSP is disconnected, adjacent GSPs supply its load, which may increase the risk of overload.

Figure 2 illustrates the GSP load redistribution under different fault cases and EV penetration. For stress testing, peak charging demand was used to capture the most critical conditions. For example, disconnecting GSP1 shifts most of its load to GSP2 with limited impact elsewhere.

In contrast, disconnecting GSP3 leads to load redistribution across GSPs 2, 4, and 5, reflecting its central position in the network.

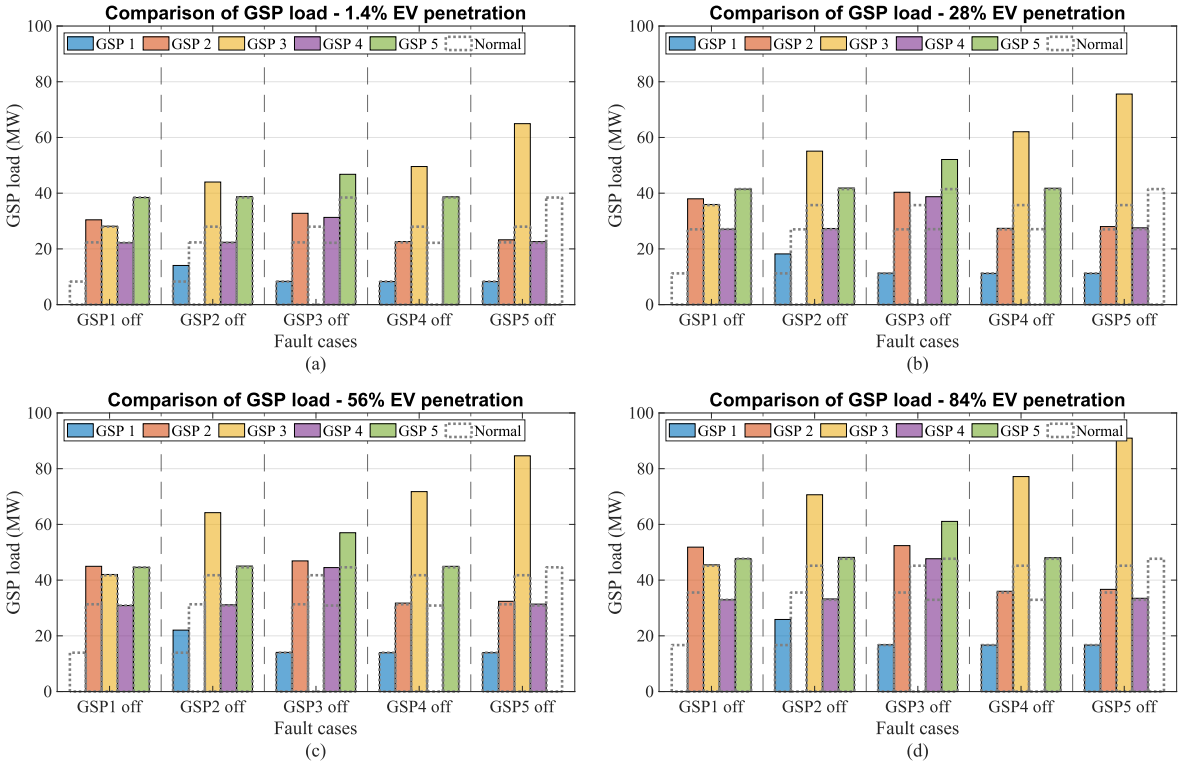


Figure 2.GSP load changes under different fault cases and EV Penetration Projections.

These results highlight that certain GSPs are more susceptible to overloading when adjacent GSPs are offline. This vulnerability increases with the growth in EV charging demand due to transportation electrification, as shown in Figure 2 (d), underscoring the need for future mitigation and shared resilience strategies at the T-E nexus.

B. Impact on Network Voltage

Voltage levels across nodes must be maintained at 94% of their nominal value as per contractual agreement. As shown in Figure 3, our simulations show that when a local GSP is offline, the new supply profiles lead to voltage drops up to 0.4% compared to normal conditions, which does not impact considerably the operation of the network. This is due to the fact that networks in urban environments are very dense, with small cable lengths, yielding to very small voltage drops.

In summary, these findings show that the network voltage plan is resilient to single climate faults but the resilience of supply points to climate events should be strengthened.

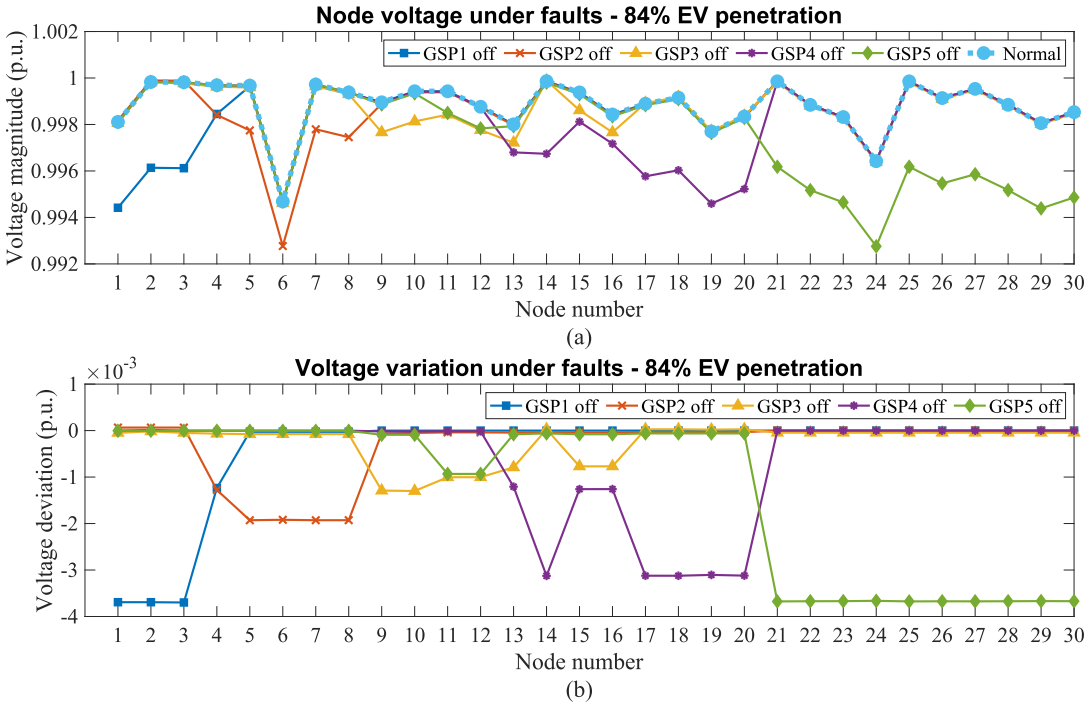


Figure 3. Node voltage and their variations under fault cases.

Conclusion

This study presents a system-level analysis of an urban 33 kV distribution network with high penetration of EV chargers. By considering GSP faults scenarios due to cable failure during climate-related events, our simulations highlight that adjacent GSP become more exposed to overloading, particularly with high EV charging demand.

Future research will examine scenarios with multiple weather-induced faults and propose mitigation strategies that leverage transport-sector flexibility to support the electrical network, highlighting the resilience benefits of transport–energy system coupling.

Acknowledgements

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Evacuation Behaviors of Electric Vehicle Drivers: Route and Charging Choice Experiments

1. Denissa Sari Darmawi Purba, Ph.D. Institute of Transport Studies BOKU University, Wien, Austria Email: denissa.purba@boku.ac.at
2. Eleftheria Kontou, Ph.D. Civil and Environmental Engineering University of Illinois at Urbana-Champaign, Urbana, IL, USA Email: kontou@illinois.edu

Abstract

During habitual travel, electric vehicle (EV) drivers' routes and charging infrastructure choices are associated with their vehicle's driving range, recharging times, and infrastructure access. During an extreme event that warrants evacuation, motorists' decisions (e.g., routing) are associated with personal and household characteristics, regional and road features, and the hazard's severity. As the number of EV drivers increases in our road networks, vehicle technological specifications may further complicate evacuation routing and charging decisions. We conduct a stated preference (SP) survey and statistical modeling to identify the effect of electric vehicle specifications and charging station characteristics on EV drivers' evacuation decisions: routing and charging choices. The stated preference survey consists of 12 route choice experiments of 100-mile and 300-mile evacuation simulations under mandatory evacuation orders. The survey considered key attributes, including evacuation distance, travel time, queuing and charging duration, battery state of charge, locations of charging stations, and correlation between route choices. The data was analyzed using two discrete choice models: a multinomial logit model and a two-level nested logit model. Our findings uncover the effects of vehicle and charging station characteristics on EV drivers' evacuation behavior and inform policy implications and evacuation preparedness recommendations.

Keywords Electric vehicles; evacuation behavior; route choice; charging decisions; stated preference analysis

Introduction

Evacuation behavior studies have extensively contributed to characterizing individual evacuation decisions (e.g., timing, destination, and routing choices) and designing effective evacuation preparedness policies that facilitate such behavior. These evacuation decisions are often associated with individual and household characteristics, hazard intensity and infrastructure impacts, traffic conditions, and evacuation orders (Collins et al., 2018; Sadri et al., 2014). As the number of EV drivers rises, evacuation decisions of EV drivers are impacted by their vehicles' technological characteristics.

Research indicates that EV drivers' charging and routing behaviors are shaped by route attributes, vehicle specifications, and charging station characteristics (Ashkrof et al., 2020; Yang et al., 2016), which may transform evacuation planning paradigms. EV drivers prefer routes that provide charging stations opportunities along the way to their destinations (Wang et al., 2024; Yang et al., 2016) and minimize their energy consumption (Ashkrof et al., 2020; Yang et al., 2016). However, in emergencies, disrupted roads and power outages can reduce charging accessibility, heighten range anxiety, and alter drivers' choices compared to normal conditions. Existing research on evacuation and EV behavior has not fully addressed how

vehicle and charging station characteristics influence route and charging decisions during evacuations. Behavioral insights on EV drivers' evacuation decisions are necessary to develop contingency plans that reflect the needs of these drivers and reduce community vulnerability levels in hazard-prone areas.

Our study proposes a behavioral analysis by employing a stated preference (SP) survey to identify the effect of various vehicle specifications and charging station characteristics on the EV drivers' evacuation route choices and en-route charging decisions. We have three research goals:

1) Identify the impact of EV and charging station specifications on evacuation route choices and charging behaviors;
2) Develop behavioral models to characterize EV routing and charging preferences during an evacuation order;
3) Provide recommendations and guidelines to planners and decision-makers to integrate charging-routing behavioral models in evacuation planning.

Methodology

Figure 1 illustrates the workflow of the EV evacuation behavioral study. Respondents are placed in two mandatory evacuation scenarios (i.e., short- and long-distance evacuations) and presented with the route and charging choice experiments. There are 12 evacuation route and charging choice tasks: six choice tasks of a short-distance evacuation scenario and six choice tasks of a long-distance evacuation scenario. The collected data were analyzed using logit-based behavioral models. A multinomial logit (MNL) model was applied to characterize route and charging choices in both evacuation scenarios. To capture unobserved correlations between route alternatives, a nested logit (NL) model was also estimated for the short-distance scenario, where the upper level represents the charging decision and the lower level represents route choice conditional on that decision. Finally, recommendations for evacuation preparedness strategies are identified based on behavioral insights.

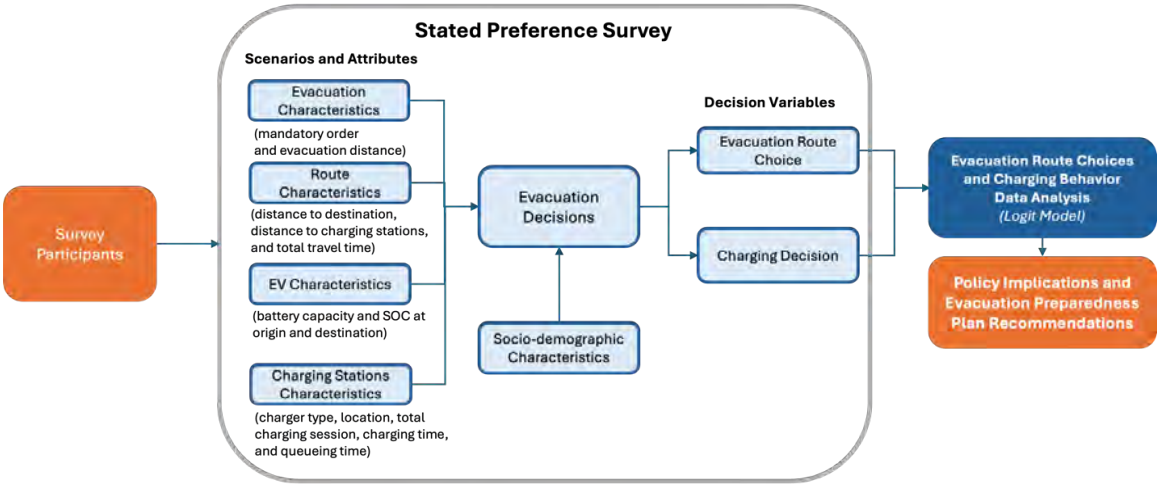


Figure 1 Electric vehicle evacuation behavior workflow

Findings

Data collection was conducted from July 26 to September 30, 2024. There are 255 total responses, with 158 valid responses for analysis. From the valid responses, there are 81 EV drivers. The final dataset comprises 1,884 choice observations used to construct the behavioral model.

EV Evacuation Route and Charging Choices in Short-distance Evacuation

In the short-distance evacuation scenario, we evaluate evacuation route choices and charging behaviors when a charging stop is not necessary. Three logit models are fitted: two MNL models and one NL model that accounts for correlations between route and charging decisions. Table 1 summarizes the model estimation parameters for the short-distance evacuation case.

In the MNL S-1 model, evacuation distance does not significantly affect route choice since EV range comfortably exceeds the distance in short evacuations. Travel, charging, and queuing times all reduce route utility, with evacuees being most sensitive to travel time (–0.021) compared to charging (–0.018) and queuing (–0.005). Routes requiring charging stops are strongly disfavored (–0.629). A higher SOC at the destination increases utility (0.090), indicating evacuees value arriving with sufficient charge. The interaction effects show that lower SOC at origin increases preference for routes ensuring higher SOC at the destination, but evacuees still avoid charging stops in short evacuations. The MNL S-2 model highlights socio-demographic impacts: EV owners (+0.198) and higher-income respondents (+0.002) show greater willingness to evacuate, while older evacuees (–0.011) are more hesitant. The NL S-1 model reveals stronger correlation among routes without charging (0.332) than with charging (0.718), suggesting evacuees perceive no-charge routes as more substitutable.

EV Evacuation Route and Charging Choices in Long-distance Evacuation

For the long-distance evacuation scenario, all evacuation routes require to stop to charge to complete the evacuation. The NL model is not relevant in this analysis; hence, we construct two MNL models. Table 2 summarizes the model estimation parameters for the long-distance evacuation case.

In the MNL L-1 model, travel, charging, and queuing times reduce route utility, but queuing time has the strongest negative effect (–0.021). Unlike the short-distance case, all long-distance alternatives require charging, making evacuees especially sensitive to queuing delays. Additional charging stops further reduce utility (–0.012), while maintaining a higher SOC at the destination strongly increases utility (0.647), the largest effect observed across models. Interactions also differ from the short-distance case. SOC at origin alone is insignificant, but its interaction with SOC at destination is complementary: evacuees starting with higher SOC still prefer routes that ensure higher SOC at the destination. Conversely, the interaction of SOC at origin with total charging sessions penalizes utility more strongly (–0.036). In the MNL L-2 model, EV ownership (+0.206) and female respondents (+0.319) increase route preference, while higher income slightly decreases it. Overall, long-distance evacuations highlight stronger concerns over queuing and SOC than short-distance cases.

Table 1 MNL and NL models for EV evacuation route and choice choices in short-distance evacuations

Parameters	**MNL S-1**			**MNL S-2**			**NL S-3**		
	Estimates	**Std Err**	**p-value**	**Estimates**	**Std Err**	**p-value**	**Estimates**	**Std Err**	**p-value**
distance	0.002	0.001		0.001	0.001		0.001	0.001	
travel time	-0.021	0.002	**	-0.028	0.002	**	-0.017	0.003	**
charging time	-0.018	0.008	**	-0.013	0.008	**	-0.016	0.006	**
queuing time	-0.005	0.005	**	-0.004	0.005	**	-0.002	0.004	**
charging session(s)	-0.629	0.202	**	-0.468	0.204	**	-0.506	0.010	*
SOC origin	-0.007	0.002	**	-0.011	0.004	**	-0.005	0.002	**
SOC destination	0.090	0.010	**	0.094	0.011	**	0.086	0.010	**
Interaction parameters									
SOC destination x SOC origin	-0.010	0.002	**	-0.013	0.002	**	-0.011	0.002	**
charge session x SOC origin	-0.011	0.003	**	-0.009	0.003	**	-0.009	0.003	**
Socio-demographic characteristics									
Female				0.252	0.241		0.057	0.078	
Income (per $1,000)				0.002	0.001	**	0.001	0.000	**
Age				-0.011	0.005	*	-0.015	0.002	**
Higher Education				-0.216	0.206		-0.006	0.081	
EV Ownership				0.198	0.198	*	0.200	0.082	*
Nested parameters									
λ_{charge}							0.718	0.389	**
$\lambda_{no-charge}$							0.332	0.126	**
Model Statistics									
LL (final)	-1418.6			-1401.47			-1395.25		
adj. rho sq	0.0675			0.0754			0.0788		
AIC	2855.2			2830.93			2820.5		
BIC	2898.84			2898.81			2893.22		

** Significant values at the 95 % level, ** Significant values at the 98 % level*

Table 2 MNL models for EV evacuation route and choice choices in long-distance evacuations

Parameters	**MNL L-1**			**MNL L-2**		
	Estimates	**Std Err**	**p-value**	**Estimates**	**Std Err**	**p-value**
distance	0.005	0.005		0.009	0.006	
travel time	-0.005	0.005	*	-0.002	0.006	*
charging time	-0.008	0.005	*	-0.011	0.005	*
queuing time	-0.021	0.004	**	-0.023	0.004	**
charging session(s)	-0.012	0.301	*	-0.159	0.308	*
SOC origin	0.002	0.002		-0.007	0.003	
SOC destination	0.647	1.555	*	0.014	0.016	*
Interaction parameters						
SOC origin x SOC destination	0.031	0.002	*	0.025	0.002	*
charge session x SOC origin	-0.036	0.053	*	-0.063	0.054	*
Socio-demographic characteristics						
Female				0.319	0.147	**
Income (per $1,000)				-0.001	0.001	**
Age				-0.002	0.004	
Higher Education				-0.161	0.137	
EV Ownership				0.206	0.148	*
Model Statistics						
LL (final)	-969.37			-961.76		
adj. rho sq	0.0531			0.0556		
AIC	1956.74			1951.52		
BIC	2000.37			2019.39		

** Significant values at the 95 % level, ** Significant values at the 98 % level*

Summary

This study conducted a web-based SP survey to analyze EV evacuation behavior, with a particular focus on route selection and charging decisions. The survey included 12 route choice experiments for short- and long-distance mandatory evacuations. The choice tasks are designed considering route, vehicle, and charging attributes. There are five logit models used to examine the impact of these attributes to EV evacuation routing and charging choices. The study confirms that travel time, charging time, and queuing time negatively impact evacuees' route utility, with a stronger sensitivity toward charging and queuing time. Additionally, the interaction between SOC at the origin and destination influences route and charging decisions differently based on evacuation distance.

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Vulnerability Assessment of Electric Vehicles and Charging Stations Network During Evacuations

1. Denissa Sari Darmawi Purba, Ph.D. Institute of Transport Studies BOKU University, Wien, Austria Email: denissa.purba@boku.ac.at
2. Eleftheria Kontou, Ph.D. Civil and Environmental Engineering University of Illinois at Urbana-Champaign, Urbana, IL, USA Email: kontou@illinois.edu

Abstract

Since the introduction of electric vehicles (EVs) in the US market, there have been no adjustments to evacuation planning to address their unique charging needs. EV drivers may face range anxiety, long recharging times, and navigate sparse public charging networks, which challenge both preemptive and short-notice evacuations. This research proposes a multi-criteria vulnerability assessment of coupled EV driver and charging station networks in various evacuation scenarios. We study flooding evacuations in Chicago, Illinois, and hurricane evacuations in the Southeast Florida road networks. Our findings show that vehicle and infrastructure characteristics (i.e., charging stations network, driving range, and vehicle type heterogeneity) and evacuation characteristics (i.e., network scale and topology, hazard type, and warning system type) impact evacuation feasibility and performance and increase drivers' vulnerability. Furthermore, the initial state of charge (SOC) and battery efficiency during extreme weather are critical in determining EV drivers' capability to initiate an evacuation. Last, we discuss potential measures that can curb vulnerability and better accommodate EV evacuations.

Keywords: electric vehicles; charging station network; evacuation performance; vulnerability assessment

Introduction

Despite the market growth of electric vehicles (EVs), these vehicles adoption subject to unique technological and infrastructure characteristics, such as driving range, long charging times, and sparse charging networks, compared to gasoline vehicles (Office of Energy Efficiency & Renewable Energy, 2018; US Department of Energy, 2021). While these specifications are manageable to support daily mobility, they may magnify existing range anxiety and charging shortcomings for EV drivers during evacuations. Studies of Hurricane Katrina and Rita show that the evacuation distance exceeded 388 miles (Hori et al., 2009; Lindell et al., 2019), which is greater than the current median range of EVs in the market, i.e., 257 miles (US Department of Energy, 2023). In US, most EV charging stations are situated in city centers, and few are available along interstates and in the outskirts (US Department of Energy, 2021), where designated safe zones are (California FPD, 2022; Texas Department of Transportation, 2023). EV drivers may be subject to frequent charging stops to reach a distant shelter and higher risk of getting stranded without enough power to complete the evacuation. Hazardous events, like hurricanes, wildfires, and floods, and their increased frequency may disrupt the transportation and charging networks, adding more risks to EV drivers' mobility during evacuations.

A coupled assessment of EV drivers and charging infrastructure network vulnerability can pinpoint the need for infrastructure adaptation and fortification, which could be crucial for

mitigating life-threatening effects of hazards posed to electrified mobility. Such a comprehensive vulnerability assessment that integrates coupled electric vehicles and their charging infrastructure, leveraging rigorous mathematical modeling of the evacuation process, is lacking; these vulnerability factors are often separately assessed (Feng et al., 2020; MacDonald et al., 2021). Hazard impact to road and charging station disruptions is often neglected in the EV evacuation assessment (Li et al., 2022; Purba et al., 2024, 2022), undermining the EV drivers and charging station network vulnerability.

Our research aims to assess the vulnerability of EV drivers and their charging infrastructure during evacuations in disaster-prone regions and provide policy recommendations that enhance the safety of these vehicles during emergencies. This research proposes a multi-criteria vulnerability assessment of coupled EV driver and charging station networks during evacuations. We assess the vulnerability against power outages, road closures, and hazard intensity scenarios at the network level, considering the share of gasoline vehicles and EVs with their unique driving ranges and refueling/charging networks. The research focuses on preemptive hurricane evacuation on a regional scale in South Florida and short notice flooding evacuation on a city scale in Chicago, Illinois.

Method

The analysis simulates EV evacuations during floods, considering both non-disrupted and disrupted transportation networks and the mix of EVs and gasoline vehicles. Key performance metrics include travel time, charging and queueing delays, charging accessibility, and the percentage of drivers who successfully complete the evacuation. Data collection includes transportation networks, charging station locations and specifications, hazard footprints, and EV adoption rates at network nodes. Figure 1 presents the vulnerability assessment framework.

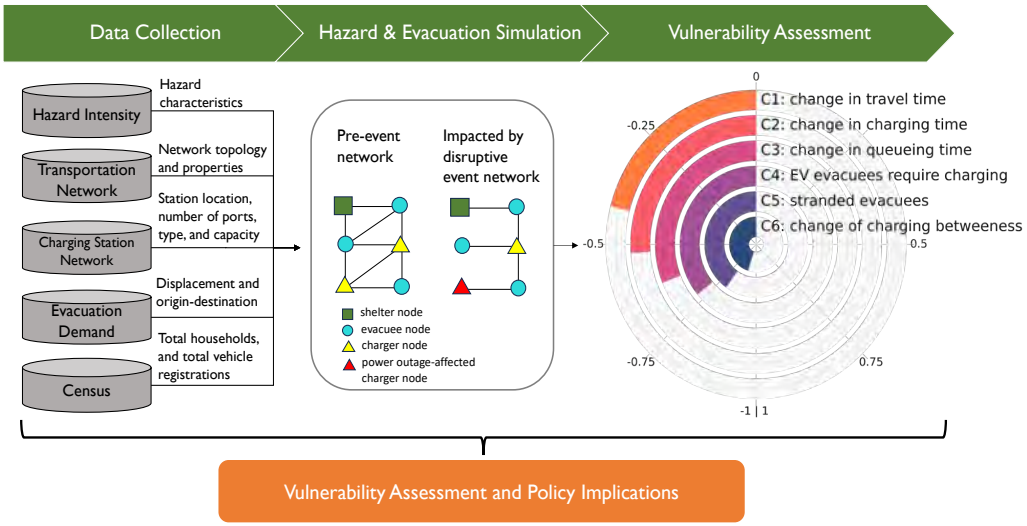


Figure 1. Workflow of vulnerability assessment of EV drivers and their charging station network during evacuations.

The framework consists of three sub-models, illustrated in Figure 2. The first model is the *Scenario Generation Schemes*. This scheme generates 30 representative scenarios of power outages and road closures based on the hazard footprint, incorporating probabilities of road blockages and outages at the network level. The second model is the *Evacuation Simulation Model*. We develop two EV evacuation simulations. The preemptive evacuation uses the |K|-Evacuation Tree Route model with range-betweenness constraints to design evacuation routes to safety with seamlessness and contraflow principles. The short-notice evacuation model uses

the System Optimum traffic assignment with range-betweenness constraints. Both simulations integrate a G/G/1 queueing model to quantify charging and queueing times at stations for preemptive and short-notice evacuations. The third model is the *Multi-criteria Vulnerability Assessment Model*. This model uses six quantitative criteria across three key components, i.e., system performance (changes in travel, charging, and queueing times), evacuees' access to charging stations and destinations (the total number of EV drivers that need to charge and the total number of stranded/isolated EVs), and charging accessibility (charging station betweenness centrality).

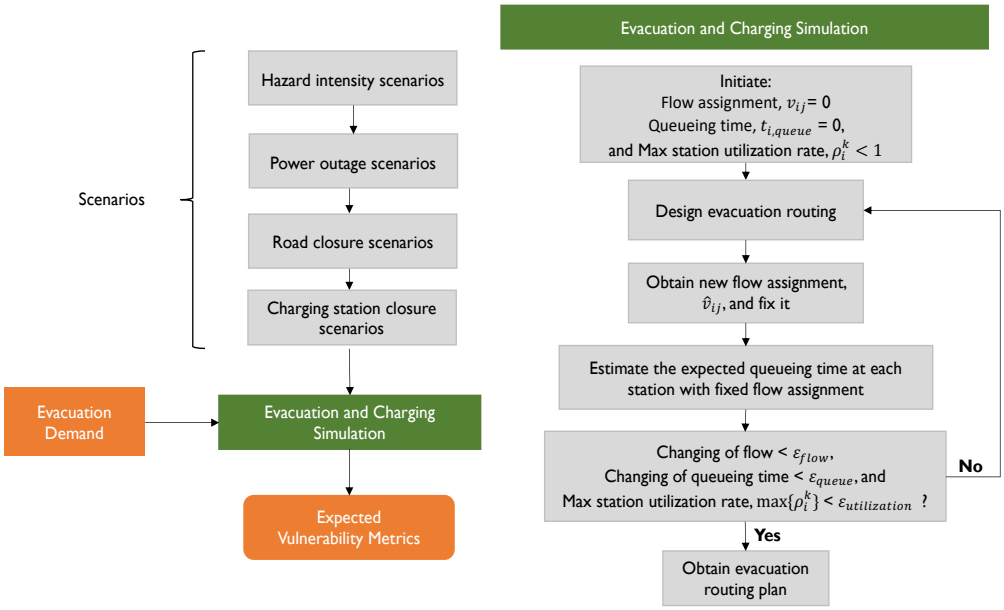


Figure 2. (a) Scenario generation and (b) the evacuation traffic assignment with EV charging queueing.

Findings

The analysis assesses the impact of hazard intensity, initial battery state of charge (SOC), and reduced battery efficiency due to cold temperature conditions on the evacuation performance of EV drivers and the accessibility of the charging network in each region. Figures 3 and 4 illustrates the impact of hazard intensity and initial battery SOC on the EV evacuation performance in each region.

Our findings show that most EV drivers in the network could evacuate safely with/without charging in mild and moderate hazard events. However, some EV drivers, especially those with short battery range EVs, rely on charging station accessibility to complete the evacuation. During rare and severe hazards, charging station accessibility dropped by 76%, and the number of stranded EV drivers increased by 75% in Chicago. Similarly, charging station accessibility decreased by 62%, and stranded EVs increased by 42% in Florida. Evacuation and charging station network performance depend on the transport network properties and hazard footprint. EV driving ranges do not significantly impact the EV evacuation performance and feasibility in the Chicago network due to its small size and evacuees' proximity to shelters. However, EV drivers have greater range anxiety and significant charging station dependencies in Florida due to a larger evacuation network and greater distances to the designated shelters. The initial SOC of EV batteries played a critical role in evacuation feasibility: in Chicago, low SOC led to a 30% increase in drivers needing to charge, and a 2.5% increase in stranded EVs. In Florida, low SOC increased evacuation time by 48% and queueing time by 14%. The vulnerability assessment results and findings are

documented on ArcGIS Story Maps and data repository.

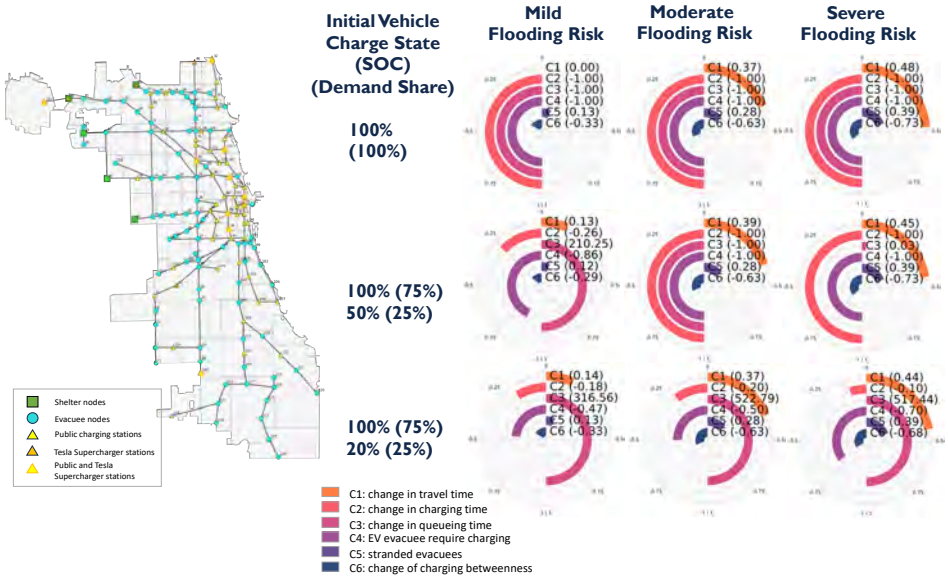


Figure 3. 3x3 vulnerability radial diagrams showing Chicago flooding evacuations under three hazard intensities and three initial EV battery SOCs

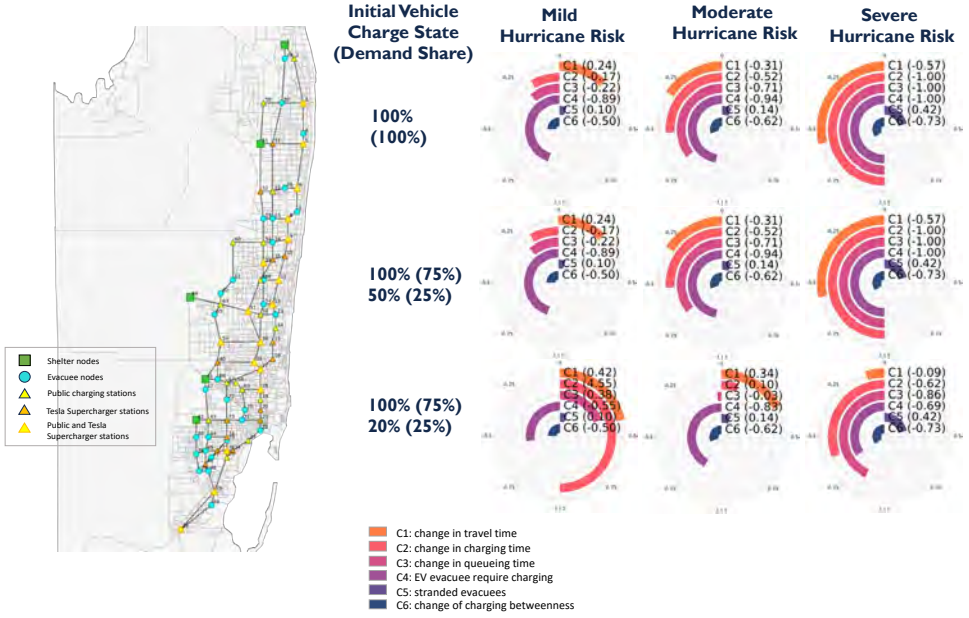


Figure 4. 3x3 vulnerability radial diagrams showing South Florida hurricane evacuations under three hazard intensities and three initial EV battery SOCs

Acknowledgements

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Monitoring future energy systems' resilience during a heatwave

Madhura Yeligeti[1], Hans Christian Gils[1], Sigrid Prehofer[2], Hedda Gardian[1]
[1] German Aerospace Center (DLR), Institute of Networked Energy Systems, Curiestrasse 4, Stuttgart, 70563, Baden-Wuerttemberg, Germany
[2] University of Stuttgart, Center for Interdisciplinary Risk and Innovation Studies (ZIRIUS), Seidenstrasse 36, Stuttgart, 70174, Baden-Wuerttemberg, Germany

Abstract

Energy systems of the future, driven by variable renewable energy can gain flexibility, balance and efficiency from sector-coupling. However, to test if sector-coupling will make energy systems more resilient to extreme events, we build distinct designs of the future energy system based on socio-economic scenarios. System performance is tested against the effects of the heatwave using an energy system optimization model. We observe that while all the system designs maintain security of supply even during the unforeseen heatwave, infrastructure constraints in different scenarios limit the systems' abilities. This yields higher costs of imports in some scenarios over other. This case-study serves as a template for further assessments with other extreme events across many scenarios to assimilate common planning strategies for enhancing resilience of sector-coupled energy systems.

Keywords: energy system optimization; heatwave; sector-coupling

Introduction

Highly renewable, future energy systems will be more sensitive to meteorological dynamics and climate-change effects than today. In addition, extreme weather events are becoming increasingly frequent. Events like heatwave inflict upon energy systems on a national to continental scale at once. A strong connection among heat, gas, transport and electricity sectors will add flexibility, balance and improve efficiency of resource utilization in energy systems. Additionally, decentralization and digitalization will foster demand-side management. Yet, whether such multi-vector energy systems can withstand widespread extreme events like a heatwave and ensure security of supply is still less-explored. In this study, we investigate the resilience of a carbon emission-free, sector-coupled, German energy system of 2050 against effects of a heatwave. The term 'resilience' here corresponds to the system's ability to adequately supply energy to meet demand. Since the future of society can evolve in a myriad of ways leading to many different energy system designs, in this study, we build three systems based on three scenarios. We test the resilience of each system aiming to gain insights on strategies for resilience in energy systems planning.

Scenarios

The scenarios aim to translate the effects of societal, political and economic change onto the energy transition leading to different boundary conditions for the energy system of 2050. Three socio-economic scenarios build upon the demand scenarios for clean transport in a GHG neutral energy German energy system in (Wulff et al., 2025) implying different degrees of Hydrogen (H_2), biofuels and electricity in the transport sector. The characteristics of the

scenarios refer to different ideals in the German society and consequential infrastructure boundary conditions. They are summarized in table 1.

. Table 1. Scenario overview

Characteristic ↓ / Scenario name →	**Mixed-Import (MI)**	**Elec-HighRE (EH)**	**Hydrogen-centralized (HC)**
Share of electricity and H_2 in transport sector	High electricity share	High electricity share	High share of H_2
Development of grid infrastructure for electricity and H_2 transfer	Very high, strongly domestic capacity expansion	High, balanced domestic and international expansion	High, with emphasis on H_2 network, balanced domestic and international expansion
Source of key energy carriers i.e. electricity, H_2 and CH4	High share of direct global imports, low European cooperation	High self-sufficiency	Strong European exchange

Assessment of energy system resilience

Extreme event: heatwave

Based on accounts from the wide-spread heatwave in central Europe in 2003, possible effects on the energy system like the rise in electricity demand, disruption in thermal power plant operation and loss of transmission efficiency and eventual shut-down of certain grid lines are estimated and a stress test is created.

Energy system optimization model

An instance of the German sector-coupled energy system is created considering the German electricity and gas network connected to its 9 neighboring countries and Italy for the year 2050. This model incorporates techno-economic data for over 70 technologies (e.g. solar photovoltaics, Li-Ion batteries, gas power plants etc.) from various sources like the Danish Energy Agency's technology catalogue (Danish Energy Agency (DEA)) , demands for heat, fuel and electricity, existing capacities of the network connections, and large power plants. The linear energy system optimization framework REMix (Wetzel et al., 2024) is used to design a cost optimal energy system that ensures sufficient energy to meet demand at every hour of the year 2050 in high spatial resolution.

Approach

The cost-optimal energy system configurations are prototype representations of the energy system infrastructure like grid capacities, power plants etc. that will be built in the three scenarios for an adequate supply of electricity, heat, natural gas and H_2 in the system. These capacities are fixed and only the operation is optimized under the effects of the heatwave to

test if the built-up infrastructure is sufficient to meet the higher heatwave-induced demand with limited power-plant and grid operation.

Results and inferences

The demand during the heatwave rises by over 80 TWh in the model scope comprising of Germany, its neighbors and Italy. Still, all the three energy systems pass the test and ensure supply security during and after the heatwave through different ways of operational reorganization. In all scenarios, hydrogen production with electrolyzers is reduced to lay off load, leading to an increase in direct import of H_2. c.f. figure 1. Thus, the electricity-hydrogen coupling serves as a decisive flexibility source in the event of a heatwave. Additionally, in the *EH* scenario, a higher biogas and fossil-CH_4 import with the higher H_2 import amount to an additional 760 million Euros in the system costs. In the *HC* scenario with a large H_2 share and limited CH_4-conversion capacity, a higher amount of H_2 is required to run H_2-driven turbines which ends up costing the system over 1300 million Euros. This effect is further aggravated in the MI scenario. With few technology options, imports skyrocket accounting for over 2000 million Euros. This shows among the three scenarios that, a high technological plurality can allow more flexibility and limit the cost of sudden fuel imports in times of crises like a heatwave, enhancing system resilience.

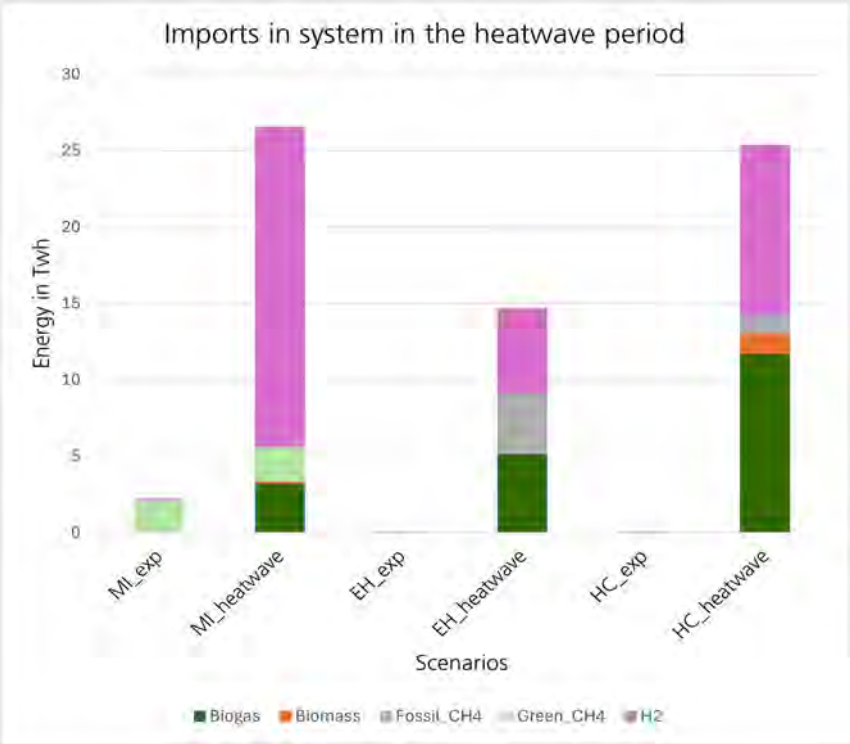


Figure 1 Overview of fuel import aggregated for the entire model scope, from the results of the no-event expansion optimization and the resilience test for all scenarios. For biogas and biomass, "import" refers to utilization of fuel-resource potential in the energy system.

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Exploring technically-resilient and practically-viable planning strategies with MGA

Francesco Lombardi [1], Koen van Greevenbroek [2,3], Aleksander Grochowicz [4], Michael Lau [5], Fabian Neumann[6], Neha Patankar [7], Oskar Vågerö, [8]

1 Department of Engineering Systems and Services, Technical University of Delft, Netherlands

2 Department of Computer Science, UiT The Arctic University of Norway, Norway

3 Earth System Science, Stanford University, United States of America

4 Department of Wind and Energy Systems, Technical University of Denmark, Denmark

5 Andlinger Center for Energy and the Environment, Princeton, United States of America

6 Department of Digital Transformation in Energy Systems, Institute of Energy Technology, Technische Universität Berlin, Germany

7 School of Systems Science and Industrial Engineering, Binghamton University, United States of America

Abstract

Energy planning models are influential in shaping decisions about the energy transition. System operators, legislators, and civil society regularly use them to inform their planning strategies. And yet, the current standard practice in using such models focuses solely on minimising costs as the guiding principle for identifying viable strategies. This practice overlooks the possibility that other feasible strategies with comparable economic costs may exist that offer additional benefits. For instance, strategies that ensure greater resilience to uncertain conditions or that are more socially acceptable.

'Modelling to Generate Alternatives' (MGA) is a method that enables going beyond the above limitations by systematically mapping out many technically feasible and economically comparable strategies and opening a space for stakeholders to appraise and discuss their trade-offs. Notably, while planning strategies that ensure increased resilience to uncertain conditions may also be found with established methods, such as robust optimisation, the combination of such methods with MGA enables further diversification of strategies to hedge against uncertainty, thereby better enabling trade-offs between resilience and other, harder-to-model features of interest.

In this conference contribution, based on our recent perspective article in Joule, we offer an overview of recent developments in MGA and illustrate how to integrate this method into energy planning models in five levels of increasing potential. The entry levels are conceptually and practically simple to implement. They are conceived for organisations with limited computational resources or burdensome models, while already ensuring higher-quality insights than simple cost minimisation. As integration levels increase, MGA enables a more thorough exploration of planning options, culminating in the ability to allow novel, interactive co-design of energy plans with all stakeholders. Moreover, we devote specific attention to the various ways to integrate MGA with resilience considerations.

Keywords: energy planning; energy system models; modelling to generate alternatives; near-optimal solutions; resilience.

Preparing for the worst: Long-term and short-term weather extremes in resource adequacy assessment

Aleksander Grochowicz [(1)], Hannah Bloomfield [(2)], Marta Victoria [(3)]
1 Technical University of Denmark, Denmark, algro@dtu.dk
2 Newcastle University, UK, hannah.bloomfield@newcastle.ac.uk
3 Technical University of Denmark, Denmark, mvipe@dtu.dk

Abstract

Security of supply is a common and important concern when integrating renewables in net-zero power systems. Extreme weather affects both demand and supply leading to power system stress; in Europe this stress spreads continentally beyond the meteorological root cause.
We use an approach based on shadow prices to identify periods of elevated stress called system-defining events and analyse their impact on the power system.
By classifying different types of system-defining events, we identify challenges to power system operation and planning.
Crucially, we find the need for sufficient resilience back-up (power) capacities whose financial viability is precarious due to weather variability.
Furthermore, we disentangle short- and long-term resilience challenges with distinct metrics and stress tests to incorporate both into future energy modelling assessments.
Our methodology and implementation in the open model PyPSA-Eur can be re-applied to other systems and help researchers and policymakers in building more resilient and adequate energy systems.

Keywords: energy system optimization model; extreme weather; resource adequacy; dunkelflauten; resilience

Introduction

Weather uncertainty poses challenges in both planning and operating future energy systems. System stress in highly renewable power systems tends to occur during “energy droughts” in the European winter when seasonally low irradiation coincides with cold temperatures and low wind speeds (van der Most et al., 2024; van der Wiel et al., 2019). While meteorological conditions for system stress have been extensively studied, the effects on the power system dynamics and insights on planning are not well understood (Craig et al., 2022; Kittel et al., 2025). Grochowicz et al., 2024 introduced an approach based on shadow prices that synthesizes weather information with the power system dynamics leading to a more accurate identification of system-defining events than energy meteorology only. However, the planning implications and which system components contributes to increased resilience under extreme weather remained unanswered.

This paper addresses these gaps by

- identifying components enhancing resilience during system stress;
- characterising types of system-defining events;
- confirming the robustness of the method and investment strategies across different configurations;

- distinguishing long-term resilience from short-term stress tests through adequate metrics and planning approaches.

We use PyPSA-Eur to model a net-zero European power system with high temporal (hourly) and spatial resolution (90 nodes) for 80 years of weather data. Our methodology identifies key periods and weather year, and is adaptable to other regions.

Energy droughts occur regularly in highly renewable systems and require resilience reserves

We identify power system stress through *system-defining events (SDEs)*: periods during which a significant portion of the energy infrastructure build-out is determined (see Table 1), measured by a rapidly accumulated cost, which is most striking for resilience provision during energy droughts.

Table 1: Characterisation of the system-defining events (SDEs) identified in this study.

Time of occurrence	Nov - Feb, higher probability in Dec and Jan
Return times	approx. every 2 years
Meteorology and renewables	Wind drives the occurrence of extreme events, but (lack of) solar due to seasonality is the necessary condition; high heating demand
Geographical scale	varying; limited for weather impacts; system impacts (prices / flexibility usage) larger if not continental
Duration	1 day - 10 days (avg. 1 week)
Severity	varying, system-dependent, many criteria
Identification	Shadow prices, threshold on accumulated electricity cost
Challenge	Provision of sufficient power / flexible generation, secondary energy provision
Order of dispatch	Renewables, battery, nuclear, biomass, hydropower, pumped hydro storage, fuel cells

In the investigated period (1941-2021), many SDEs fall into the lifetime of energy infrastructure. During SDEs, adverse weather conditions reduce the seasonal share of wind power from about 50% to 15-30% of generation in Europe, whilst lower temperatures raise electricity demand. “Net load” (demand - net renewables) spikes during extreme periods up to 540 GW in our study (peak load < 700 GW). We classify three types of flexibility providers apart from transmission (Table 2, Figure 1).

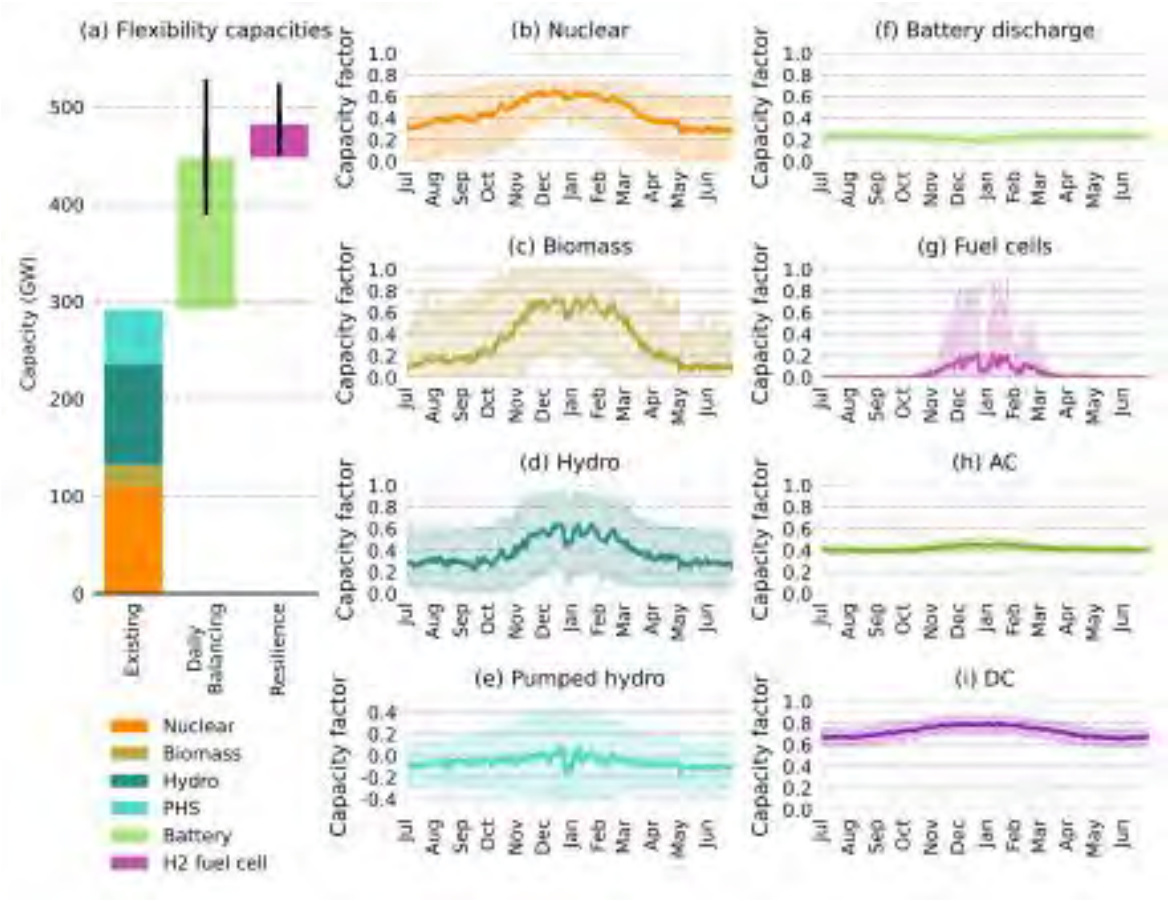


Figure 1: Installed capacities and annual generation profiles of flexibility providers. (a) shows the capacities of the three categories of flexible generation (existing dispatch, daily balancing, resilience back-up) with uncertainty bars showing the spread of capacities across different weather years for batteries and fuel cells. Capacities of existing dispatch are assumed to be fixed (Methods). (b) - (i) show the annual capacity factor profiles for nuclear, biomass, hydropower, pumped hydro storage (PHS), battery dischargers, fuel cells, as well as AC and DC transmission. The 10- and 90-percentiles are marked.

Table 2: Flexibility providers available in this study. The capacities for daily balancing and resilience back-ups vary according to the weather year used in the optimisation.

Flexibility provider	Technologies	Capacity	Characteristics
Existing dispatchables	Nuclear, biomass, hydro power, pumped hydro	300 GW	Historical reasons, insufficient for 1000h/year
Daily balancing	Batteries	100-230 GW	Sized with solar, helpful but insufficient for SDEs
Resilience back-up	Fuel cells or hydrogen/methane turbines	0-80 GW	Low capacity factor, only used during difficult periods in winter (~100-150 hours)

System-defining events are as variable as the weather and as convoluted as the power system

The system copes with SDEs by dispatching flexible generation in order of marginal prices (Table 1). When wind droughts (usually over the North Sea) align with elevated demand, this net load anomalies occur (Figure 2) and, due to transmission, shadow prices spike continentally. Simultaneously, flexible generation, especially resilience back-up, is being activated on a scale larger than the area experiencing weather anomalies (Figure 2).

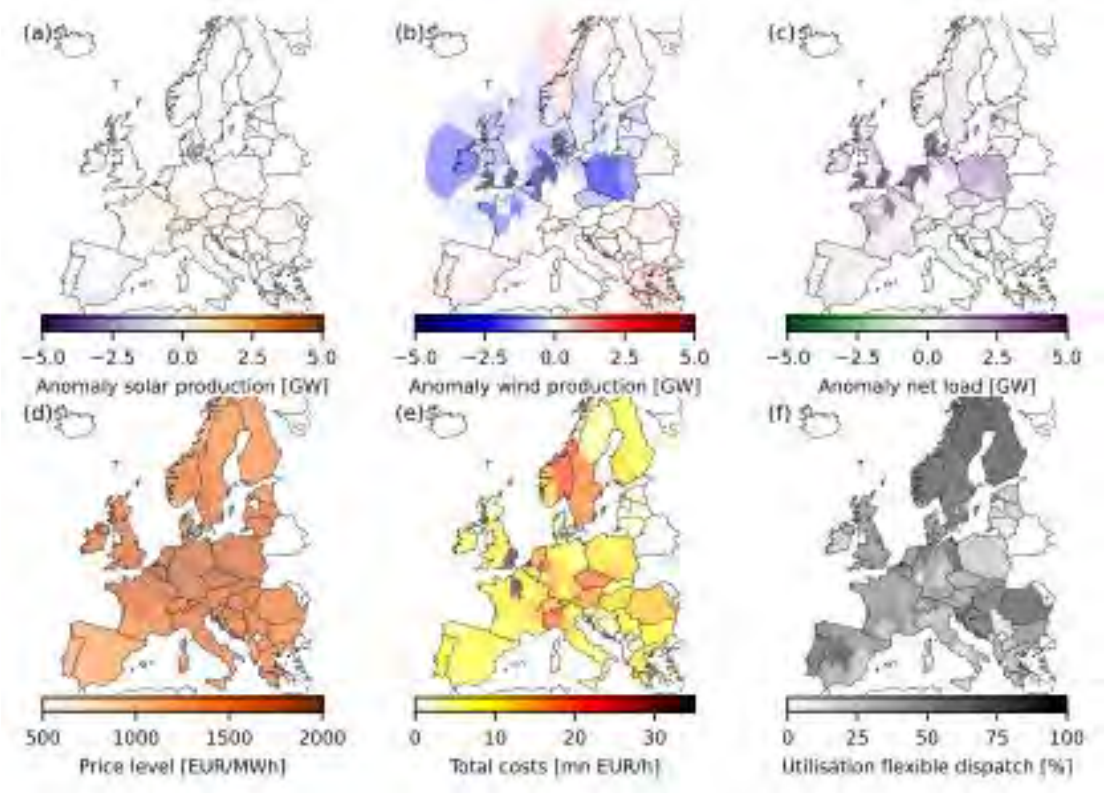


Figure 2: Composites of power system impacts during the identified SDEs. The maps show the averages across all 41 system-defining events for anomalies of (a) solar generation, (b) wind generation, (c) net load, as well as (d) the average shadow price, (e) average hourly system costs, and (f) the utilisation of flexibility capacities defined as in Figure 1(a).

Our filtering reveals four SDEs types spanning widely from longer energy to shorter power capacity deficits (Figure 3). The most extreme are *severe power deficit events* which are relatively rare confluences of load and wind anomalies resulting in high net load (Figure 4); during short-lived price spikes resilience back-ups recover capital cost in the optimisation model. Energy deficit events are less consistently identified across different configurations (Figure 5) carrying a lower stranding risk. They can be dealt with long-duration storage or limited fuel-based generation (e.g. synthetic fuels or relaxed emissions).

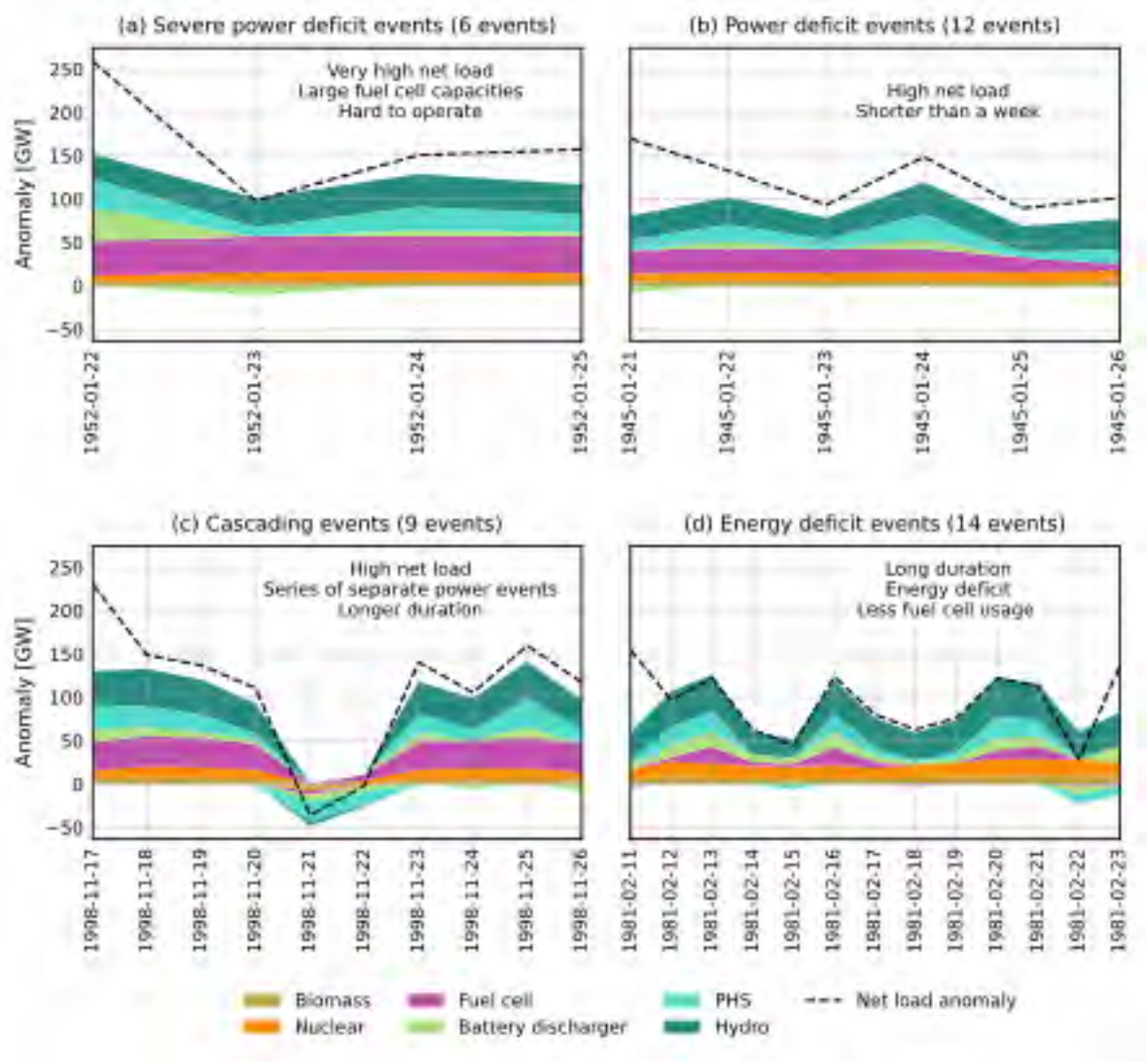


Figure 3: Overview over the four clusters of SDEs with an example event each. For the different forms of flexibility and net load the anomaly is relative to its seasonal average, and resampled to daily values. The daily resampling explains why the net load and generation anomalies do not necessarily overlap, in particular on the first and last day of a system-defining event. For instance, operating when a severe power deficit event occurs requires larger flexible dispatch than is seasonally normal (hydropower, pumped hydro, and particularly fuel cells). Power deficit events rely less on fuel cells, while the long duration and price spikes of cascading events are challenging from an energy cost perspective (up to 10 days, high deficits usually limited to 5 days). Energy deficit events cause less investment in resilience back-ups.

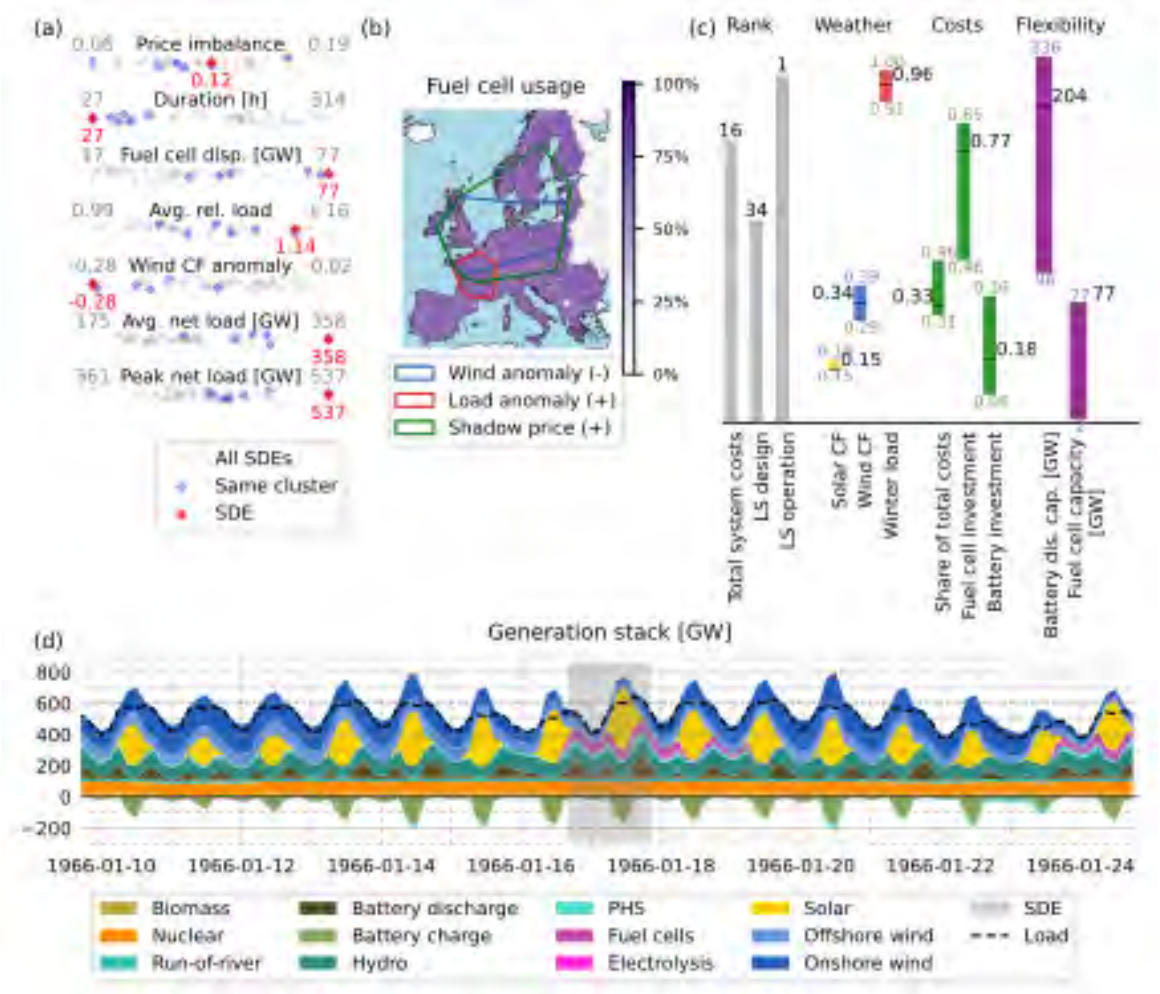


Figure 4: Dashboard containing information about one identified severe power deficit event to exemplify characteristics of system-defining events. On the left, we show the metrics used to cluster the SDEs (Methods) showing that event 11 (in January 1966) is the most extreme period identified when it comes to net load, wind anomaly, as well as fuel cell dispatch. The map in the centre shows that the areas affected by weather (load and wind anomalies) are smaller than the geographical extent of system effects (high shadow prices and fuel cell usage). On the right, we compare the difficulty according to different resilience metrics (Methods) both describing short- and long-term stress. The bottom plot shows the generation mix during the SDE, as well as before and after, showcasing the renewable energy drought and how the flexibility capacities compensate it.

System design determines severity of extreme event, but insights prevail across different system configurations

A challenge in planning for power deficit events is that optimal investment strategies across weather years differ significantly: fuel cells are already at the edge of profitability and a brief extreme event can upend system operations and spur investment for resilience back-ups. Severe power deficit events remain consistently difficult even if we investigate sensitivities such as transmission expansion, equity requirements, and emission reduction scenarios (Figure 5).

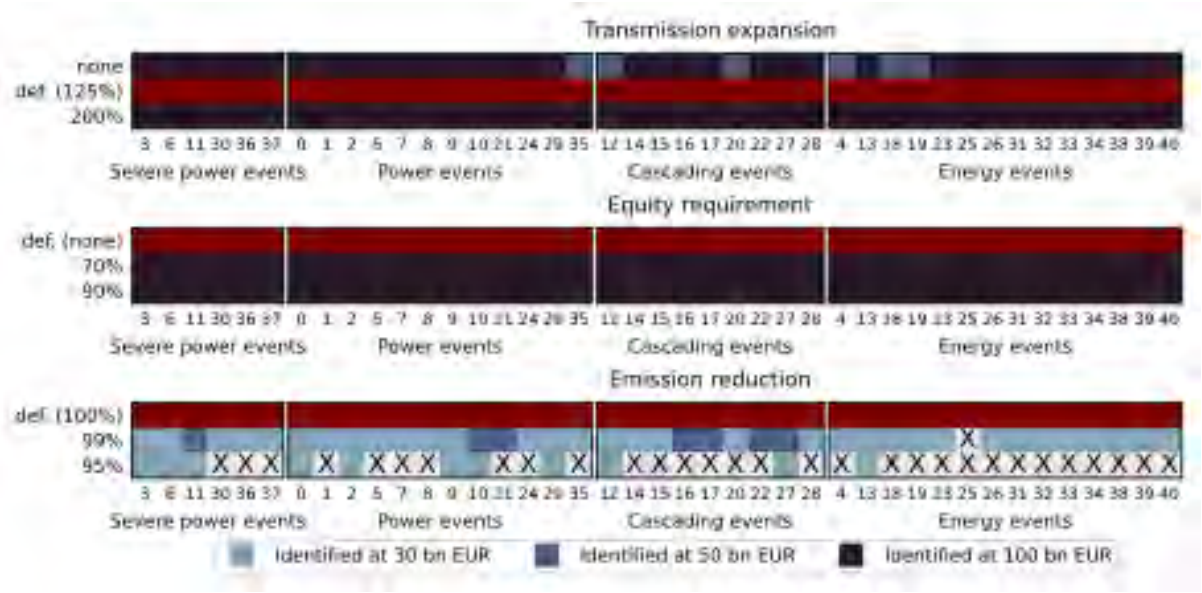


Figure 5: Identification of SDEs across different system configuration varying assumptions on transmission expansion, equity requirements, CO_2 emission reductions. The colours indicate at which threshold (shades of blue; thresholds on accumulated costs based on shadow prices) the periods identified in the default scenarios (in red) are also identified in the sensitivity scenarios. Crosses (only for the emission reduction scenarios) indicate that these periods do not inflict significant cost on the system given the assumptions of the sensitivity scenario and hence are not identified as SDEs.

When CO_2 emissions are reduced by 99% instead of 100%, relative to 1990, existing gas power plants cover peak generation entirely replacing fuel cells as resilience back-ups. Existing gas stock covers energy deficit events, but power deficit events are still identified at lower cost thresholds. However, the operation of existing gas power plants in this scenario is unprofitable and in none of the 80 years are the capital costs of this flexibility back-up recovered.

A resilient system must withstand energy drought years and shorter extreme periods in different ways

Short-lived power deficit events may be invisible in annual values (e.g. average heating load, annual capacity factor of wind power) which tend to correlate well with total system costs (Gøtske et al., 2024); a common measure to assess challenging weather years (Grochowicz et al., 2023). Drought years such as 1962/3, 1984/85, and 1941/42 (Figure 6) are worth including in analyses.

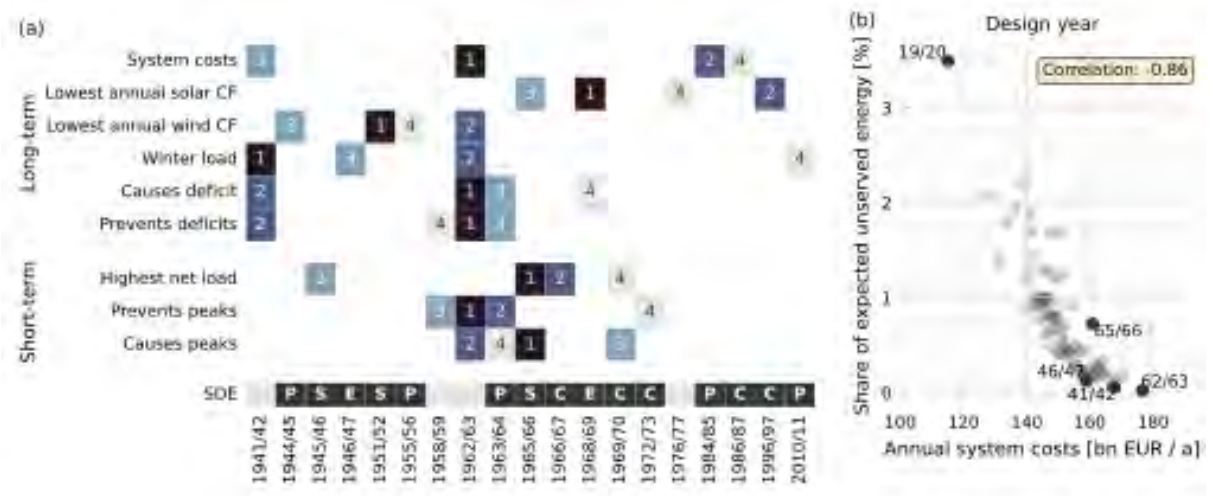


Figure 6: (a) shows the ranking of different weather years relating to metrics measuring resilience in short-term operation or long-term planning. The long-term metrics are total system costs, annual capacity factors of wind and solar power, average electricity load during the winter, as well as expected energy not served (EENS) coming from the validation using dispatch optimisations. A weather year "causes deficits" if it being operated on other design years leads to high expected energy not served (EENS), and "prevents deficits" if its system layout leads to low EENS for other weather years. The short-term metrics show the years with the highest net load and the highest power deficits coming from the validation using dispatch optimisations. A weather year "causes peaks" if it being operated on other design years leads to the largest expected power deficit, and "prevents peaks" if its system layout leads to the lowest expected power deficit. We mark whether a year contains a system-defining event with the corresponding type of event ("S", "P", "C", "E" correspond to severe power deficit, power deficit, cascading, and energy deficit events). (b) shows the non-linear relationship between the total system costs based on a given weather year and the average share of expected unserved energy (EENS) when that capacity layout is operated on the remaining 79 weather years.

Short-term resilience requires back-ups sized by net load. Across 80 weather years, we have not seen the "perfect storm" of a harsh winter with an equally severe extreme event. Instead of 80 weather years, resilience considerations should include both years with long-term challenges and years with short-term extremes as stress tests. Handling extremes - whether long-term or short-term - comes with a resilience premium and needs to trade-off energy security and affordability (Ruggles et al., 2024; Schmitz et al., 2025) with a focus on the desirable resilience level.

Discussion and Conclusions

We show system-defining events (SDEs) can be responsible for a third of annual electricity costs and high prices during SDEs raise social concerns (Brown et al., 2025). A small CO_2 budget eliminates many SDEs, but still needs resilience back-up capacities operated with low capacity factors are needed to secure a reliable supply. In energy markets, resilience back-up capacities recover the bulk of their capital cost in reoccurring but irregular SDEs with considerable financial risk.

Our results align with ENTSO-E's European Resource Adequacy Assessment (ERAA) which finds that 50 GW of new gas capacity would be needed by 2050, but low utilisation factors render much of existing gas power plants economically unviable by 20309/6/2025 8:06:00 AM. Inter-annual variability drives sizing of renewable capacities significantly, and yet latest ERAA is based on only three weather scenarios, disregarding their meteorological difficulty or caused system stress.

Our results offer more nuance in distinguishing long-term resilience challenges from short-term ones: while long-term stress (e.g. 1962/3, 1941/2) is captured by total system costs, short-term stress (e.g. 1965/66) needs to be evaluated with other relevant metrics such as shadow prices and net load. Crucially, severe SDEs need not overlap with harsh winters - they did not in our dataset of 80 weather years - and pose related, but distinct challenges to planning renewables-based power systems.

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Climate-resilient energy transition via surrogate-assisted optimization

De Marco, Francesco [1] Ampellio, Enrico [2] Sansavini, Giovanni [3]
(1) ETH Zurich, Switzerland, fdemarco@ethz.ch
(2) ETH Zurich, Switzerland, eampellio@ethz.ch
(3) ETH Zurich, Switzerland, sansavig@ethz.ch

Abstract

As the energy system increasingly relies on weather-dependent renewables, climate risks increasingly threaten security of supply. Energy shortages can drive up prices and undermine reliability, making it essential to plan for resilience: the ability to supply demand under a wide range of climatic conditions, including unexpected ones. Yet the combination of system complexity and deep climate uncertainty challenges current methods, which struggle to capture the full range of climatic events and consider this range for system planning. Against this background, we combine a machine-learning–based climate parametrization with a surrogate-assisted optimization framework. Our approach identifies which system designs are most resilient under different resilience metrics, providing quantitative guidance to balance resilience, cost, and emissions.

Keywords: climate resilient planning, transition pathway, macro energy systems, design under uncertainty

The energy transition comes with increasing climate risks

The transition to a low-emission energy system is a cornerstone of global climate mitigation. As energy production increasingly relies on renewable energy sources such as solar photovoltaics, wind power, and hydropower [1], the security of supply faces new and unprecedented challenges [2]. While these technologies are essential for reducing carbon emissions, they depend on weather conditions; this introduces vulnerabilities that increase climate risks [3]. Extreme climate events—such as droughts, heatwaves, cold spells, or prolonged periods of low wind and solar output (dunkelflaute)—can simultaneously lower renewable generation and exacerbate energy demand [4]. When such shortages occur over wide areas and extended periods, they stress the system, causing high energy prices and, in the worst cases, the inability to supply demand. Empirical evidence shows that the frequency and severity of these events have risen over the past decades [5] and are projected to intensify under future climate change [6]. As the energy system undergoes major structural transformations, it becomes essential to account for these risks already in the planning phase [7].

Energy systems planning: from Risk to Resilience

Traditionally, energy system planning has relied on probabilistic risk assessments, relying on well-characterized probability distributions. Yet, as system complexity increases, traditional approaches struggle to capture the interactions between conversion, transmission, and storage technologies, particularly when facing climate events with high spatio-temporal dimensionality. Deep uncertainty characterizes the climate system, and different weather conditions can stress energy systems in unexpected ways. This makes it difficult to identify the

events that most stress the system and their probability. Therefore, we are facing a shift from planning based solely on risk to designing systems for resilience [8]. A resilient energy system is one that can supply demand under a wide range of climate conditions, including extremes. Resilience can leverage the quantitative tools of risk analysis, and broadens the perspective by considering both expected and unforeseen conditions. In the face of growing climate uncertainty and system complexity, planning for resilience is not optional—it is fundamental for ensuring secure and reliable energy transitions.

Optimizing climate-resilient energy transition pathways

This study investigates transition pathways of the sector-coupled European energy system, that are climate-resilient. The full spectrum of climate uncertainty is included in a surrogate-assisted energy optimization model, and resilience is evaluated for candidate designs based on different risk-based metrics. The three aspects of (i) climate uncertainty, (ii) surrogate-assisted modeling, and (iii) resilience evaluation are explained in the following paragraphs.

(i) Climate parametrization to capture uncertainty

Energy planning often explores climate uncertainty through scenario-based approaches [9], [10]. Scenario data has a high spatio-temporal resolution and includes various parameters, like renewable generation or energy demand. As a result, physically consistent scenarios require historical climate data [11], [12], [13], [14], or future climate models [15], [16], [17], [18]. However, historical climate data cannot capture climate changes, and computational costs restrict the scenarios from climate models. To address this, we train a machine-learning–based climate parametrization on extensive climate model outputs, enabling the rapid generation of millions of physically coherent scenarios that also incorporate probabilities. This approach allows for a more comprehensive and systematic representation of climate uncertainty in energy system planning.

(ii) Surrogate-assisted energy systems optimization

Energy planning relies on optimization models [19] and typically addresses uncertainty through methods such as sensitivity analysis [20], robust optimization [15], or stochastic optimization [18], [21], [22]. Since computation time increases exponentially with the size of the optimization models, adding climate scenarios quickly makes models intractable. To overcome this limitation, we use a Kriging-based surrogate model trained on a detailed, sector-coupled multi-year energy system optimization model. This surrogate enables the evaluation of thousands of candidate transition pathways against an even larger number of climate scenarios, providing performance indicators such as total system cost, demand not supplied, and carbon emissions. By making uncertainty exploration computationally tractable, this approach allows us to assess system designs across the full spectrum of climate conditions.

(iii) Resilience evaluation on different Risk-based metrics

By combining climatic parametrization with surrogate-assisted optimization, we obtain quantitative performance indicators for a wide range of transition pathways. Resilience can then be assessed through different risk-based metrics: for example, a more risk-averse metric minimizes unmet demand under the worst-case scenario, while a more risk-prone metric

minimizes average unmet demand across all scenarios, weighted by their probability. As a result, we can analyze which systems perform best under different definitions of resilience, and evaluate trade-offs between resilience, cost, and sustainability in the energy transition.

Conclusion

This study provides quantitative insights to support energy planners in designing transition pathways that are both cost-effective and climate-resilient. By comparing system designs across alternative resilience metrics, we show how different transition pathways emerge depending on the resilience metric. Our framework thus enables to identify energy systems that not only ensure reliability under deep climate uncertainty but also balance resilience with costs and emissions.

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Strategic Resilience Enhancement Planning for Future Renewable Power Grids

Freja Bruncrona [1], Geoffrey De Sena [2], Robert Eriksson [1], Malin Göteman [2]
1 Uppsala University, Department of Electrical Engineering, Uppsala, Sweden, freja.bruncrona@angstrom.uu.se, robert.eriksson@uu.se
2 Uppsala University, Department of Electrical Engineering, and the Centre of Natural Hazards and Disaster Science, Uppsala, Sweden, geoffrey.desena@angstrom.uu.se, malin.goteman@uu.se

Abstract

Resilience explores the grid's capability to handle extreme events. Through the energy transition, the composition of the grid is set to change. Meanwhile, climate change, geopolitical tension, and grid digitalization expose the grid to new vulnerabilities. As grid development planning is a complex and expensive process, it takes place decades in advance. The bulk of existing resilience literature looks at how the current system would respond to recorded events. By contrast, this study creates a framework to determine the optimal enhancement strategies to ensure the resilience of future grid scenarios.

Keywords: Energy transition, Resilience, Strategic Grid Planning

Introduction

Power system resilience explores ways to mitigate system degradation, maintain critical services, and recover rapidly during high-impact grid events. There exist significant research gaps in ensuring these capabilities for future renewable power grids. Traditionally, resilience has been studied largely using deterministic indicators based on historical data. As the grid adopts new resources for both generation and consumption, historical grid behavior becomes less representative of how a future system might behave. Additionally, the new resources bring new sources of uncertainty. Thus, modeling future systems requires novel strategies for considering these uncertainties.

The transmission grid consists of generators, consumers, and system operators, which interact through market-based mechanisms and regulation in an external environment. There are three key dimensions of grid development that affect resilience: How infrastructure will develop, how resources will be organized, and what types of events the grid will be subjected to. These trajectories contain uncertainties, which translate to risk for resilience enhancement strategies. The bulk of resilience literature focuses on aleatory risk, or known knowns, such as technical failure or weather-related events. However, risks related to the evolution of the grid, such as market development or the emergence of new threat types, have been largely neglected. Grid development planning takes place decades in advance, and as proven by [1], optimal placement and deployment of grid resources can massively improve the resilience performance. Developing methods for reinforcing the grid, considering non-aleatory risk types, such as the effect of increased penetration of inverter-based resources, is crucial to developing a resilient, renewable, and resource-efficient future power system.

This study aims to develop a framework for strategic resilience enhancement planning. To do so, it develops tools for analyzing drivers of change and their interdependencies, to gather probable future grid scenarios. Using the scenarios, the study develops a methodology for holistic and risk-aware grid resilience enhancement optimization. The study aims to answer the following research questions:

1. How does the energy transition affect grid resilience?
2. How can the uncertainty in energy transition trajectories be considered in strategic resilience enhancement planning?
3. What tools can be used to develop optimal and risk-aware resilience enhancement strategies, and how can the strategies be used to steer grid policy and build-out?

Grid resilience enhancement optimization

The objective of grid resilience planning is to build a system that can prepare for adverse events, absorb their impact, adapt in order to maintain critical services, and restore the system to a normal or improved state. Methods for attaining these capabilities depend on the system composition. For example, grids with different ratios between synchronous generators and inverter-based resources will have vastly different ways of responding to a disturbance, and different grid topologies enable different types of remedial actions during high-impact grid events. Developing resilience enhancement strategies, therefore, requires predictive analysis of future grid development trajectories.

To predict the structure of the future grid, it is possible to analyze drivers, trends, and dependencies of system components to yield future scenarios. While there is extensive literature in this field, few studies define the relative likelihood of the scenarios materializing. This study explores the combined use of probability modeling tools, such as Bayesian Network modeling [2], and strategic foresight tools, such as the 2x2 matrix framework [3], for probabilistic scenario development.

Enablers of resilience enhancement, such as storage capacity or adaptive steering methods, can be formulated for each scenario. The definition of the enablers allows for the construction of an optimization problem where resilience performance and resource efficiency can be maximized through the adoption of different enhancement strategies in different scenarios. Through analyzing previous literature, this study identifies methods of defining scenario-specific resilience enablers and constructs an optimization problem that yields resilience enhancement strategies.

Once strategies for resilience enhancement are formulated, their risk can be analyzed by weighing the cost and resilience improvement against the relative likelihood of the respective scenarios. This allows system operators to analyze the risk levels of distinct development strategies. Furthermore, it indicates the resource needs of each scenario and how development towards more efficient alternatives can be incentivized through grid codes and market development that target specific drivers.

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Structural Indicators for Quantifying Power System Resilience

Paul Runte[1], Ann Kathrin Seyfried[2]
1: University of Bremen, Germany, runte@iat.uni-bremen.de
2: Fraunhofer-Institut für Chemische Technologie (ICT), Germany, ann.kathrin.seyfried@ict.fraunhofer.de

Abstract

The global transformation toward a defossilized energy system represents one of the defining challenges of the 21st century. As electrification becomes the backbone of decarbonization, the functionality of power systems is critical to safeguarding economic and societal well-being. Especially, increasing system complexity, uncertainty in future conditions, growing exposure to weather-dependent or cyber-physical risks make resilience assessment a priority in both research and policy. While most prior studies have focused on event-specific evaluations, this work combines a structural approach to resilience quantification, with performance-based measures. Using structural indicators, open-source model power systems are analyzed in steady-state operation and tested under high-impact, low-probability stress scenarios, ranging from natural disasters to targeted cyber-attacks. The statistical relationship between structural properties and operational resilience is evaluated using a regression model. This work demonstrates that structural metrics can be effectively used to predict and enhance resilience, enabling planners and policymakers to identify system characteristics that support robust, sustainable energy transitions.

Keywords: Resilience; Power systems; Structural indicators

Introduction

Decarbonizing society and industry reshape global energy systems. The transformation in energy consumption towards highly electrified systems is driven by the availability of cost-effective technologies for renewable power generation and the advantageous efficiency of power systems over alternative energy carriers (Armaroli & Balzani, 2011; Christoph Kost et al., 2024; Pinto et al., 2023). The extensive electrification of heating, transport and industry, results in a massive increase in electricity consumption (Armaroli & Balzani, 2011; Pinto et al., 2023). In parallel, system operators must ensure reliable supply while minimizing emissions. This dual transformation introduces unprecedented levels of uncertainty in system design and operation, particularly in the context of evolving technologies, market dynamics, and environmental risks. Given the central role electricity plays in supporting modern society, the resilience of future power systems has emerged as a critical concern for sustainable development.

For this work, the resilience definition is based on the U.S. National Research Council (National Research Council, 2012): *"[…] resilience is the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events."* Despite this growing attention, there is currently no universally accepted methodology for its quantification in power systems. Nonetheless, a number of approaches to quantifying resilience have been put forth in the literature, which can be divided into three categories: structural, time-dependent, and performance-based (Jesse et al., 2019; Mishra et al., 2021; Poulin & Kane, 2021; Shafiei et al., 2025). The performance-based resilience quantification approach analyzes system properties before, during and after stress scenarios. Pre-shock properties such as robustness, stability, and reliability help minimize the impact of disruptive events by reducing the likelihood of a decline in performance. The period immediately following a disruption is typically referred to as the vulnerable, emergency, or disturbance phase, during which indicators of vulnerability are commonly used. In contrast, the subsequent period is known as the restoration or recovery phase, where post-shock attributes such as flexibility and adaptability become central to performance improvement (Ghosh & De, 2022; Gong et al., 2021; Jesse et al., 2019; Panteli et al., 2017).
The performance-based resilience analysis approach can be further divided into probabilistic, accounting for the likelihood of disruptions, or deterministic, which does not consider such probabilities (Hosseini et al., 2016). Based on time dependency, a distinction is also made between dynamic and static analysis. An example of a framework for dynamic performance-based system resilience assessment was proposed in (Tran et al., 2017).

Complementing performance-based approaches, structural resilience quantification examines general structural features and network topology. A significant body of research in power system resilience has focused on graph-theory based metrics, such as centrality, connectivity, and average path length (Cuadra et al., 2015; Shafiei et al., 2025). However, most structural studies to date focus on isolated graph-theoretic metrics (such as centrality or connectivity) without integrating diverse structural, spatial, and functional attributes into a unified framework. Especially, the comparative analysis of different structural indicators and their statistical linkage to performance-based resilience outcomes remains underexplored.

This lack of integrated methods hinders the ability of planners and policymakers to make data-driven decisions that strengthen resilience cost-effectively. This work addresses the gap by

combining structural and performance-based approaches and tries to answer the following research question:

1. How can resilience in power systems be quantified in a way that captures both inherent structural properties and operational performance under stress?

Methodology

Figure 1 illustrates our approach to answering the research questions with a twofold resilience assessment. Therefore, previous work by the authors (Runte et al., 2025) was extended by incorporating geospatial information and additional network components into established indicators, like diversity metrics (disparity, variety, and balance). Furthermore, novel structural indicators are introduced, and a comparative analysis with established topological metrics from the literature is performed (Cuadra et al., 2015; Shafiei et al., 2025). The novelty of our approach lies in combining spatial, topological, and diversity-based metrics into a unified evaluation framework for structural resilience. Afterward, data-driven (regression) analysis methods are used to evaluate the correlations with performance-based results from stress scenarios.

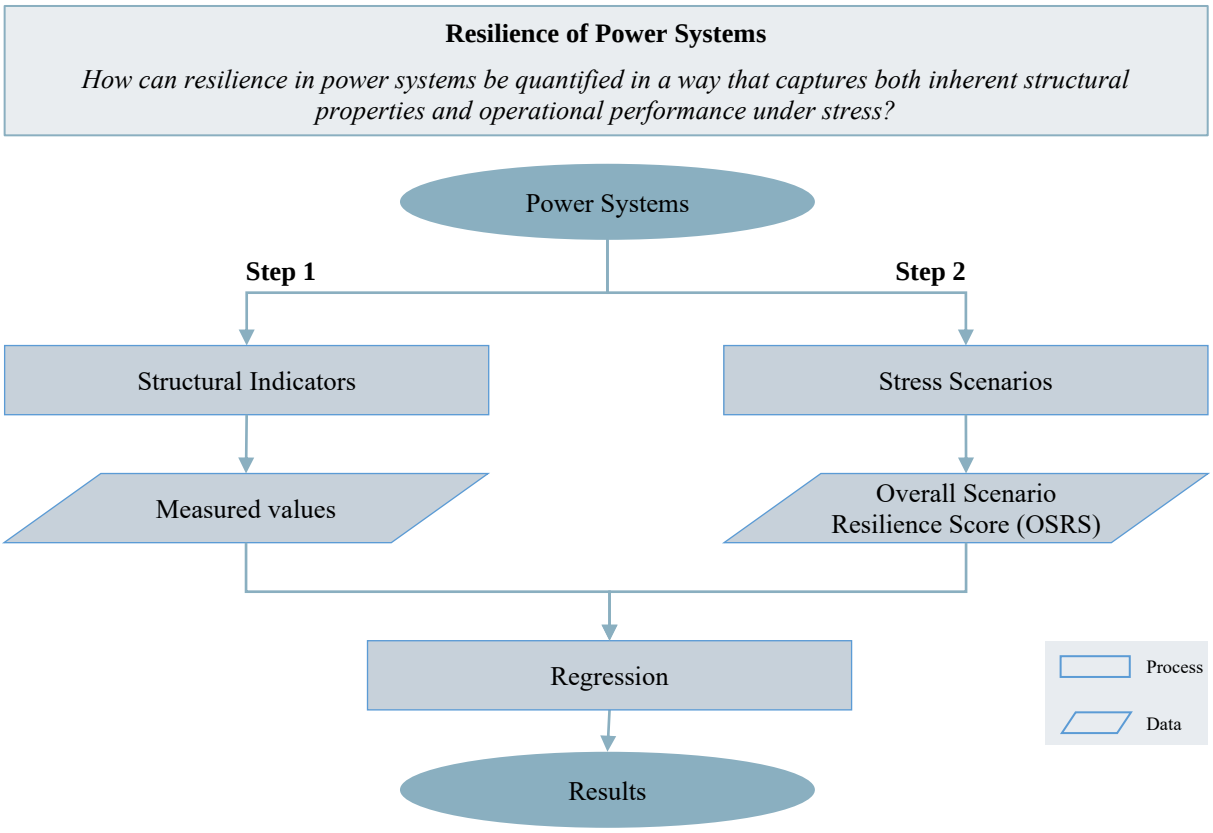


Figure 1 Structural research approach, Author's own illustration.

Outlook

Preliminary results reveal that four structural indicators consistently exhibit a strong positive correlation with resilience. Together, these factors explain approximately two-thirds of the variance in resilience scores across all scenarios. This suggests that certain structural features are not only theoretically desirable but also empirically linked to operational robustness. This highlights the practical value of structural indicators for power system planning. Unlike purely scenario-based assessments, structural metrics can be evaluated early in the design phase, long before detailed operational data is available. Therefore, enabling planners to prioritize investments in redundancy and flexibility, identifying vulnerable subsystems that require targeted reinforcement or comparing alternative network designs based on inherent resilience. The framework also supports policy-level decision-making, where resilience objectives must be balanced with cost, efficiency, and sustainability targets.

Conclusion

While the approach integrates structural and performance-based assessments, it remains limited to steady-state power flow conditions. Future research could extend the framework to include dynamic stability, market interactions, and interdependencies with other critical infrastructures. Additionally, incorporating probabilistic models of hazard occurrence could improve the accuracy of long-term resilience forecasts. Further development of open-access datasets and standardized indicator definitions would also enhance comparability between studies and facilitate broader adoption of resilience metrics in planning practice.

The accelerating transformation of energy systems requires not only decarbonization but also the ability to withstand and adapt to diverse disruptions. This study demonstrates that structural indicators can provide valuable insights into the resilience of power systems. The findings support the integration of structural metrics into planning and policy frameworks, enabling more robust, reliable, and sustainable power systems for the future.

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Securing Digital Twins at the Energy-Transport Nexus

Stefanos Evripidou[1], Xicheng Li[1], Mohammad Alquraan[2], Runze Cheng[2], Ahmad Taha[2], Muhammad A. Imran[2], David Flynn[2], and Dimitrios Pezaros[1]
1 School of Computing Science, University of Glasgow, UK
2 James Watt School of Engineering, University of Glasgow, UK
stefanos.evripidou@glasgow.ac.uk, xicheng.li@glasgow.ac.uk, mohammad.alquraan@glasgow.ac.uk, runze.cheng@glasgow.ac.uk, ahmad.taha@glasgow.ac.uk, muhammad.imran@glasgow.ac.uk, david.flynn@glasgow.ac.uk, dimitrios.pezaros@glasgow.ac.uk

Abstract

Digital Twins (DTs), digital representations of physical assets, are gaining traction due to their ability to support complex societal challenges, including decarbonisation. Nevertheless, the system integration required to develop such complex DT ecosystems heightens their cybersecurity risks. Such risks are still poorly understood, making research in cybersecurity paramount in order to enhance the resilience of these critical infrastructures. In this work, we present our ongoing research on digital twinning for transport decarbonisation, including the development of a DT interface at the Energy-Transport nexus, and future research plans for technical and social research.

Keywords: Digital Twins; Cybersecurity; Transport; Decarbonization

Introduction

The adoption of advanced digital technologies is essential for achieving a decarbonized future where energy and transport systems are increasingly coupled. Digital Twins (DTs) are gaining traction for their ability to digitally represent and interface with physical systems, allowing for operational improvements and predictive capabilities (Bennett et al., 2023). Despite the benefits of such digital coupling, the interconnection of Energy and Transport DTs leads to a growing attack surface and heightens their cybersecurity risk, due to their connection with physical infrastructure and potential exposing of operational data. Safeguarding and enhancing the resilience of DTs is therefore vital, given that their compromise can disrupt the provision of essential services and destabilise economy and society. To achieve this, holistic measures that consider technology, processes, and people are required (Alcaraz & Lopez, 2022a).

In this work, we present our ongoing research in DT cybersecurity in the context of transport decarbonisation. We first describe key DT components and outline critical cybersecurity challenges in cyber-physical systems. We then present our ongoing research, describing the development of a model testbed linking a smart grid network with charging infrastructure within an urban traffic simulation environment, discuss organisational cybersecurity challenges, and outline our next steps.

Background

At their core, DTs comprise three main components: a physical system, its digital representation, and a connectivity link between them (Grieves, 2023). Certain systems are inherently fundamental to DT operations: particularly those at the interface of the physical and digital systems, including Operational Technology (OT) environments, (i.e., technologies that sense and actuate physical processes) and their underlying connectivity. This inherent coupling introduces unique cybersecurity challenges, including need for cross-domain expertise (e.g., Control & Instrumentation, IT, cybersecurity), which has traditionally been scarce (Evripidou et al., 2023). Organisationally, OT and IT-based functions have traditionally been siloed, hindering collaboration efforts and weakening their governance (Michalec et al., 2022). At a regulatory level, while directives have been a successful driver for improving OT cybersecurity, the Transport sector is more fragmented than the Energy sector, further complicating cybersecurity governance. Many OT systems are legacy with long lifecycles, comprising heterogeneous and often proprietary technologies which lack cybersecurity features such as encryption, let alone more advanced anomaly detection and mitigation functionalities across systems boundaries. Strict operational requirements, including process availability and safety, and the limited resources in instrumentation further constrain cybersecurity provisioning.

Research from our group has focused on developing novel techniques to enhance OT cybersecurity. One such area is the use of programmable networking technology to embed cybersecurity functionality in the operation of an industrial networking stack, natively implementing, for example, asset identification and encryption while upholding strict latency requirements of OT environments (Holik et al., 2025). Moreover, these environments generate unique multi-modal data which have been largely unexplored. Research has employed graph deep neural networks to analyse heterogenous data streams, including sensor and network data to improve anomaly detection and response capabilities (Nahalka et al., 2025). Similarly, research has explored how the memory artefacts of Programmable Logic Controllers (PLCs), a central technology in OT processes, can provide a universal data source for anomaly detection (Cook & Pezaros, 2025).

Ongoing Work

The emergence of connected DTs amplifies cybersecurity challenges, as increasingly diverse and previously unconnected systems need to be integrated. Electrified transport networks increase interdependencies between Energy and Transport systems, potentially giving rise to cybersecurity vulnerabilities and enabling threat propagation across systems and their shared infrastructure – including data. As such, our ongoing work examines these challenges in a decarbonised Transport context.

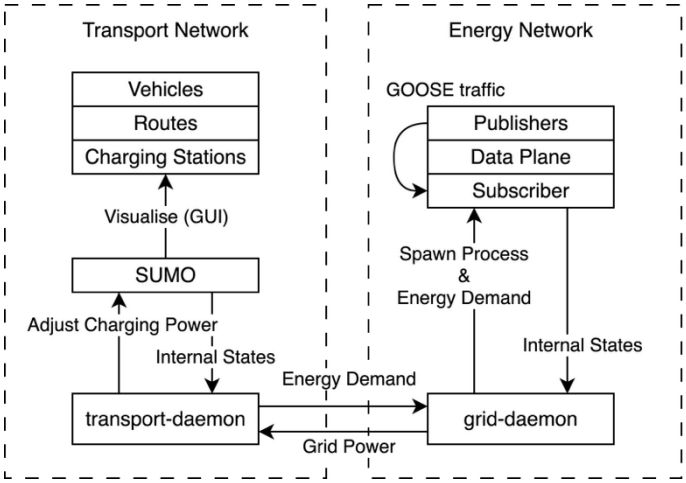


Figure 1. Architecture design of the transport-energy joint testbed.

We have developed an interconnected urban traffic network and a smart grid communication simulator to investigate cybersecurity challenges towards the integrated DT networks. The Transport network[1] models an EV charging infrastructure and the resulting Energy demand, while the Energy network simulates smart grid operations and energy supply in response to fluctuations on the demand side. We have focused on the dynamics of EV traffic and their associated charging behaviours. Specifically, retrieving energy supply data from the smart grid component, the simulation dynamically adjusts the charging power at each station to align with the capacity of its upstream grid component. This allows the framework to simulate and analyse cyber-attacks on the energy system, such as load-alternating attacks, in which coordinated fluctuations in regional charging demand can destabilise the grid and stress the network infrastructure, and trigger cascading effects on the Transport network. Finally, we are developing a security solution to enable transparent traffic monitoring and access control. It also provides early detection capabilities such as false data injections and replay attacks, while introducing minimal latency to operational processes. The attached video illustrates grid load per simulation tick and corresponding output fluctuations under conditions of elevated energy demand, additionally impacting charging stations on the same upstream grid.

Organisationally, cybersecurity is usually an afterthought, with the literature lacking in-depth exploration of the risks that arise with DT implementation. Technical research has largely overlooked non-technical challenges, such as stakeholder collaboration and governance limiting real-world applicability. It is unclear how organisations, including those in Energy, Transport, and digital services can collaborate to develop and secure emerging DT ecosystems, and how secondary stakeholders such as regulators affect this process. Moreover, while current cybersecurity concerns focus on confidentiality and access control mechanisms, less attention is given to active approaches in detecting and responding to cyberattacks. To understand how practitioners envision and prioritise the risks of DT system integration in the context of

[1] Implemented using SUMO, a well-established modelling tool for urban traffic systems.

transport decarbonisation, we have commenced research with relevant practitioners and preliminary insights will be presented at the conference.

Conclusion

Transport decarbonisation requires cross-sector systems integration, and adoption of advanced digital technologies and connectivity. DTs are a promising mechanism for facilitating this integration and simulating future scenarios. In this work, we describe cybersecurity challenges and present our ongoing research in developing technical simulations between Energy and Transport systems, and understanding how these systems can be securely adopted through social research to enhance cyber resilience at the nexus of Transport and Energy sectors.

Acknowledgements

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Resilient integrated transport-energy system configuration spaces for deep decarbonization pathways

Francesco Sanvito [1], Francesco Lombardi [2], Stefan Pfenninger-Lee 3
1 Faculty of Technology, Policy and Management, Delft University of Technology, Netherlands, F.Sanvito@tudelft.nl
2 Faculty of Technology, Policy and Management, Delft University of Technology, Netherlands, F.Lombardi@tudelft.nl
3 Faculty of Technology, Policy and Management, Delft University of Technology, Netherlands, S.Pfenninger@tudelft.nl

Abstract

Achieving deep decarbonization in Europe requires coordinated transitions across energy and transport sectors, yet uncertainties in technology adoption, infrastructure development, and policy coordination risk locking systems into inflexible pathways. This study develops a novel methodology to (1) identify resilient solution spaces, which are ranges of near-optimal configurations that maintain flexibility to change direction based on as-yet uncertain future developments, and (2) map transition pathways through these solution spaces that preserve system adaptability. Preliminary results highlight synergies between generation technologies, transport electrification, and infrastructure deployment, demonstrating how resilient pathways can guide policymakers in avoiding lock-in risks and designing robust, sector-coupled decarbonization strategies.

Keywords: Resilient pathways; Integrated energy-transport systems; Deep decarbonization; Near-optimal solutions

Introduction

Europe is committed to reducing carbon emissions by 55% by 2030 and achieving climate neutrality by 2050 (European Commission, 2019, 2021, 2022). Meeting these goals requires a strong, precise, and coordinated policy framework to steer a transition across structurally diverse sectors, each facing very different decarbonization pathways and speeds.

The transport sector accounts for roughly one quarter of Europe's carbon emissions (European Commission, 2024). While renewable technologies have already established themselves as the technological choice for decarbonising the power sector, the situation in transport remains more uncertain. Adoption barriers, entrenched fossil fuel interests, and infrastructure constraints, particularly in heavy freight and long-haul transport, continue to raise doubts about viable technological options.

This uncertainty is compounded by the lack of holistic planning between the energy and transport sectors, even though their interdependencies are deepening. Energy provision for transport will increasingly depend on energy policies, while transport itself has the potential to offer flexibility to the power system. Without coordinated planning, policymakers—often hiding behind the principle of "technology neutrality"—risk steering systems into rigid pathways that erode flexibility, thereby reducing the resilience needed to adapt to future technological and policy uncertainties (Financial Times, 2025; Posaner, 2022, 2023).

In this long abstract, we present a new methodology designed to provide policymakers with a spectrum of near-optimal pathways. The approach focuses on identifying pathways that enable a coordinated energy transition across the energy and transport sectors. It highlights technological tipping points and defines manoeuvring spaces within which systems can evolve without incurring lock-in risks.

Methodology

We propose a novel approach to designing and quantifying sector-coupled energy transition pathways, focusing on the interdependence of energy and transport systems. Central to this approach is the concept of *resilient solution spaces*—regions in which several near-optimal solutions can cohabit. Within these spaces, decisions remain robust across diverse technological, policy, and societal futures (Figure 1).

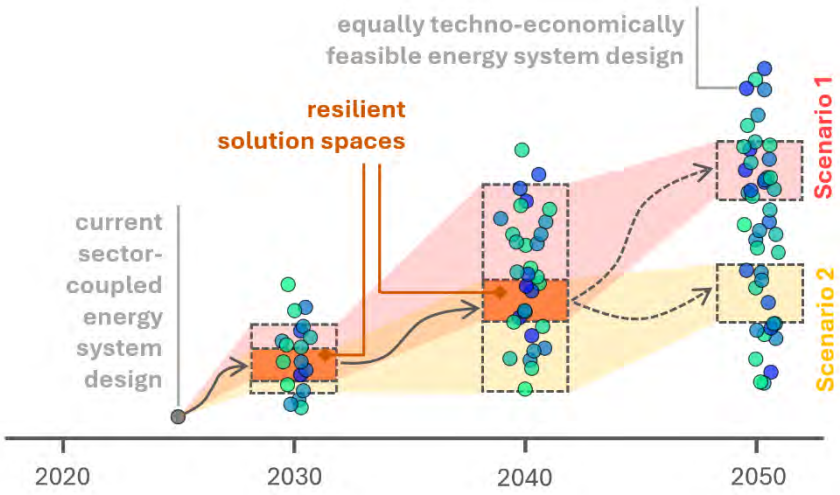


Figure 1. The figure illustrates two pathways leading to different scenarios, following a trajectory that remains adaptable until branching occurs in 2030 and 2040. Defining pathways through resilient energy system design spaces keeps the configuration adaptable to uncertainty and reduces the risk of lock-in and the effects of tipping points.

Energy transitions can be conceptualised as sequences of policy-driven equilibrium states, where small deviations may lead the system to stabilise in alternative equilibria. Resilient solution spaces delineate the boundaries within which these equilibria maintain flexibility and adaptability, whereas pathways outside these spaces risk rigidity and diminished responsiveness to change.

This study builds on recent advancements in Modelling to Generate Alternatives (MGA) combined with long-term energy system planning (DeCarolis et al., 2016; Lombardi et al., 2020, 2023; Pickering et al., 2022; Sinha et al., 2024). Unlike previous work (van Greevenbroek et al., 2025), our methodology combines a myopic long-term planning perspective with a novel synthesis stage that identifies tipping points endogenously from the structure of near-optimal solution spaces—an advancement over traditional Dynamic Adaptive Policy Pathways (DAPP) that define tipping points a priori (Haasnoot et al., 2013). Outcomes are clustered into scenario families based on technology preferences, enabling exploration of

near-optimal spaces while providing a framework to translate them into resilient pathways. This allows decision-makers to anticipate critical thresholds, explore manoeuvring spaces, and design pathways that remain flexible and resilient under deep uncertainty.

Preliminary and expected results

Building on preliminary academic work applying a limited version of the here-presented methodology (van der Weerd, 2023), we found that energy targets across multiple countries will drastically reduce the feasible solution space. Current studies often overlook the need for coordinated renewable deployment policies, which can further constrain system flexibility. Similarly, when accounting for national geographies, coordination challenges may arise not only across regions but also between sectors.

Our approach highlights synergies between energy carrier production and infrastructure types. For example, photovoltaic solar aligns well with direct electrification in passenger transport due to the temporal match between PV generation profiles and vehicle charging demand. In contrast, hydrogen production for transport couples more effectively with energy sources that exhibit a smoother, more stable profile, such as onshore and offshore wind.

At the infrastructure level, the development of hydrogen transmission networks or expanded electric grids also creates strong interdependencies with electrification pathways, reinforcing the need for coordinated planning across sectors. These dynamics, illustrated in Figure 2, demonstrate how resilient solution spaces emerge from the interplay between generation technologies, infrastructure deployment, and sector coupling, providing critical guidance for policy and investment decisions in low-carbon transitions.

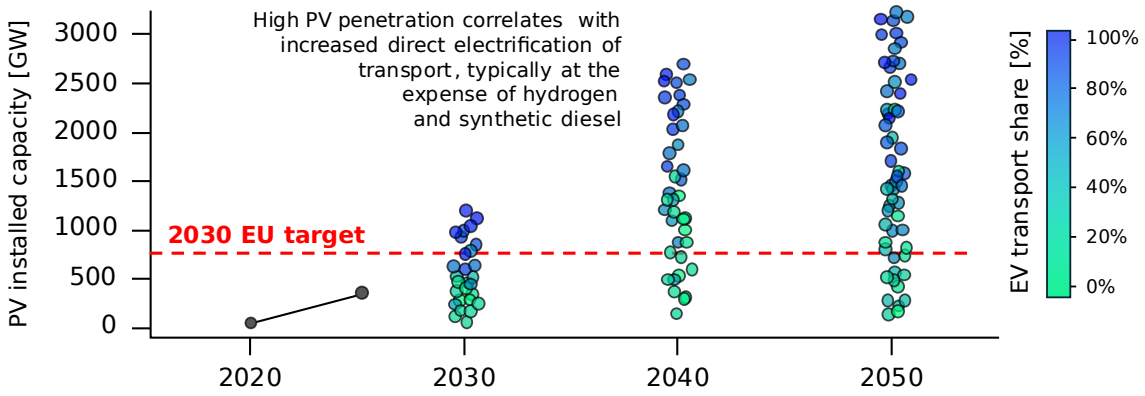


Figure 2. *Near-optimal solutions ranked by PV deployment across Europe. Solutions are color-coded to indicate EV penetration in the transport sector. Alternative options to direct electrification include hydrogen and synthetic diesel. The figure highlights a strong correlation between solar deployment and direct transport electrification.*

These results will be extended to cover all major technologies, explicitly identifying tipping points in transport technology adoption and energy infrastructure deployment. This analysis will uncover potential lock-in risks arising from transitional technology choices that constrain flexibility across sectors. Incorporating renewable national targets will allow the definition of realistic transitional scenarios and the evaluation of manoeuvring space provided by inter-

country coordination, while highlighting inconsistencies in current policy. Overall, the study aims to delineate resilient solution spaces for coordinated energy–transport transitions, accounting for both sector-specific adoption uncertainties and cross-sectoral interdependencies, thereby supporting flexible and robust system planning under deep uncertainty.

Conclusion

These preliminary results highlight the importance of identifying resilient pathways to guide the coordinated transition of energy and transport systems. Early findings suggest that leveraging synergies between generation technologies, transport solutions, and infrastructure deployment can create robust solution spaces that preserve system flexibility, while uncoordinated policies risk lock-in effects that constrain adaptability. By expanding the analysis to cover all major technologies and explicitly identifying tipping points, the framework aims to provide policymakers with actionable insights into resilient pathways—sequences of decisions that maintain flexibility under uncertainty—thereby supporting the design of coordinated and robust decarbonization strategies across sectors and countries.

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Resilient Scenarios for GHG-Neutral Methanol Imports to Europe

Wolfgang Männer[1,2], Joshua Fragoso García[1], Benjamin Lux[1], Giovanni Sansavini[2]
1 Fraunhofer Institute for Systems and Innovation Research ISI, 76139 Karlsruhe, Germany,
wolfgang.maenner@isi.fraunhofer.de, joshua.fragoso@isi.fraunhofer.de,
benjamin.lux@isi.fraunhofer.de,
2 Institute of Energy & Process Engineering, ETH Zurich, 8092 Zurich, Switzerland,
wmaenner@ethz.ch, sansavig@ethz.ch

Abstract

Importing renewable energy to Europe can reduce system costs, ease infrastructure expansion, and limit domestic land use. Yet global exporting regions differ in renewable seasonality, geological suitability for hydrogen storage, and country risks—factors that shape their competitiveness. Developing countries often face higher costs of capital for electricity generation and conversion technologies, which can distort competitiveness between global exporters and Europe. To assess these dynamics consistently, we integrate high-potential renewable regions outside Europe into a sector-coupled European energy system model that jointly optimizes renewable generation, hydrogen and methanol production, transport, and storage. This multi-regional framework captures cross-regional variations in renewable resources, financing conditions, and transport infrastructure, enabling a consistent evaluation of domestic versus imported production pathways across the full value chain. We find that high country- and sector-specific investment risks for capital-intensive electrolysis and carbon-capture technologies can outweigh strong renewable potentials, raising system costs and shifting cost-optimal mitigation efforts toward lower-risk regions. Further, the planned analysis will examine how these constraints alter optimal transport capacity needs. We expect moderate diversification to offer security gains at limited additional cost.

Keywords: GHG-neutral methanol; energy-system optimization; supply-chain resilience, diversification

Introduction

Meeting the Paris targets requires industrialized regions to reach net-zero GHG emissions by 2050 (IPCC 2022). The EU's carbon-management strategy and Green Deal Industrial Plan therefore promote both large-scale carbon-dioxide removal and the substitution of fossil feedstocks (European Commission 2023), directing attention to GHG-neutral methanol for maritime, aviation and petrochemical use.

However, domestic renewable resources are unlikely to satisfy projected EU methanol demand. Even optimistic assessments show sustainable biomass covering only a minor share (Millinger et al. 2025). Imports from regions with superior solar and wind resources are thus pivotal. The resulting geographic cost gradient—the "Renewables Pull Effect" (Samadi et al. 2023)—

creates incentives to relocate energy-intensive production steps abroad; such relocation could yield notable cost savings (Verpoort et al. 2024). At the same time, scenario projections hinge on uncertain hydrogen and captured carbon costs (Béres et al. 2024), as well as on the seasonal variability of renewable resources, which necessitates storage and buffering infrastructure. Financing conditions may further alter relative competitiveness across regions by affecting capital-intensive technologies differently. Beyond pure cost-optimality, policymakers increasingly emphasize resilience and supply security in energy trade.
Against this background, this study addresses the following research questions:

- Which techno-economic factors drive volumes and routes of GHG-neutral methanol imports?
- How does seasonality of energy imports impact energy import costs and infrastructure?
- What is the system cost of ensuring basic resilience through supplier diversification?

We address these questions with a spatial linear cost-optimization model covering EU-27+3 plus explicitly integrated global export regions. The model couples hourly energy balances with regional biomass limits, multiple CO_2-sourcing pathways and trade links, and then evaluate cost-optimal solutions according to national capacity additions and cost-allocation patterns. The resulting resilient import scenarios to 2050 inform policy on infrastructure priorities, trade strategy and integrated carbon management.

Methods and Data

We employ the hourly-resolved, country-level Enertile optimization model to co-optimize electricity, heat, hydrogen, methanol and CO_2 infrastructure for EU-27+3 plus global exporting countries. Inputs include technology cost curves, renewable potentials, and sectoral demand projections consistent with EU net-zero targets.

The Energy System Model Enertile

Enertile is a country-level European energy-system model with hourly resolution that co-optimizes expansion and dispatch of electricity, heat, hydrogen and synthetic methane. It balances demand by investing in generation, conversion, storage and transport assets. Temporal flexibility—batteries, pumped-hydro, heat stores, hydrogen caverns, vehicle batteries—is complemented by spatial flexibility from endogenous electricity and hydrogen grid expansion. Hydrogen arises from electrolysis and can be reconverted to power or heat; CO_2 from DAC enables methanol synthesis from hydrogen.

Novel features include:

- Explicit transport links for hydrogen (pipeline, shipping) and methanol (shipping) to global supply countries Morocco, Namibia, Brasil, Chile and Canada.
- Country- and sector-specific weighted average cost of capital (WACC) for electrolysis, DAC and renewables.
- Linear resilience constraints:
  – Supplier-share cap (≤ 20 % of EU demand per exporter, adjustable).
  – Excluding most cost-competitive supplier to assess resilient next-best options

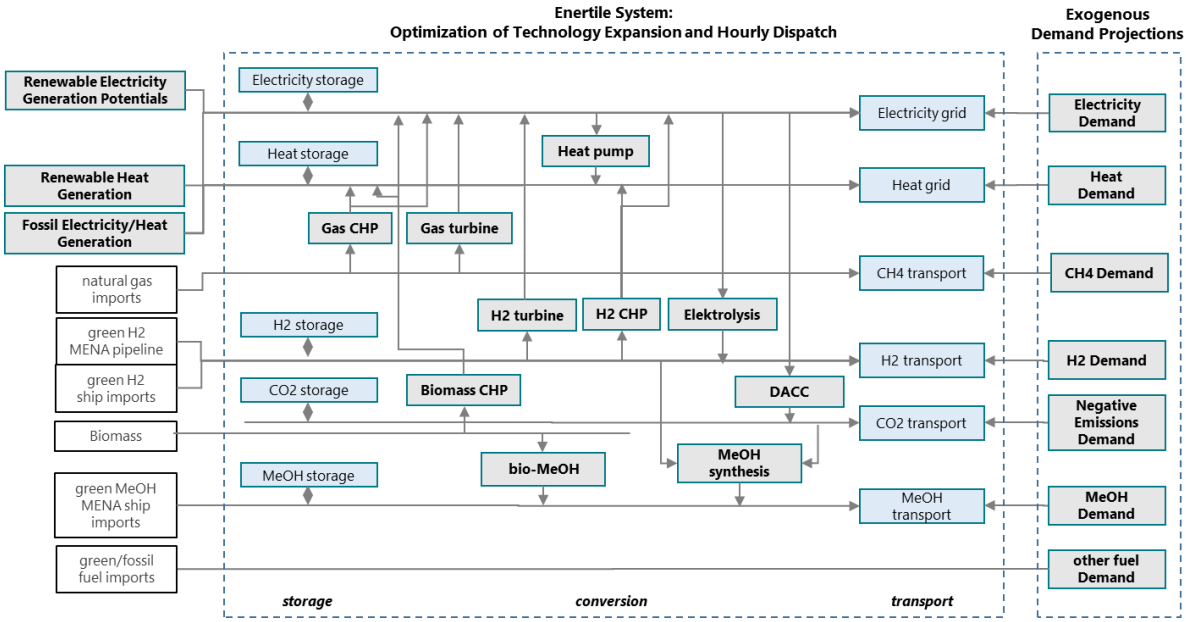


Figure 1. Schematic depiction of the model framework Enertile.

Scenario Definition

The base scenario assumes globally shifted value chains while Europe still produces strategic goods: domestic steel and basic chemicals use selective H_2 process heat, with other energy-intensive primaries imported. Transport is mainly electrified, synthetic and/or biofuels cover aviation and shipping. The final-energy demand for basic chemicals and for centralized electricity and heat generation determines the required quantities of hydrogen and synthetic or biogenic fuels or feedstocks. In two scenarios the renewable fuel and feedstock demand are varied. In six further scenarios the supply narrative of renewable methanol is altered according to the specifications listed in Table 1. Besides, sensitivities regarding electrolyzer, DAC and storage CAPEX are calculated to test the robustness of the analysis.

Table 1. Scenario variation for fuel and feedstock supply

ID	MeOH supply strategy	Diversification / constraint	CO_2 supply mix	Purpose

BASE	Cost-optimal mix	None	Regionally optimized DAC, fixed Bio-C	Benchmark
DOM-MAX	Domestic only	None	as BASE	Feasibility of self-supply
IMP-MAX	Imports only	None	as BASE	Upper bound on trade reliance
DIVERSITY	Least-cost	20 % share cap	as BASE	Test supplier diversification
ROUTE-CUT	Least-cost	Largest-supplier connection cut	as BASE	Resilient import capacity

Expected Contributions

This paper provides new insights into the structural determinants of methanol supply under cost-optimal GHG-neutral energy system configurations.

First, it shows that in the baseline configuration, global supply concentrates strongly in structurally advantaged renewable regions. Among the studied supply countries, Chile emerges as the single dominant supplier, with additional contributions from Morocco. Trade patterns are primarily driven by hydrogen production economics, reflecting solar resource advantages in combination with low-cost battery storage, which together enable competitive electrolysis. Methanol production co-locates electrolysis and DAC where renewable electricity is cheapest. High CO_2 transport costs limit cross-border carbon flows within Europe, reinforcing localized carbon utilization and shaping hydrogen corridor development toward European demand centers.

Second, the analysis demonstrates that country- and sector-specific investment risks materially influence system outcomes. Elevated risk premiums for capital-intensive electrolysis and carbon capture can outweigh strong renewable potentials, shifting cost-optimal mitigation efforts toward lower-risk regions and increasing overall system costs.

Third, the results reveal that export-oriented configurations require substantial additional storage capacity in supplying regions to manage seasonal renewable variability. Large-scale methanol import strategies therefore entail not only renewable generation expansion but also structural investments in seasonal buffering.

Finally, introducing diversification constraints leads to more than a redistribution of trade shares. Removing the cost-optimal supplier increases European hydrogen and methanol production, while methanol synthesis remains concentrated in Western Europe with additional clusters emerging in Poland and Norway. This indicates that diversification policies can induce endogenous regional industrial development rather than merely altering import patterns.

Together, these findings contribute to a more nuanced understanding of how resource endowments, storage economics, financing conditions, infrastructure costs, and policy-driven diversification interact to shape resilient methanol supply structures.

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Balancing the Energy Trilemma: Measuring Energy Supply Security in the Rheintal Valley

Matthias Sulzer[1], Georgios Mavromatidis[1], Robin Mutschler[1]
1 Empa - Swiss Federal Laboratories for Materials Science and Technology

Abstract

Energy supply security becomes an increasingly critical dimension of the energy trilemma, which requires balancing sustainability, equity, and security. In this work, we present the application of the Energy Supply Security Pyramid (ESS Pyramid) framework to the Rheintal Valley's integrated energy system, an urban–industrial cluster. The ESS Pyramid organizes energy security into five hierarchical levels: Self-Production, Autonomy, System Adequacy, Self-Sufficiency, and Autarky. Additionally, each level is accompanied by dedicated quantitative metrics to form the Energy Supply Security Index (ESSI). By applying these metrics on the Rheintal project, we evaluate the valley's current and projected energy security performance under progressive and restrictive scenarios for the year 2050. Our findings reveal that while Rheintal achieves significant improvements in Self-Sufficiency and Autonomy through electrification, waste heat utilization, and CCS deployment, it remains far from attaining full Autarky. The analysis highlights critical trade-offs between energy independence and economic feasibility, underscoring the importance of flexible infrastructure and diversified energy imports. This study also further demonstrates the value of the ESS Pyramid as a complementary tool to existing sustainability and equity assessments, enabling more resilient and strategically informed energy system design. Finally, it provides a replicable methodology for integrating energy security metrics into regional energy planning, offering insights for policymakers navigating the complex interdependencies of the energy trilemma.

Keywords: Energy; Supply Security; Trilemma; Optimization; Integrated Systems

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Finding Bottlenecks Before They Trigger Crises: Stress Testing Critical Infrastructures Systems for High Impact Low Probability Events

Ali Cheshomi, Nazli Yonca Aydin, Tina Comes Faculty of Technology, Policy and Management, Delft University of Technology, Delft, The Netherlands

Abstract

Our societies are increasingly exposed to high-impact low-probability (HILP) events, that can trigger systemic disruptions in interconnected Critical Infrastructures (CIs). Stress Testing (ST) is a promising method to help prepare for these extremes. However, preliminary findings from our ongoing systematic literature review indicate that existing ST methodologies, while useful in assessing vulnerabilities, exhibit several limitations: (1) they typically examine CI sectors in isolation and overlook cascading failures, (2) they emphasize the physical domain over social, informational, and organizational dimensions, (3) they focus on predefined hazards and underestimate the unpredictability and non-linear nature of cascading failures, and (4) rely on data-intensive approaches that are not always practical in HILP contexts.

To address these gaps, this study proposes a semi-quantitative, resilience-based ST methodology co-designed with stakeholders. The approach integrates both physical interdependencies, analyzed through Fuzzy DEMATEL, and decision-making interdependencies, modeled using Complex Network Clustering to map out the critical nodes and links. The resulting network is then stress-tested using network analysis techniques. Data are collected in one-day stakeholder workshops across two European cities, combining problem structuring, mapping of physical interdependencies, and mapping of decision interdependencies.

The methodology enables the identification of bottlenecks in physical and decision networks during early response and recovery, highlights actors critical to coordination and information flow, and provides a system-level view of how cascading failures may unfold. By combining technical, organizational, and decision-making perspectives, the proposed approach advances resilience-based ST and supports the design of more effective adaptation strategies for managing HILP events. This participatory approach ensures that results are scientifically robust and practically relevant.

Keywords: Stress Testing; Critical Infrastructure; High-Impact Low-Probability (HILP) events

Introduction

Our societies are increasingly facing High-Impact Low-Probability (HILP) events, such as the 9/11, unprecedented heatwaves and wildfires and the Fukushima nuclear accident. Although rare and uncertain in occurrence, these events have significant impacts on society and infrastructure (Clarke & Obrien, 2016).

Critical Infrastructures (CIs), such as energy, transport, water, oil and gas, and ICT, are the backbone of modern society (Comes et al., 2013; Tsionis et al., 2016). While their interconnectedness enables efficient and sophisticated services (Rinaldi et al., 2001), it also

makes them highly vulnerable to disruptions. These CIs are prime examples of systemic risk (Renn et al., 2022), as planners and decision-makers establish complex interdependencies among infrastructures and with their environments (Heinimann & Hatfield, 2017). Such dependencies can propagate failures across systems, amplifying societal losses (Zimmerman & Restrepo, 2006). Ensuring their resilience, as socio-technical networks exposed to both known and unknown threats, is therefore of paramount importance (Renn et al., 2022).

Among the methodologies developed so far for assessment of the CIs against threats, Stress testing (ST) methodologies stand out as crucial assessment tools, designed to test the vulnerability and resilience of individual CIs and infrastructure systems. ST methodologies have been developed to identify the conditions or thresholds under which systems fail. The ST concept initially was developed in medicine and material science to test the physical strength and biological responses to stimuli. From there, ST has evolved into a critical tool in industries such as finance and banking, nuclear power, and then CIs (Linkov et al., 2022). The existing literature shows a wide array of ST applications across CIs (e.g., transportation, water, energy, telecommunications, etc.). Despite advancements in infrastructure resilience, recent HILP events reveal significant vulnerabilities in our socio-technical networks that previous ST methodologies have not adequately addressed.

Findings from our ongoing systematic literature review current ST methodologies face several limitations. First, they often examine CI sectors in isolation, neglecting interdependencies that drive cascading effects during crises (Rinaldi, 2004). Second, they focus narrowly on the physical domain, overlooking other critical dimensions such as informational, social, cyber, and institutional. This restricts the range of adaptive strategies to mainly technical solutions, neglecting policy, governance, and social measures. Third, many methodologies are designed around specific hazards, such as climate-related, geospatial, or man-made, making them ill-suited for unknown or unforeseen threats. Furthermore, methodologies developed so far are mostly focusing on risk ST or and even resilience-oriented ST approaches tend to emphasize robustness and absorptive capacity, while giving little attention to cascading failures during response and recovery, phases that strongly shape long-term outcomes when risk mitigation options are limited. In addition to these shortcomings most existing methods rely on data-intensive, bottom-up simulations, which are impractical when data are scarce or interdependencies are too complex to capture fully. Since HILP events often defy prediction, effective methodologies must also integrate stakeholder knowledge and judgment, particularly when informing preparedness and policy decisions.

These limitations underscore that there is a need for ST methodology that is tailored to evaluate the resilience of CI. Within this context, resilience-based ST should have systemic perspective that enables evaluation of interconnected CI structures across multiple domains, and should capture cascading failures across phases of a disaster, and allows for meaningful stakeholder engagement.

In this study, we propose a semi-quantitative, resilience-based ST methodology designed to examine how systems and their interrelated components respond to HILP events. Unlike existing approaches, it integrates both physical interdependencies and decision-making dependencies, with particular emphasis on early response and early recovery. Co-designed *with stakeholders, for stakeholders*, the methodology aims to: (i) provide a shared system-level understanding, (ii) identify bottlenecks that may trigger cascading failures across physical and

decision-making layers, and (iii) enhance CI resilience in contexts where triggering events cannot be controlled.

Methodology

Acknowledging the importance of co-ownership, we propose a co-design process, in which stakeholders are involved in the ST design, workshop, and analysis and validation. The participatory steps are combined with data collection to support scenario design as well as data analytics to process the ST results.

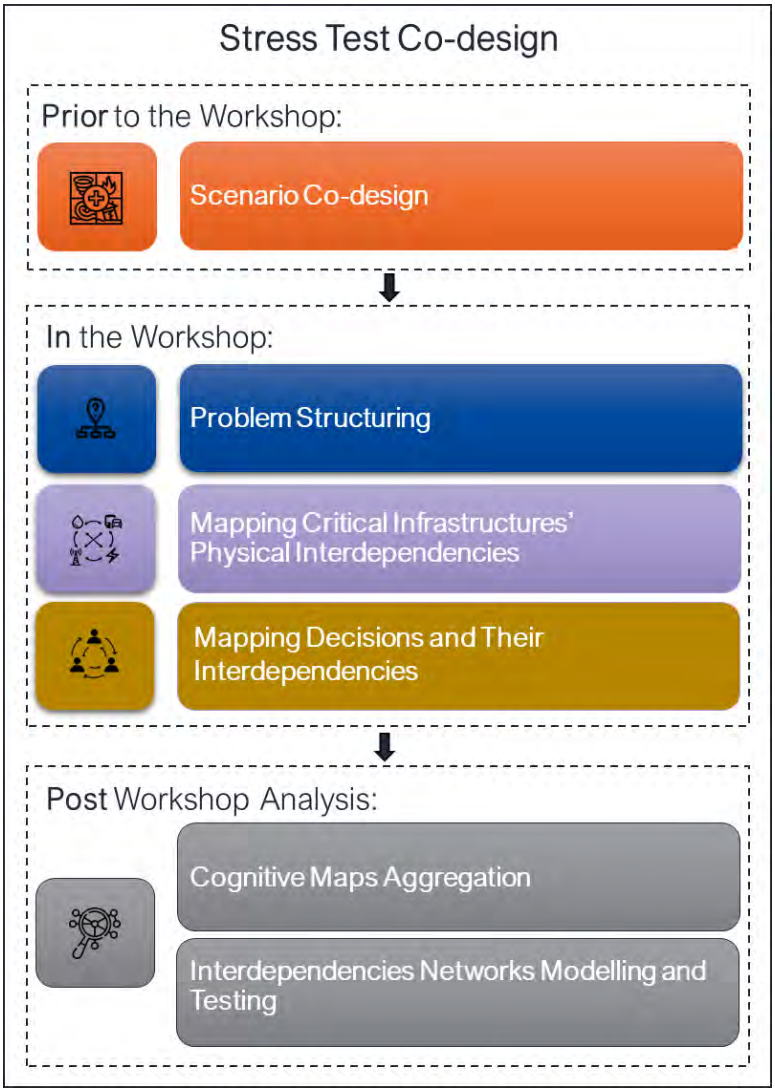


Figure 1: Co-Design of the Scenario, Stress Testing Workshop and Analysis Steps

Pre-workshop Scenario Co-design

Scenarios are co-designed with the case study host to map interdependencies and create a shared space for stakeholder reflection and discussion. Their design draw on system definition provided by the host (e.g. boundaries, stakeholders involved), host priorities (e.g., focus on cyberattacks), and supporting documents and datasets such as risk profiles and open-access data. Through an iterative process, a HILP scenario will be refined to meet host needs, engage

diverse stakeholders, and remain broad enough to explore cascading effects across interdependencies.

Stress Testing Workshops

The proposed methodology follows a participatory approach relying primarily on stakeholder input gathered during ST workshops conducted across case studies in European countries.
For each case study, a one-day workshop is organized in collaboration with the local partner. The workshop is carefully designed to (a) generate relevant information for the ST analysis while simultaneously collecting data, and (b) provide immediate value to participants by serving as a forum for training, learning, and reflection. Each workshop typically engages 30–40 participants from diverse organizations, including CI providers, emergency management authorities, and community groups.
The workshop structure allows participants to examine the unfolding of different phases of an emergency. The first part of the workshop focuses on the onset and immediate response, while the second part addresses the early recovery phase. This format ensures that both critical stages, when cascading effects are most likely to emerge, are systematically considered.
The workshop design follows a decision-theoretical set-up comprising three main elements, see Figure 1:

- Problem Structuring and Elicitation of Objectives and Preferences,
- Mapping of Physical Interdependencies, and
  Mapping of Decisions and their Interdependencies.

This structure enables a systematic exploration of both physical and decision-making dependencies, ensuring that the collected data are directly applicable to the development and testing of resilience-based ST methodologies.

Post-workshop data analysis

Following data collection, the final part of ST focuses on synthesizing the primary objectives, concerns and preferences of stakeholders and modeling and testing both physical interdependencies and decision interdependencies within CIs.
For physical interdependencies, we employ Fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL), a soft computing method well suited to contexts with limited data availability. Unlike data-intensive approaches such as agent-based modeling, fuzzy DEMATEL efficiently captures cause–effect relationships between infrastructures and assesses the relative significance of CI components (Huang et al., 2014). Its graph-theory basis makes it particularly feasible for HILP contexts where data are scarce.
For decision interdependencies, we analyze the networks of response operations that emerge and evolve during disasters. These dynamic networks form clusters of actors coordinating around specific tasks, which shift across the response and early recovery phases (Hossain & Kuti, 2010). To model these dynamics, we use Complex Network Clustering, drawing on Coordination Matrices developed during workshops. By examining clustering patterns and actor centrality, we identify key information hubs whose roles are critical for communication and coordination within and across organizations (Noori et al., 2016).

Together, fuzzy DEMATEL and Complex Network Clustering provide complementary insights: DEMATEL identifies critical physical interdependencies, while clustering reveals organizational and informational bottlenecks. These outputs form the basis for network-based ST, where targeted and random attacks on critical nodes and links are simulated to assess how failures may cascade across interconnected physical and decision-making systems, building on approaches that integrate ST with graph theory (Aydin et al., 2018).

Expected results

The methodology will be implemented in the Rotterdam (Netherlands) and Venice (Italy) case studies in fall 2025. From these workshops, we expect to gain insights into the primary concerns and objectives of different stakeholders in the context of HILP events. Furthermore, we will develop and analyze both physical and decision-making networks to identify potential bottlenecks. These can emerge in the early response phase, when timely action is required under severe resource and information constraints, and during the early recovery phase, when resources must be strategically prioritized to restore the most critical infrastructures. By combining these findings with the intervention measures collected during the workshops, as well as other possible alternatives, we expect to be able to propose adaptation strategies that extend beyond purely technical solutions to include organizational and decision-making dimensions.

Acknowledgements

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Resilience-Based Threat Assessment to Evaluate Infrastructure Protection

1. Marc Menne 2. Prof. Dr.-Ing. Max Spannaus
1.University of the Bundeswehr Munich, Institute for Structural Engineering, Germany, marc.menne@unibw.de
2.University of the Bundeswehr Munich, Institute for Structural Engineering, Germany, max.spannaus@unibw.de

Abstract

In the research project BASIS, a methodology is being developed to evaluate and design structural protection measures for exposed infrastructure. The starting point is a scenario-based threat analysis, which uses influence factor and consistency analysis to identify security-relevant hazards. The evaluation follows a two-level approach: the overall system is assessed qualitatively, while the protective structure is evaluated quantitatively. The primary objective is to minimize resilience loss under exceptional impacts and to derive functional and design-related requirements for protection measures. The resulting key criteria include variability, interchangeability, cost-efficiency, scalability, and adaptability.

Keywords: Resilient Design; Structural Protection; Infrastructure; Threat Analysis

Introduction

Attacks on critical infrastructure have become a reality in Europe (Jones, 2025). Ongoing armed conflicts clearly demonstrate that infrastructure not only forms the backbone of functioning civil societies but also constitutes a key prerequisite for the freedom of military operations (see e.g., Tagesschau, 2025; Tagesschau, 2025). As a result, such infrastructures are increasingly targeted in conventional warfare and in the context of hybrid or terrorist threats.
These developments highlight the necessity of systematically accounting for the spectrum of exceptional impacts, particularly the effects of weapons (cf. NATO, 2019), in the planning and reinforcement of exposed infrastructure. In the context of the BASIS research project, exposed infrastructures are defined as all assets that fall under the categories of critical, defense-essential, or defense-relevant infrastructure.

The Research Project BASIS

The BASIS research project (**B**uilding-**A**daptive **S**hielding of exposed **I**nfrastructures with **S**teel-Sandwich-Constructions) directly addresses the problem outlined above. Its objective is to integrate structural protection measures as a last line of defense within a necessarily multi-layered protection concept for exposed infrastructure.
At the core of the project lies the question of how protective structures can be designed and evaluated in a way that ensures resistance against targeted weapon effects under realistic threat scenarios. The project begins with a structured threat analysis based on two guiding questions:

"What is the actual threat?" and

"What are the resulting requirements for structural protection?".

Building on the threat analysis methodology, the project also involves the design and optimization of steel-sandwich-constructions (SSCs) as protective structures. This is supported by experimental investigations, including material characterization, ballistic testing, and explosive loading tests. The accompanying numerical simulations are validated using the data obtained from these high-dynamic experiments.

Threat Analysis

Threat identification, together with scenario methodology, forms the overarching framework of the developed approach (see Figure 1). The starting point is an all-hazards-oriented threat space, which is narrowed down to relevant subsets by applying the scenario methodology. In the present context, the threat spectrum focuses primarily on terrorism, hybrid attacks, and military conflicts, with particular emphasis on weapon effects.

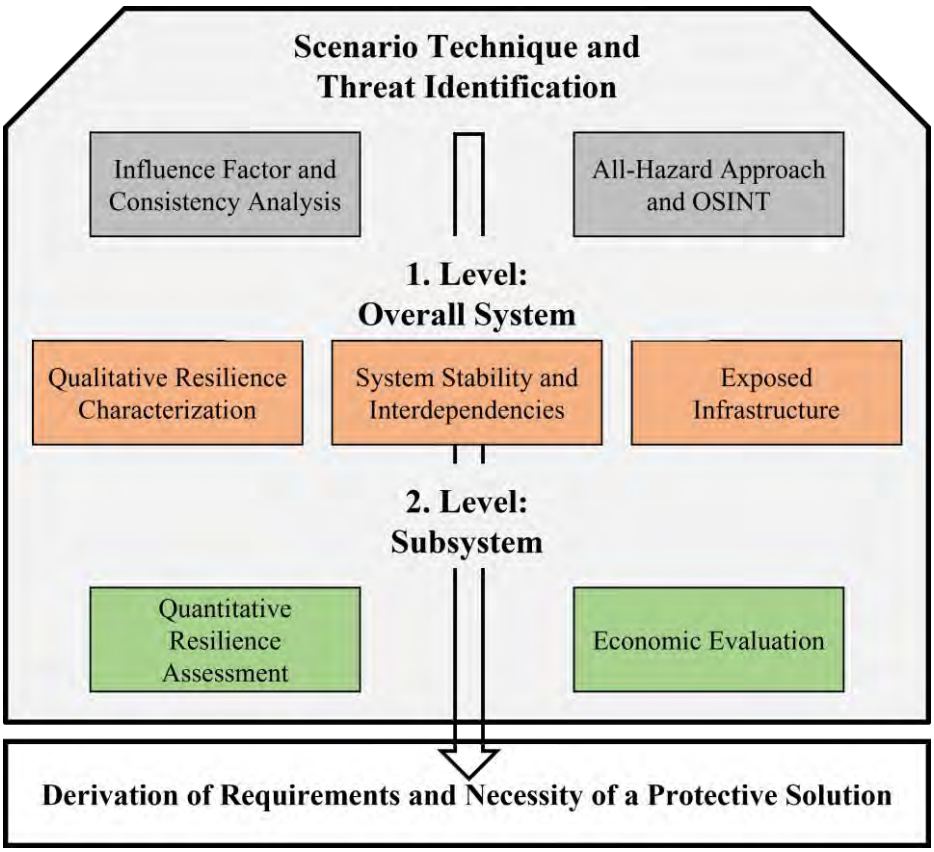


Figure 1. Overview of the complete threat analysis methodology developed in the BASIS research project. The coloured boxes (grey, orange, green) represent individual methodological components, each assigned to the corresponding bolded section titles above.

The scenario methodology (see Kosow et al. 2008) is based on an influence factor analysis involving seven key factors: the security policy context, the intended target, the attacker type, the weapon type, the expected effect (e.g., net explosive mass), the strategic framing of the attack, and the technical and logistical feasibility. The combination of these factors in various manifestations allows for a detailed description of threat scenarios. A subsequent consistency analysis ensures logical coherence. The factor manifestations are derived from open-source

intelligence (OSINT) and qualitative insights gathered through expert interviews with stakeholders from industry, the military, and academia. In this context, the scenario methodology functions as a filtering mechanism that derives coherent and security-relevant threats from the broader all-hazards approach documented in a draft bill by the German federal government from 2024 (Bundesregierung, 2024).

The first level of analysis focuses on the overall system of exposed infrastructures in the context of each scenario and is conducted qualitatively (cf. Vurgin et al., 2010). The aim is to identify general boundary conditions and protection needs, as well as potentially endangered and priority assets.

The qualitative system evaluation is based on several methodological components. The interdependence analysis according to Schmitt (2020) quantifies and describes functional and physical dependencies between infrastructure elements. Additionally, the concept of system stability and network logic according to Vester (2019) is applied, in which the degree of interconnectivity is interpreted as a proxy for system stability and performance. Infrastructures with a high degree of connectivity may be robust against local disruptions but are also prone to systemic cascading effects. Dependencies therefore play a key role in determining the extent of secondary impacts within the overall system and provide a basis for assessing structural vulnerability.

This structural vulnerability is further captured by the vulnerability concept introduced by Kröger & Zio (2011), which defines vulnerability not as a function of probability, but as an inherent susceptibility of the system to external disruptions. Within the first level of analysis, this is closely tied to the attacker's perspective, which is used to identify protection priorities from the outside-in.

The second level of analysis focuses on the structural protective solution. Here, resilience is assessed quantitatively based on the framework by Bruneau et al. (2003), which considers four dimensions: robustness, redundancy, resourcefulness, and rapidity (see Figure 2).

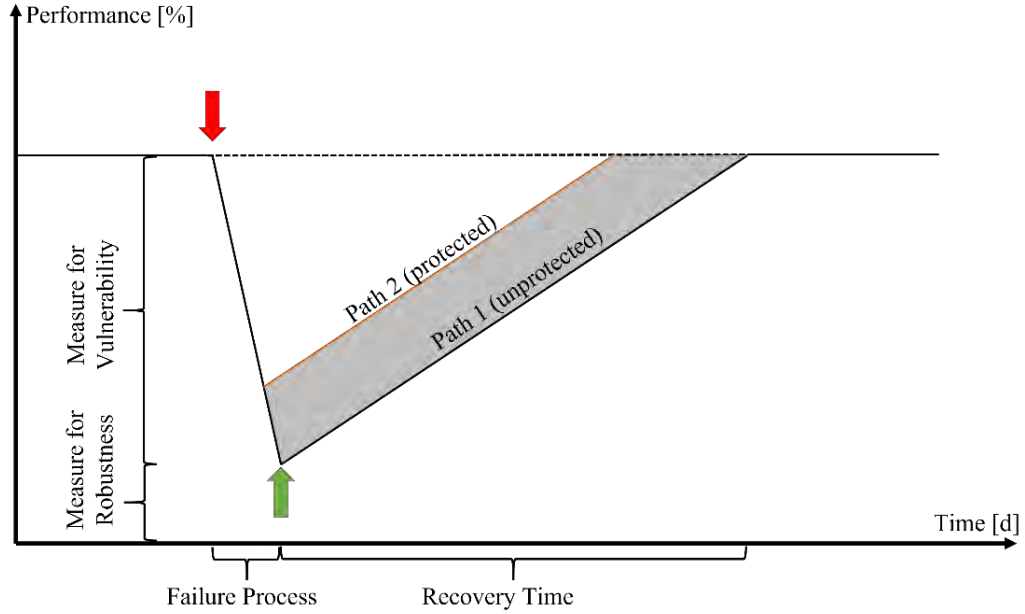


Figure 2. Performance-over-time diagram for the quantification of resilience. A key characteristic, and thus specific to each system, is the recovery trajectory over time. The two paths differ solely in that the system in Path 2 is equipped with a passive structural protection measure.

The analysis assumes a system that, following a disruption, returns to its original performance level without remaining in a degraded or transformed state. Redundancy is not directly represented in the performance-over-time diagram but can be understood, in the context of protective construction, as a pre-emptive physical buffer. For example, a net against unmanned systems (functionally comparable to initiation plates that increase the stand-off distance), or a layered, adaptively designed protective wall. The relationship between vulnerability and robustness can be interpreted as an indicator of the immediate impact of the event. The slope of the recovery curve reflects the system's resourcefulness, while rapidity corresponds to the duration required to regain the original performance level.

The overarching goal of structural protection is to reduce resilience loss, which is graphically represented in Figure 2 as the area between two performance curves, one for the unprotected state (Path 1), and one for the protected state (Path 2). A reduction in performance loss through protection typically results in a greater-than-proportional reduction of resilience loss. The difference between the two curves can be interpreted as a monetary benefit in a cost-benefit analysis. It represents the theoretical upper limit of investment justified for implementing the protective measure.

In addition, an economic evaluation of potential damage is carried out following the approach by Pant et al. (2014). This includes three categories of costs: first, restoration costs, such as expenses for repair or reconstruction after an attack; second, opportunity costs, arising from service outages, production losses, or sustained performance degradation over time; and third, cascading systemic effects, caused by dependencies on other infrastructures or critical system properties.

Design Requirements

Based on the methodology, five key design requirements for structural protective solutions can be derived. Variability and interchangeability result from the resilience dimensions of resourcefulness and rapidity and imply a simple, modular system architecture. Cost-efficiency is derived from the economic evaluation of damage potential and ensures that protective measures remain proportionate to the achievable resilience gain. Scalability is essential, as exposed infrastructures vary widely in their spatial and functional characteristics. The requirement for adaptability arises from evolving threat landscapes and dynamic geopolitical developments.

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Sustained Resilience in Prioritising Critical Infrastructure Recovery in War-Impacted Built Environments

Nadiia Kopiika[1], Roberta di Baria[2], Sotirios Argyroudis[3], Stergios-Aristoteles Mitoulis[4]
1 The Bartlett School of Sustainable Construction, University College London, Gower Street, London, WC1E 6BT, UK, n.kopiika@ucl.ac.uk
2 University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK, r.dibari@bham.ac.uk
3 Department of Civil and Environmental Engineering, Brunel University London, Kingston Lane, Uxbridge Middlesex, UB8 3PH, UK, sotirios.argyroudis@brunel.ac.uk
4 The Bartlett School of Sustainable Construction, University College London, Gower Street, London, WC1E 6BT, UK, s.mitoulis@ucl.ac.uk

Abstract

The rising frequency of wars, disasters, and systemic disruptions underscores the urgent need for effective strategies to guide critical infrastructure recovery. Existing prioritisation frameworks largely focus on climate-related hazards, leaving post-conflict and multi-hazard contexts underexplored. This gap creates challenges for countries seeking to rebuild while aligning with global development goals and donor expectations. This paper presents a sustainability- and resilience-driven prioritisation framework for infrastructure reconstruction. The approach integrates structural resilience, sustainability, and adaptive capacity into a transparent scoring system, supporting both urgent restoration and long-term resilience planning. A case study on bridge portfolios in Ukraine illustrates the framework's application, showing how it informs strategic investment, identifies vulnerabilities, and balances short-term recovery with sustainable transformation. The study extends prioritisation methods beyond climate hazards to conflict and disruption contexts, offering a structured pathway toward adaptive, inclusive, and future-ready infrastructure systems.

Keywords: prioritisation; resilience; sustainability; conflict-induced hazards; bridges; proactive and reactive measures

Introduction

Bridges are essential for transport networks, enabling mobility, economic activity, and emergency response. Their disruption—due to ageing, natural hazards, or deliberate attacks—can have severe socio-economic consequences (Al Jazeera & News Agencies, 2024). In conflict-prone regions, threats such as blasts, shelling, and military overloading exacerbate existing deterioration from inadequate maintenance (Kopiika et al., 2025a), disrupting supply chains, humanitarian aid, and evacuation routes (Hay et al., 2019; Mitoulis et al., 2023).

Existing resilience frameworks mainly address natural hazards, leaving a gap for post-conflict recovery where urgent needs require prioritisation of critical infrastructure. Integrating

conflict-aware resilience metrics—robustness, redundancy, resourcefulness, rapidity—with sustainability across economic, environmental, and social dimensions provides a holistic decision-making approach (Argyroudis et al., 2021).
This paper builds on recent research (Kopiika et al, 2025b) by presenting a scoring-based framework for prioritising bridge reconstruction in Ukraine, optimising resource allocation for both immediate recovery and long-term resilience.

Methodology

Conflict-induced damage to infrastructure, particularly bridges, poses severe economic, social, and environmental challenges. Addressing these requires a unified framework that integrates resilience (ability to absorb and recover from shocks) and sustainability (long-term economic, societal, and environmental impacts). While traditionally assessed separately, both dimensions intersect and provide complementary insights for prioritising proactive and reactive measures in infrastructure management.

The proposed framework employs a scoring-based methodology that evaluates assets using **resilience** attributes (robustness, redundancy, rapidity, and resourcefulness) alongside sustainability metrics (from **economic**, **social**, **environmental** dimensions), such as repair costs, downtime, casualties, indirect detour losses, and environmental impacts (e.g., embodied and operational CO_2 emissions). Assets are ranked according to their cumulative scores, enabling decision-makers to identify bridges whose failure would have the most critical consequences (Figure 1).

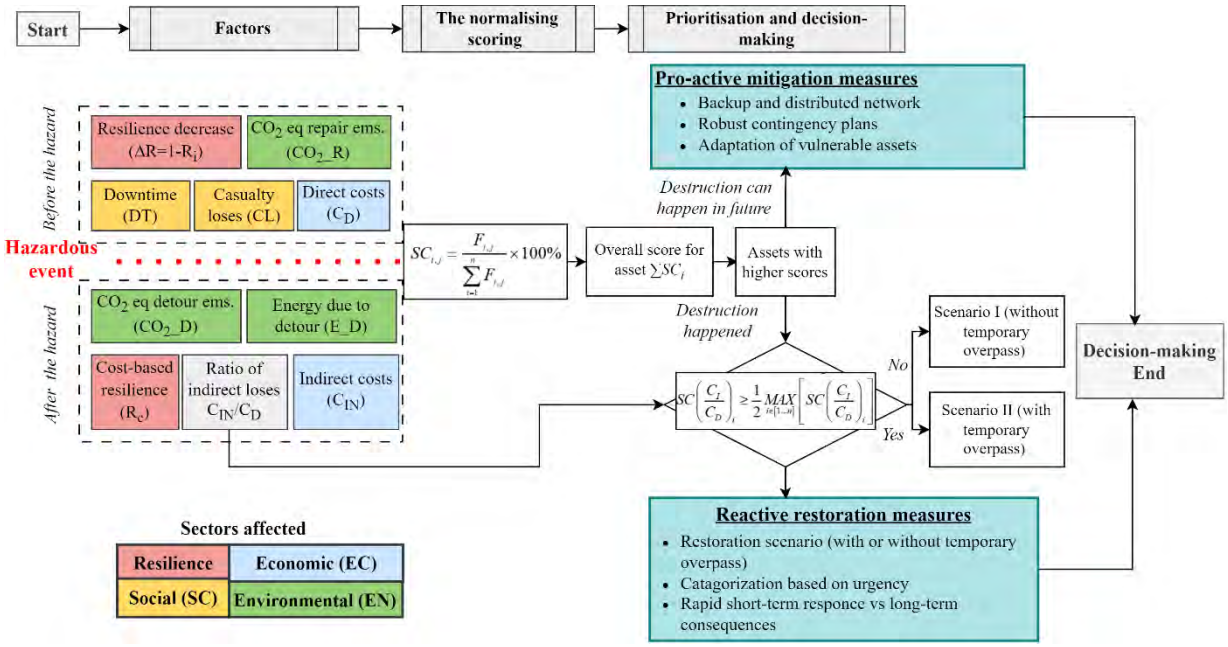


*Figure 1. The scoring framework for sustainability- and resilience-driven decision-making for critical infrastructure restoration in hazardous areas. The three dimensions of sustainability impact are indicated with colours: **blue**-economic, **yellow**-social, **green**-environmental. Resilience components are shown in **red**.*

Two pathways are considered:

- **Proactive measures**, focusing on structural upgrades, monitoring systems, and protective strategies to mitigate direct losses before damage occurs.
- **Reactive measures**, addressing post-damage restoration, where time-dependent indirect impacts (traffic detours, economic disruptions, emissions) often outweigh direct repair costs.

The framework introduces normalised dimensionless scores $SC_{i,j}$, allowing diverse factors to be combined into a global index for each asset. It also differentiates between restoration scenarios—with or without temporary overpasses—to minimise indirect socio-economic losses during recovery.

By systematically integrating resilience and sustainability metrics, this novel approach (Kopiika et al, 2025b) supports efficient allocation of scarce resources in conflict-prone regions. It enables policymakers to balance immediate recovery needs with long-term development goals, ensuring that critical transportation assets are restored and strengthened against future disruptions.

Case Study: Portfolio of Bridges in Ukraine

The proposed framework is applied to Ukraine's transport infrastructure, which has been severely impacted by both long-term ageing and conflict-related damage. Approximately 81% of Ukrainian bridges were constructed before 1981, with many exceeding their intended service life and suffering from deterioration caused by corrosion, fatigue, outdated design standards, and increased traffic loads. Recent assessments indicate that only about 14% of bridges are in satisfactory condition, while the remainder are marginally safe under restricted traffic conditions (UA radio news,2023).

The ongoing conflict has significantly intensified these vulnerabilities. Bridges have become strategic targets due to their essential role in logistics, trade, evacuation, and humanitarian aid delivery (Rice, 2022). Their destruction disrupts regional connectivity, isolates communities, and impedes both military and civilian mobility.

For this study, a portfolio of 18 of Ukraine's largest bridges was analysed, spanning major urban and industrial centres such as Kyiv, Dnipro, Kherson, Mykolaiv, and Zaporizhzhia (Figure 2). These assets are critical for maintaining east–west connections across the Dnipro River and for sustaining national and international supply chains. Their size, strategic role, and exposure to hazards make them high-priority candidates for resilience- and sustainability-driven reconstruction planning.

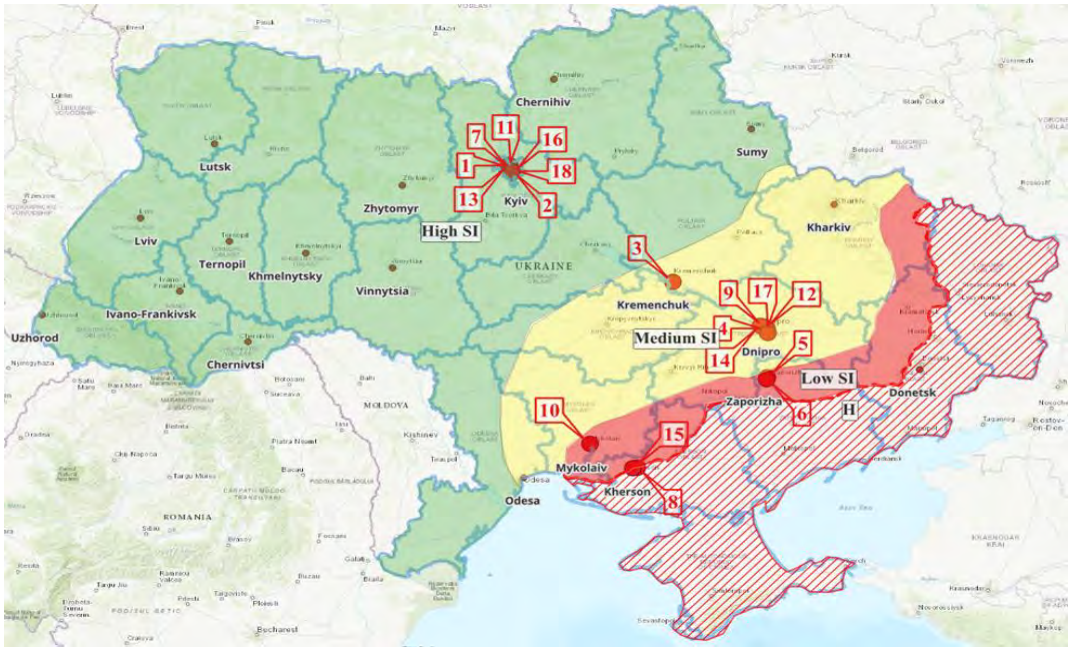


Figure 2. Location of 18 bridges included in the case study, with red markers denoting the assets, administrative borders in blue, and coloured zones indicating proximity-based safety index (SI) classifications: red hatch for active hostilities (as for spring, 2024), red for Low SI, yellow for Medium SI, and green for High SI

This case study illustrates how the proposed framework can guide decision-makers in identifying vulnerabilities, prioritising resources, and developing recovery strategies that address both current damage and long-term risks (Figure 3).

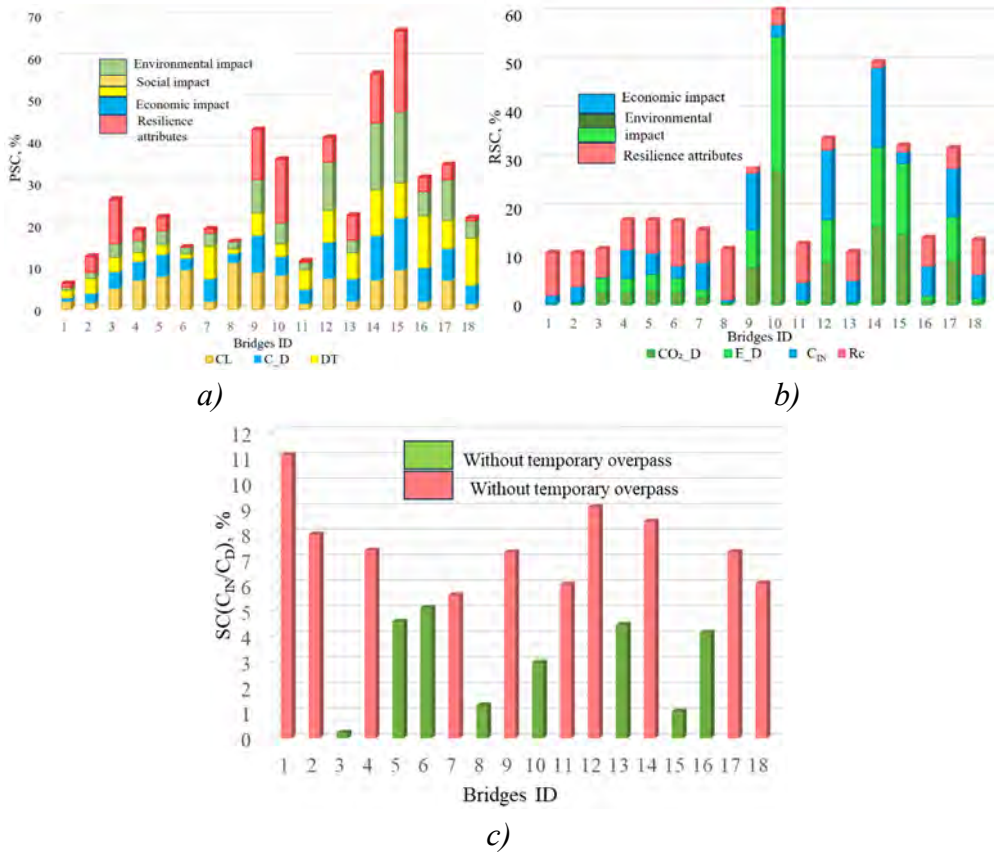


Figure 3. Results of global scores for the bridges of the case study: (a)- for proactive measures (PSC), (b)- for reactive measures (RSC), (c)-normalised scores SC(CIN/CD) as the criterion to choose the restoration scenario

Conclusions

This study introduced an integrated scoring-based framework for prioritising bridge reconstruction in conflict-affected regions, combining resilience and sustainability metrics to guide both proactive and reactive measures. The case study of 18 major Ukrainian bridges demonstrated how factors such as strategic importance, alternative routes, traffic demand, and environmental impacts shape prioritisation decisions. By linking proactive risk reduction with rapid recovery strategies, the framework supports safer, more functional, and more sustainable transport networks.

The approach is adaptable to multiple hazards, offering decision-makers a structured tool for resource allocation under uncertainty. While refinements are needed—such as incorporating region-specific data, predictive modelling, and broader social and economic metrics—the framework provides a novel pathway for aligning immediate restoration with long-term resilience. It highlights the urgency of resilience- and sustainability-driven planning in post-conflict reconstruction, ensuring that infrastructure recovery strengthens connectivity, community well-being, and future adaptability.

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From Static Maps to Risk Clocks: Spatio-Temporal Labels for Healthcare Accessibility

Mikhail Sirenko[1] Maria Pregnolato[2] Tina Comes[3] Bas Jonkman[4]
1 Delft University of Technology, the Netherlands, M.Sirenko@tudelft.nl
2 Delft University of Technology, the Netherlands, M.Pregnolato@tudelft.nl
3 Delft University of Technology, the Netherlands, T.Comes@tudelft.nl
4 Delft University of Technology, the Netherlands, S.N.Jonkman@tudelft.nl

Abstract

Timely access to healthcare during floods depends not only on where water accumulates but also on when people and staff are moving through the city. However, most studies treat exposure or access as static, masking critical time-of-day effects. To address this gap, we propose a dynamic analytical framework that combines hourly origin–destination (OD) data with flood water levels on the road network for Rotterdam, the Netherlands. This framework results in an intuitive Climate Risk Label (CRL) for road segments and healthcare facilities: hospitals and elderly homes. The CRL is explicit in space, time, and scenario and allows us to quantify how flood hazard degrades timely access to hospitals and elderly homes across the day. Using hourly OD matrices, along with socio-economic attributes, routable road graphs, and flood depth, we compute: (i) marginal added travel time for routes to the nearest K healthcare facilities; (ii) healthcare-weighted network criticality and redundancy; and (iii) population coverage within meaningful thresholds (15/30/60 minutes) for hospitals and elderly homes (including staff shift windows). We then map these metrics into two labels: a Road-segment CRL graded A–F by 95th-percentile added minutes and a Facility Access CRL graded A–F by coverage thresholds, with equity checks for districts with a high concentration of vulnerable individuals. We finally combine CRL into Risk Clocks to highlight hours of greatest operational concern that shift labels by ≥2 grades. The framework supports pre-event planning (detours, rostering), real-time decision support, and investment planning, while remaining transparent, auditable, and generalizable to other cities and hazards.

Keywords: vulnerability; resilience; spatio-temporal; healthcare; emergency response.

Background

Urban resilience is fundamentally spatio-temporal (Chelleri et al., 2015). People concentrate in different districts across the day for work, school, shopping, and care (Sirenko et al., 2024); and the same flood depth can have very different consequences at 08:30 than at 22:30 (Viglione et al., 2010). Yet most risk assessments for healthcare access are static: they report average travel times or binary connectivity, often under a single “design” flood, without reflecting

hourly OD patterns or the specific needs of hospitals and elderly homes (Tariverdi et al., 2023). Hospitals must preserve rapid access for emergencies (“golden hour”), while elderly homes depend on predictable staff inflows at fixed shift windows (typically morning, mid-afternoon, late evening). A resilience metric that ignores these temporal rhythms can under- or over-estimate real risk. We respond with a dynamic, healthcare-centric Climate Risk Label that communicates network reliability by hour and scenario, makes equity impacts visible, and ties directly to manageable, local interventions.

Materials & Methods

Our framework utilises the following data sets. We derive hourly origin–destination (OD) patterns from the mobility panel to represent how people and staff move across the city over 24 hours, and we combine these with district-level socio-demographic, economic and health data (age 65+/80+, disability, income, and car ownership) to calculate the vulnerability weight of each origin. We supervise it with spatial healthcare infrastructure data on hospitals and elderly homes, and build a routable road network from Overture Maps. Finally, we add flood depth for Rotterdam-relevant scenarios, which provide either hourly or peak depth for each road segment.

We then model dynamic access in four steps. First, we construct twenty-four-hour origin sets and assign each origin a vulnerability weight, resulting in a time series of demand fields. Second, we translate flood depths into using transparent rules: shallow water reduces speed; deeper water closes the segment; duration imposes a reliability penalty. Third, we compute shortest-time routes from each origin to the nearest K hospitals and elderly homes on both a dry baseline graph and a flood-affected graph, storing the added minutes for each hour. Fourth, we evaluate healthcare-weighted network structure by calculating edge betweenness (centrality) with OD weights to healthcare facilities at each hour and estimating redundancy as the ratio of the best alternate path time to the baseline time when a candidate edge is impaired.

We convert these metrics into two labels that are explicit in space, time, and scenario. The Road-segment Climate Risk Label grades each edge A–F by the 95th-percentile added minutes experienced by OD pairs that traverse it: A(<5), B(5–10), C(10–20), D(20–30), E(30–60), and F(>60 or disconnection). We adjust grades down if an edge is highly central and poorly redundant and up if it is peripheral and easily bypassed, and we set a safety floor to prevent optimistic grading on segments with deep, persistent inundation. The Facility Access Climate Risk Label summarises hourly coverage to hospitals and elderly homes: hospitals are graded by the share of vulnerability-weighted people who can arrive within 30 and 60 minutes; elderly homes are graded by 30-minute access for staff during shift windows (06–10, 14–16, 22–24) and 30-minute emergency access at all hours. We apply an equity modifier that downgrades the label if the most vulnerable districts fall disproportionately below the citywide coverage.

Preliminary Results

These results are illustrative of the framework's outputs and reporting style; values are placeholders consistent with Rotterdam’s network structure and a plausible flood scenario.

Under the flood, hospital access remains strong before the morning peak, degrades around midday, and recovers in the evening. (Table 1). Elderly homes show sharper dips during staff shift windows, even when hospitals stay within acceptable bounds (Table 2). At 12:00–15:00, shallow but widespread flood approaches to key crossings, which coincides with baseline congestion, pushing Erasmus MC to C (≈85% within 30 min; ≥96% within 60 min) and Maasstad briefly to D (≈72% within 30 min), with near-full recovery by 21:00.

Facility	**06:00**	**09:00**	**12:00**	**15:00**	**18:00**	**21:00**	**00:00**
Erasmus MC (ED/Trauma)	A	B	C	C	B	A	A
Maasstad Hospital	B	C	D	C	B	A	A

Table 1. Hospital Risk Clocks (hourly Facility Access Climate Risk Label grades).

Havenzicht elderly home drops to E at 15:00 as it is flooded and staff must detour across a constrained crossing; the share of staff within 30 minutes falls near 55–60%.

Facility	**06:00***	**09:00***	**12:00**	**15:00***	**18:00**	**22:00***	**00:00***
De Zorghoek	B	C	C	C	B	C	B
Havenzicht	C	D	D	E	C	D	C
Parkzicht	A	B	B	B	A	B	A

Table 2. Elderly Home Risk Clocks (hourly Facility Access Climate Risk Label grades).

As a result, each facility receives a compact “scenario card” combining its Risk Clock (hourly A–F grades) and a list of the top three nearby segments whose Road Segment Climate Risk Label drives the grade. Each flagged road segment is colored by its A–F grade on the map and annotated with added minutes, a redundancy score, and a recommended (micro)measure with an indicative “minutes-saved-per-euro.”

Discussion

The preliminary results underscore three design insights that are invisible in static maps. First, timing matters as much as depth: the worst healthcare access occurs when modest flood depth coincides with peak baseline demand at constrained crossings. Second, elderly-home staffing is fragile at shift windows; even non-closure slowdowns can push staff coverage below operational thresholds. Third, small works at a few pinch points (raising short approaches, adding culverts or flap valves, improving cross-fall) can shift road grades by two classes and lift facility labels back into acceptable bands, often more cost-effectively than large schemes. These labels are auditable (clear rules and inputs), portable to other cities, and suitable for pre-event operations: detours, staffing and signal plans.

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Integrated framework for Risk and Resilience Assessment of critical Transport Infrastructures using Traffic Module Analysis

saimir osmani - saimir.osmani@rina.org, Miltiadis Kontogeorgos - miltiadis.kontogeorgos@rina.org, Vincenzo Cerreta - vincenzo.cerreta@rina.org, Rina consulting (Italy)

Abstract

This paper presents an integrated framework for assessing the risk and resilience of critical transport infrastructures under natural hazard scenarios, developed within the SARIL project. The proposed approach is applied to a small transport network in the Mantua area, near the Mincio River, and is organized into three main components. First, a detailed vulnerability and risk analysis of key infrastructure assets is conducted to develop disruption functions that quantify expected damage and service interruptions due to natural hazards. Second, these disruption functions are implemented within a dynamic traffic model developed using TRANSCAD, allowing for the simulation of hazard impacts at the asset level and the assessment of their consequences on overall network performance. This allows for the evaluation of cascading effects from asset-level failures to network-wide disruptions. Finally, a comprehensive resilience assessment is performed, estimating direct and indirect economic losses, as well as broader societal impacts, including potential casualties. The framework offers decision-makers valuable insights to strengthen disaster preparedness, improve emergency response planning, and guide strategic investments in resilient transport infrastructure.

Keywords: Critical transport infrastructure; Vulnerability analysis; Risk, Resilience; Traffic modeling; Economic impact; Natural hazards

Introduction

This paper introduces an integrated framework for the comprehensive assessment of risk and resilience in critical transport infrastructures subjected to natural hazard scenarios. Developed within the scope of the SARIL project, this framework aims to support decision-makers in understanding, anticipating, and mitigating the impacts of natural disasters on transport systems, which are vital for economic stability and societal well-being. The framework is demonstrated through its application to a small transport network surrounding the city of Mantua (Italy), located near the Mincio River. In this study, the focus is on flood events and their associated impacts, specifically on bridges affected by river inundation and roads vulnerable to flooding from the river.

The methodology is structured around three interrelated components, each addressing a critical aspect of infrastructure risk and resilience.

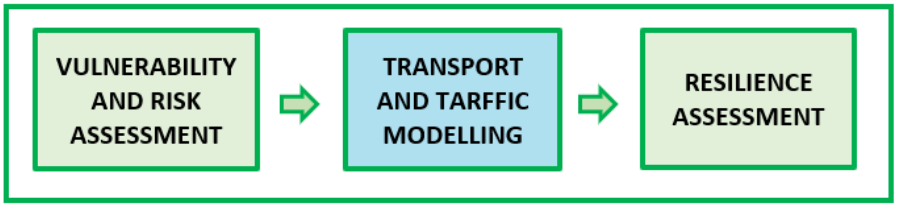


Figure 1. Framework main components

Vulnerability and Risk Assessment

The first component centers on comprehensive vulnerability and risk analysis of key infrastructure assets, primarily bridges and roads. This process begins with an in-depth characterization of these assets from both geometric and mechanical perspectives, considering their design features, construction materials, service provided and physical conditions. Concurrently, the natural hazard exposure within the study area is quantified by analyzing the frequency, intensity, and spatial distribution of flood events. By combining all the gathered information, the probability that a bridge or road will experience a specific level of damage is calculated and then passed on to the traffic module for further analysis.

Traffic Modelling

The second component integrates the derived disruption functions into a dynamic traffic simulation model developed using TRANSCAD. This allows for the realistic simulation of traffic-flow changes and network performance under various flood-induced disruption scenarios. By modeling impacts at the asset level, the framework can assess not only localized failures but also their cascading effects on the entire transport network. This network-level analysis provides insights into traffic rerouting (additional travel time and distances), congestion patterns, and service degradation, which are critical for emergency management and contingency planning.

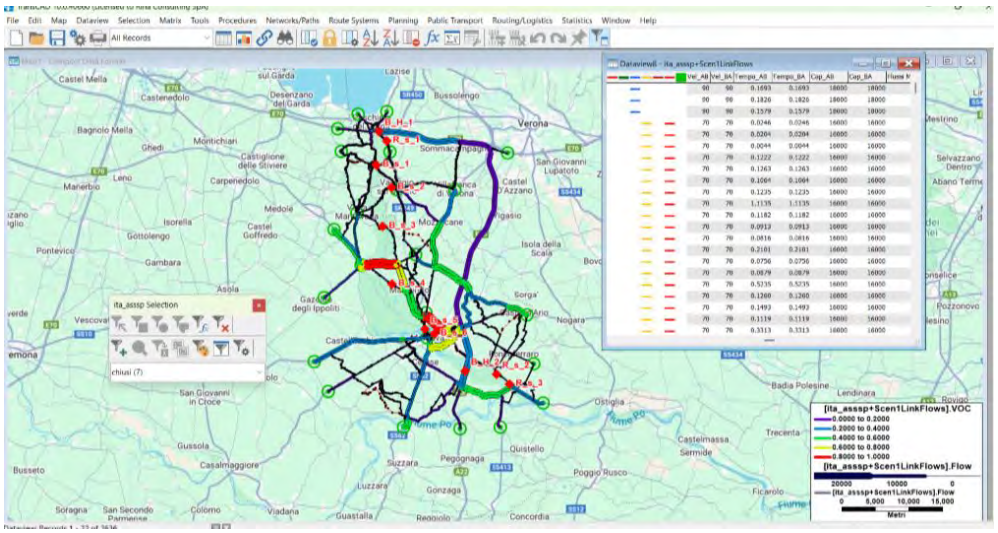


Figure 2. Traffic Model of the transport network in Mantua.

Resilience Assessment

The third component expands the analysis to include both resilience and risk assessment, quantifying resilience levels alongside direct and indirect economic impacts as well as potential casualties. The key outcomes from applying the framework to the case study for three different disruption scenarios are summarized below.

Direct and Indirect Losses

Direct losses are quantified through the Repair Cost Ratio (RCR), representing the portion of an asset's construction cost required for repairs after extreme events. Indirect losses encompass economic impacts due to service disruption, including increased travel time and costs, reduced accessibility and connectivity, lost productivity, and spillover effects on other economic sectors.

Loss Curves and Expected Annual Loss (EAL)

Loss curves plot economic losses against risk levels for various damage states. The area under the loss curve provides the Expected Annual Loss (EAL), which estimates the average yearly loss as a fraction of the asset's construction cost. This metric helps prioritize maintenance and resilience investments.

Level of Service (LoS)

The Level of Service, indicated by the Volume over Capacity (VOC), represents the average criticality of the network. It measures a road's capacity to handle traffic demand based on factors such as traffic flow, vehicle speed, and density. Comparing these parameters during normal and emergency conditions reveals the impact of floods on infrastructure performance.

Resilience Assessment

Resilience curves are developed by analyzing asset recovery and operational losses over time post-event, illustrating the restoration of functionality at asset and system levels. Network resilience focuses on the most critical recovery scenario within specific sections of the transport network, evaluated via the Origin-Destination (O-D) matrix used in the Traffic Module. This approach quantifies resilience for each route by examining the associated recovery trajectory.

In the following table the indirect economic losses and VOC values are reported.

Table 1. VOC and cost-difference to the base case for the disruption scenarios in the Mantua region

Category	VOC	Running cost [Fuel]	People and goods loss	Total Indirect costs /day
Base case	**0.398**	**-**	**-**	**-**
Disruptive case 1	**0.46**	**+ 208,528.92 €**	**+ 5,769.18 €**	**+214,298.10 €**
Disruptive case 2	**0.41**	**+103,502.49 €**	**+ 4,563.65 €**	**+108,066.13 €**
Disruptive case 3	**0.400**	**+66,182.09 €**	**+ 4,111.56 €**	**+70,293.65 €**

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A Particle Filter Estimation of Taylor's Law Fluctuation Scaling in Water Demand

Bernhard Jonathan Sattler[1], Siew Ann Cheong[2], Tobias Koch, Jonas Joerin[3], Peter F. Pelz[4]

[1] Institute for the Protection of Terrestrial Infrastructures, German Aerospace Center, Germany

[2] School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore

[3] Future Resilient Systems, Singapore-ETH Centre, Singapore

[4] Chair of Fluid Systems, Technical University of Darmstadt, Germany

Abstract

Uncertainty of water demand is a major consideration for the resilience and risk management of water distribution systems, which are critical infrastructures. This demand uncertainty has been shown to exhibit heavy-tailed characteristics, i.e., extreme deviations from expected behavior are more common than conventionally anticipated. Taylor's Law of fluctuation scaling has been used for the risk management of systems subject to similar heavy-tailed uncertainty. Using the example of urban water demand time series, we show that a Particle Filter-type Bayesian estimation can be used to uncover fluctuation scaling in infrastructure demand time series following Taylor's Law with time-variant scaling parameters. Furthermore, we demonstrate that the observed fluctuation scaling exceeds what is assumed by conventional water demand models. We then discuss how this insight impacts the management of critical infrastructures and how future research can address the arising challenges from these results.

Keywords: water demand, water distribution systems, heavy tails, Taylor's Law, Particle Filter

Introduction

The goal of critical infrastructure (CI) management and operation is the provision of essential services or functions to the members of a society, even in extraordinary or extreme conditions. The ability of CIs to cope with such extreme, often disruptive, conditions is what we consider resilience. Strategies, i.e., rules or decision frameworks, for the management and operation of these CIs have to account for uncertain boundary conditions. A major source of uncertainty in the optimization of such strategies is the user behavior, e.g., the amount of services requested by its users, which in many cases is directly related to the physical strain on the infrastructure. Understanding the characteristics of this demand is therefore pivotal for the resilience of CIs.

To understand how uncertainty in demand can impact the resilience of CIs, we examine the example of urban water distribution systems (WDSs). Specifically, we investigate the stochastic characteristics of urban water demand with a special focus on its extreme values, and analyze these characteristics' impact on strategies for WDS management and operation.

Methods and theoretical background

To characterize the uncertainty in water demand, we investigate time series data of the water outflow of WDSs on a neighborhood level. We consider the uncertainty in the time series data as variability that can be stochastically modeled. Using this approach, we briefly summarize our previous results investigating heavy-tailed characteristics of this demand. Heavy-tailed characteristics refer to the empirical distributions of data showing a higher frequency of values far from the mean of the distribution than a normal distribution. Such distributions with HTs are pivotal to the risk management of system in which they appear and are generally considered a challenge for conventional statistical methods (Barabasi, 2005). These challenges for many statistical methods necessitate specific approaches, one of which is the use of Taylor's Law.

Taylor's Law

Taylor's Law was originally described as a relation between the fluctuation and the mean of samples in the observation of populations in ecology (Taylor, 1961). The Law refers to the observation, that samples drawn from a randomly distributed population scale following

$$\sigma^2 = \alpha\mu^\beta, \tag{1}$$

with the sample variance σ^2, the sample mean μ, and the parameters $\alpha, \beta > 0$. α and β are constant for each population, with ecological surveys typically yielding $1 < \beta < 2$.

Taylor's Law has been shown to also apply to heavy-tailed distributions (Cohen, Davis, & Samorodnitsky, 2020) and has been used as a basis of risk-adaptive supply strategies, e.g. for the stock management of consumer goods (Sakoda, Takayasu, & Takayasu, Retail Strategy to Reduce Waste Keeping High Profit Utilizing Taylor's Law in Point-of-Sales Data, 2019), whose demand typically also exhibit heavy tailed characteristics (Moss, 2002).

Particle Filter

The Particle filter (PF) is a recursive approach to estimate system states in dynamical systems. Similar to other recursive filters, e.g. the Kalman Filter, it uses Bayesian Inference to integrate noisy observations of a systems state to estimate the underlying system dynamics. It does so by sampling system states (in our case parameter combinations) from a proposal distribution of potential system states. These system states are called particles. Subsequently, the next (or first) observation from the time series is added and each particle is evaluated based on the likelihood of said observation considering the particle. Based on this evaluation, the proposal distribution is updated and the particles are resampled from the updated distribution. This can be considered a Monte-Carlo based implementation of a Bayesian Inference Framework for time series data.

Due to its limited assumptions about the structure of the underlying system process and observation process, the PF is particularly suited for non-linear system dynamics and non-Gaussian system and measurement noise. This enables us to estimate time-variant parametrizations of CI demands following TL. A similar approach of estimating TL parameters has previously been shown by (Sakoda, Takayasu, & Takayasu, Tracking Poisson Parameter for Non-Stationary Discontinuous Time Series with Taylor's Abnormal Fluctuation Scaling, 2019).

Results and discussion

Our results show, that the analyzed water demand time series exhibit “mild” HTs, i.e. extreme values are more common than would be assumed under the assumption of Gaussian process noise. We furthermore show, that Taylor’s Law-type fluctuation scaling can be observed in these time series. The scaling exponents exceed the scaling exponents predicted by conventional water demand models, are time-variant, and can be locally estimated using a Particle Filter-type Bayesian inference. These results could be used to (i) improve stochastic water demand models, (ii) highlight potential shortcomings of current risk management approaches caused by the underestimation of extreme demand values, and (iii) develop risk-responsive WDS management based on real time data assimilation.

Conclusions and outlook

We show that time series of urban water demand exhibit heavy tailed characteristics and that their fluctuation scales according to Taylor’s Law with time-variant scaling parameters. We employ a Bayesian approach to estimate these parameters from the time series data and discuss the impact of these results for the resilience of critical infrastructures.

Our presentation will briefly outline the methods and results described above and highlight the impact of these results for risk and resilience management and operation of CIs. Furthermore, we outline prospects for further research and invite the audience for feedback and potential collaboration in their respective CI contexts.

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Operationalizing the Capability Approach in the Context of Critical Infrastructure Disruptions and Resilience

Sangeeta [1] , Rui Teixeira [2], and Beatriz Martinez-Pastor [1]
1 University College Dublin, Ireland, Beatriz.martinez-pastor@ucd.ie, sangeeta.sangeeta@ucd.ie 2 Trinity College Dublin , Ireland, rui.Teixeira@tcd.ie

Abstract

Disruptions to critical infrastructure, including road networks, healthcare facilities, energy systems, and communication networks, have significant societal impacts, constraining households' ability to access essential services and maintain daily activities. Existing resilience metrics often focus on system-level indicators, such as service restoration time or network throughput, but provide limited insight into the human-level consequences of infrastructure failures. In particular, these metrics rarely capture how disruptions affect household well-being, individual freedoms, and access to critical amenities. Addressing this gap, this research asks how the household-level impacts of critical infrastructure disruptions, with an emphasis on road networks, can be conceptualized, quantified, and operationalized through the lens of the Capability Approach (CA).

This study operationalizes the CA by linking infrastructure disruptions to household-level capabilities, framing well-being in terms of the ability to perform essential activities, such as accessing healthcare, education, employment, and emergency services, under network stress. The approach moves beyond traditional connectivity metrics, considering functional opportunities provided by infrastructure and the resulting freedoms and choices available to households. By focusing on capability preservation, the study integrates structural and functional dimensions of resilience with human welfare outcomes.

Methodologically, the research employs spatial network analysis, graph-theoretic metrics, and scenario-based disruption simulations to quantify how failures propagate through interdependent infrastructure systems and affect household capabilities. Disruption scenarios simulate the removal of nodes or edges to represent hazard-induced failures, such as flooding or localized accidents, and cascading effects are modeled across interconnected infrastructure layers. Empirical analyses integrate these network metrics with household-level assessments to identify capabilities most sensitive to infrastructure failures. The research develops a capability-based resilience index that aggregates heterogeneous impacts across capabilities and infrastructure types into a unified metric. This index enables the comparative evaluation of disruption scenarios, highlights spatial inequalities in capability loss, and informs prioritization of resilience investments.

By combining network science, spatial modelling, and CA methodologies, this study provides a quantitative, human-centered framework for assessing critical infrastructure resilience. It demonstrates how disruptions in road networks and related systems propagate to measurable losses in household capabilities, offering actionable insights for policymakers and urban

planners. The framework supports decisions to enhance infrastructure redundancy, ensure equitable access to essential services, and strengthen societal resilience. Ultimately, this research advances resilience metrics that are both technically rigorous and socially meaningful, integrating structural, functional, and normative dimensions to support equitable, human-centered resilience planning.

Keywords: Capability Approach; Critical Infrastructure; Human-Centered Resilience; Cascading Effect

Resilience assessment framework based on criticality and resilience properties

Bartosz Skobiej, Arto Niemi, Nikolai Kulev, Frank Sill Torres
DLR Institute for the Protection of Maritime Infrastructures, Germany
bartosz.skobiej@dlr.de, arto.niemi@dlr.de, nikolai.kulev@dlr.de, frank.silltorres@dlr.de

Abstract

Resilience evaluation in modern infrastructures, particularly in critical energy systems, is increasingly important due to rising complexity and interconnectivity. This study builds on recent advances in resilience capacities and properties, using criticality analysis and functional decomposition to characterize offshore wind farms. A preliminary assessment based on modularity and redundancy is conducted. Results indicate that a single aggregated resilience index may obscure trade-offs, as distinct configurations can yield similar values. Future work will integrate high-fidelity simulation data to refine property parameters. The present assessment constitutes a first step toward more robust resilience quantification.

Keywords: resilience; criticality; modularity; redundancy; offshore wind

Introduction

The proposed methodology assesses quantitatively the resilience of infrastructures by systematically considering system parameters in a hierarchical manner. It is structured into three fundamental steps: (1) hierarchical functional decomposition, (2) extraction of resilience properties and capacities at the top layer, and (3) detailed parametrization through high-fidelity modeling.

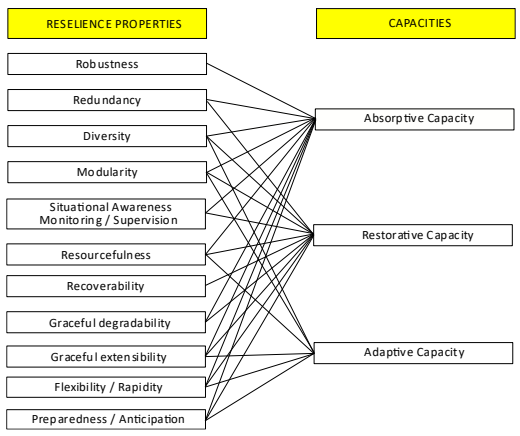


Figure 1. Resilience properties and corresponding capacities, based on (Mentges et al., 2023).

Step (1) involves breaking down the infrastructure into progressively smaller, functionally distinct subsystems. Established approaches, like those discussed by (Ouyang, 2014) and (Rinaldi, Peerenboom, & Kelly, 2001), can be applied here. Typically, the decomposition follows a top-down procedure: starting from the overall mission or function (e.g., energy provision), the system is divided into major subsystems (e.g., generation, transmission, distribution), and further refined into specific processes or assets. This representation highlights functional

dependencies, critical nodes, redundancies, and potential pathways for failure propagation. An example for an offshore wind farm (OWF) is illustrated in Figure 2.

Step (2) builds on the extracted top-layer functions and focuses on the associated resilience properties and capacities, as illustrated in Figure 1. For each property, the corresponding parameter RP_{prop} is identified, with *prop* denoting the set of properties shown in Figure 1 (e.g., redundancy, modularity). After normalization, these parameters are aggregated to derive the resilience capacities RC_{cap}, where *cap* refers to the set {*absorptive*, *restorative*, *adaptive*}. Each capacity is associated with a subset of properties $cprop_{cap}$, as indicated in Figure 1. For example, the property set of the resilience capacity *adaptive* is $cprop_{adaptive} = \{RP_{diversity}, RP_{modularity}, RP_{flexibility\_rapidity}, RP_{preparedness\_anticipation}, RP_{resourcefulness}, RP_{graceful\_extensibility}\}$. The combination is based on weighted normalization (Petit, 2013):

$$RC_{cap} = \frac{\sum_{i \in cprop_{cap}} (w_i \cdot RC_{cap,i})}{\sum_{i \in cprop_{cap}} (w_i)} \quad (1),$$

where w_i represents the weight of the property i in the set $cprop_{cap}$, while $RC_{cap,i}$ denotes the value of the resilience capacity for property i.

In Step (3), all properties are parameterized on the basis of high-fidelity modeling and simulation of the individual subsystems. Such modeling yields, for example, component failure rates and reliabilities, potential failure paths, and other performance-relevant parameters.

Modularity and redundancy

When aiming at meaningful analysis, the estimation of the resilience properties is not trivial. For illustration, this work focuses on the properties modularity and redundancy.

Modularity refers to the extent to which a system can be decomposed into independent modules that perform distinct functions without interfering with one another (Newman, 2006). The modularity index, which represents functional independence obtained through functional decomposition (U.S. DoD, 2001), is defined as the number of edges connected to a vertex within a functional block graph at the same level of decomposition, as exemplarily illustrated in Figure 2. This study is limited to energy flow channels. As an example, consider the sub-function “Energy provision” of an OWF, which corresponds to the turbine level. Here, modularity is determined, among others, by the number of internal strings to which the turbines are connected, and which separate the turbines in individual groups. For a system with s equal strings, the modularity M_f of this sub-function f is given by s.

In the context of infrastructures, redundancy is understood as the existence of additional elements beyond those strictly necessary for system operation. Its primary role is to sustain functionality despite failure of individual components (Zio, 2016). Several approaches exist to quantify redundancy at the system level. In reliability theory, the redundancy R_{ssys} of a sub-system *ssys* results from (Birolini, 2017):

$$R_{ssys} = 1 - \prod_{i \in comp}(1 - RL_i) \quad (2),$$

where RL_i denotes the reliability of component *i* within the set of components *comp* of the sub-system.

For many infrastructure systems, the Failure Mode, Effects, and Criticality Analysis (FMECA) method, based on MIL-STD-1629A (U.S. DoD, 1980), has proven effective (Ge et al., 2025). The outcome of a CA is typically expressed in terms of a criticality index *CI*, which facilitates the prioritization of system elements. For a sub-system *ssys*, the criticality index can be estimated as:

$$CI_{ssys} = \sum_{i \, \epsilon \, comp}(\lambda_i \cdot \alpha_i \cdot \beta_i) \quad (3),$$

where CI_{ssys} denotes the *CI* of the sub-system *ssys*, λ_i is the failure rate of component *i* within the set of components *comp* of the sub-system, α_i means the conditional probability that the failure mode occurs given component failure and β_i is the probability that the failure effect results in sub-system failure. For normalization, unit interval ranking has been chosen, which proves to be robust to adding and or removing of low-impact items. Thus, the normalized criticality index $\overline{CI_{ssys}}$ results from:

$$\overline{CI_{ssys}} = \frac{CI_{ssys}}{\max(CI_{sys})} \quad (4),$$

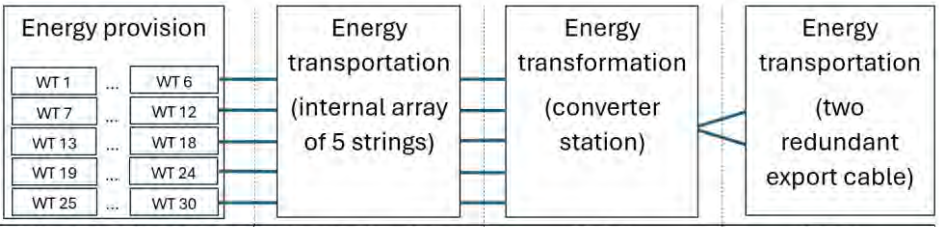
where CI_{sys} is the set of all critical indexes of the system *sys.* This value is then employed as property weight *w* for the properties in Equation (1).

Results

Following the CA in the context of functional decomposition, as it is shown in Figure 2, the least critical element of Offshore Wind Farm (OWF) is Wind Turbine (WT) which is achieved via redundancy. Criticality of each WT is estimated as ca. 3.3 %. The most critical elements are converter station and export cable, both assumed as 100 % of criticality. It is assumed that all four function blocks in Figure 2 are critical to system functionality.

Modularity index understood as functional independence suggests that export cable is the most independent element of OWF with only 1 connection. The most interconnected element is internal array of OWF with 10 sub-system dependencies for all 5 strings.

The most redundant elements are Wind Turbines (WTs) as components responsible for energy provision. The least redundant elements are energy converter station and export cable.



Criticality	(3.3 % * 30) = 100 %	(20 % * 5) = 100 %	100 %	100 %
Modularity	5	10	6	2
Redundancy	0	0	0	1

Figure 2. Functional decomposition of OWF with selected indicators and interconnections based on energy flow.

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A Narrative-based Framework for Power Grid Resilience Assessment

Jenny Martinez[1], Luca Podofillini[2], Matteo Spada[1]
1 Institute for Sustainable Development (INE), School of Engineering (SoE), Zurich University of Applied Sciences (ZHAW), Switzerland
2 PSI Centers for Nuclear Engineering and Science and for Energy and Environmental Sciences, Laboratory for Energy Systems Analysis, Paul Scherrer Institute, Villigen PSI, Switzerland

Abstract

This study develops structured narratives through expert-driven workshops to map disruption and recovery scenarios and their propagation across power grids and interconnected systems (residential, commercial, industrial, etc.). These narratives facilitate an understanding of how different phases of disruption and recovery interrelate, how businesses are affected, and how they interact with one another. The first workshop brings together power grid, IT security, and critical infrastructure experts to characterize realistic cyber threats, analyze the propagation of disruptions within the grid and to dependent systems, and outline grid-level recovery scenarios. The second workshop involves financial experts, social scientists, and other stakeholders to assess the broader economic and social impacts of the disruption scenarios from Workshop 1, prioritize recovery actions based on sectoral criticality and resource availability, and define a set of resilience indicators. The developed narratives will serve as input for quantifying indicators used in assessing the Economic Resilience Criticality (ERC) index.

Keywords: resilience; power grid; cyber disruptions; narratives; scenarios.

Introduction

The increasing digitalization of electric power grids has significantly improved operational efficiency but has also introduced critical vulnerabilities to cyberattacks, with potentially cascading consequences for urban infrastructure systems (Baggott & Santos, 2020). Modern grid architectures, particularly those incorporating smart grid technologies and IoT-enabled devices, face sophisticated threats ranging from ransomware attacks on control systems to false data injection, which compromises grid stability (Rahiminejad et al., 2023). These cyber-related disruptions necessitate resilience assessment methodologies that extend beyond traditional technical analyses to incorporate narratives to identify potential cyberattacks and define disruption and recovery scenarios in electrical power grids.

Narrative-based approaches have emerged as a particularly valuable method for characterizing critical infrastructures and how disruptions can propagate in time, affecting the security and resilience of the system. Unlike purely quantitative models, structured narratives developed

through expert workshops can capture complex interdependencies and human factors (CISA, 2023). For example, in Strong et al. (2020), narratives were structured to guide disaster risk reduction scenarios and inform preparedness planning. Similarly, Einola et al. (2021) applied narrative networks to capture the evolution of smart city solutions. Hanf et al. (2024) developed three urban water risk adaptation scenarios through a participatory process and visualized them as “narrative images” using the city of Hamburg as a case study. These studies show how narratives transform technical hazards into detailed sequences of events, revealing interdependencies, stakeholder actions, and recovery pathways crucial for resilience planning and decision-making.

Based on these premises, this research aims at developing narratives for 1) characterize possible cyberattacks in Winterthur power grid, from the initial breach, to control system compromise and cascading outages, 2) identify the spatial propagation of disruptions across the power grid nodes and interdependent networks, such as impacts on water pumps, transportation networks, healthcare facilities, and society, 3) develop potential recovery scenarios and their associated cost, and 4) develop a resilience indicators set. This approach underscores the importance of stakeholder engagement in identifying credible cyberattack scenarios and shaping effective recovery strategies for critical infrastructure systems.

Methodology

The methodology employs a structured two-workshop approach to develop comprehensive narratives on cyber-related disruptions and recovery for power grid resilience assessment (Fig. 1). The first workshop brings together power grid experts, IT security specialists, and critical infrastructure experts to identify credible cyber threats to grid control systems and analyze ICT-network interdependencies. Participants examine how disruptions might cascade from power infrastructure to dependent systems, such as water supply, transportation, and communication systems, while quantifying impacts through technical metrics, including outage duration and affected load capacity. In addition to disruption analysis, participants also outline recovery scenarios at the power grid level, such as system reconfiguration, rapid isolation of compromised nodes, and staged restoration of load. Through collaborative exercises, workshop participants generate event descriptions called "happenings." These happenings, which are pieces of stories, are then combined and ordered to develop narratives. These narratives fully describe the progression of attacks and recovery pathways by mapping the sequential relationships between events.

The second workshop brings together financial experts, social scientists, and other relevant stakeholders to assess the broader impacts of the disruption scenarios developed in Workshop 1. Participants evaluate economic consequences, such as the value of lost load and business interruption costs, as well as social impacts, including reduced access to essential services and potential population displacement risks. Building on these impact assessments, the workshop also examines the cost-benefit tradeoffs of various mitigation measures and prioritizes recovery actions based on sectoral criticality and resource availability. Temporal recovery sequences are outlined to distinguish between immediate response actions (e.g., isolating compromised nodes within the first six hours), short-term stabilization efforts (e.g., restoring critical services within

24 hours), and long-term restoration plans for full system recovery. The outputs from both workshops are systematically integrated into comprehensive disruption narratives that map cyberattack progression and cross-sector impacts, along with detailed recovery narratives specifying actionable restoration protocols and resource allocation plans.

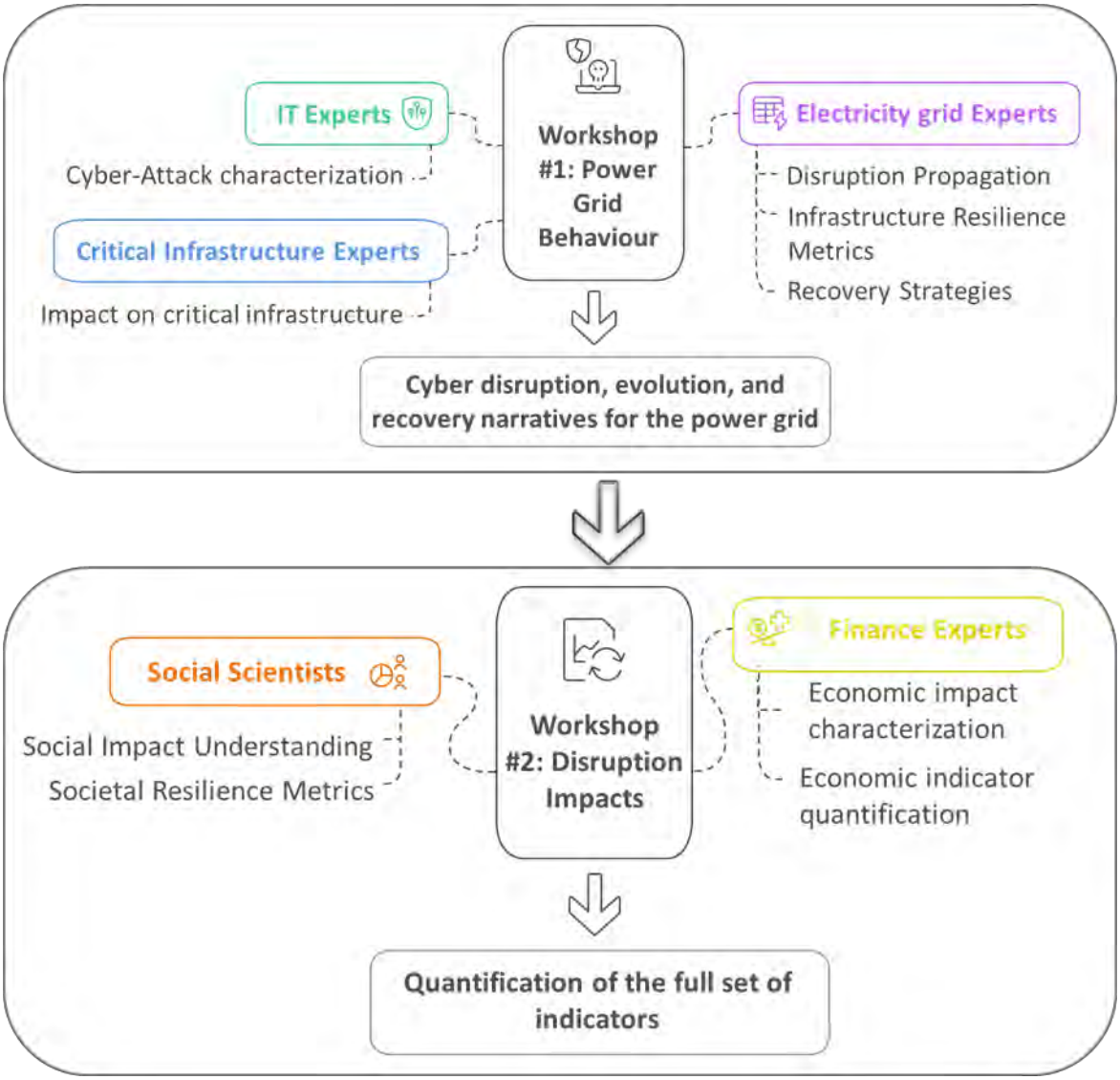


Figure 1. Methodological approach for developing narratives.

Results

These co-created narratives serve as foundational inputs for quantifying resilience indicators within the Economic Resilience Criticality (ERC) index, enabling spatial vulnerability mapping of grid nodes, cost-effective mitigation planning, and stakeholder-aligned recovery prioritization. The participatory methodology ensures the resulting narratives reflect real-world operational constraints while effectively addressing evolving cyber-physical threats to critical infrastructure systems. By combining technical vulnerability assessment with socio-economic impact analysis through structured expert engagement, this approach provides a robust framework for developing actionable resilience strategies that account for the complex

interdependencies characteristic of modern power grids and their connected urban systems. The methodology's emphasis on collaborative scenario development and its direct linkage to quantitative resilience metrics offer a novel contribution to critical infrastructure protection research and practice.

Acknowledgements

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On the role of sensitivities in safety-driven infrastructure systems

Rui Teixeira Department of Civil Structural And Environmental Engineering, Trinity College Dublin, Dublin 2

Abstract

Complex infrastructure systems face unprecedented challenges as deep uncertainties such as climate change, societal dynamics, and long service lifetimes increasingly compromise the reliability of conventional design approaches. Traditional methods, based on fixed assumptions and probabilistic safety margins, often fail to address non-stationary conditions that emerge across decades of operation. This work discusses the need for new rationales for safety proofed future complex infrastructure systems: where sensitivities are leveraged to identify vulnerabilities, anticipate tipping points of safety, and embed adaptive pathways into design and operation of infrastructure.

To this, sensitivity analysis is discussed as key for future-proofing infrastructure. Sensitivities quantify variations in inputs and how these propagate into system outputs and risk. They have a dual role: (i) enhancing safety by revealing intrinsic vulnerabilities and dependencies often hidden in stress-testing approaches, and (ii) enabling flexible design by informing which variables should remain adaptable to accommodate uncertain futures. This shift reframes engineering design away from purely robust or "over-design" strategies towards purposeful inclusion of flexibility, allowing systems to be adjusted when future knowledge improves.

A conceptual framework is proposed linking uncertainty, sensitivity, and safety, emphasizing their integration. Importantly, it is discussed how sensitivity analysis can be applied in both probabilistic and agnostic settings, enabling exploration of system behaviour even when assumptions about future conditions cannot be agreed upon.

Examples of application are used to provide an empirical understanding on the discussion and underscore the practicality of embedding sensitivity-driven insights into safety assessments and long-term complex infrastructure management.

This discussion advances a manifesto for rethinking engineering design under deep uncertainty. Instead of solely seeking insensitive or robust solutions, design should integrate flexibility informed by sensitivity analysis. This involves identifying critical parameters for adaptation, monitoring variables that govern safety margins, and explicitly planning for decision pathways that preserve safety as conditions evolve. Sensitivity thus becomes a unifying thread linking uncertainty assessment, risk management, and adaptive design.

In conclusion, the work argues for a paradigm shift in engineering practice. Embedding systematic sensitivity analysis provides a foundation for complex infrastructure systems that are not only reliable under present assumptions but also resilient to unforeseen futures.

Keywords: Sensitivity analysis, system safety, uncertainty, adaptive design, resilience, infrastructure systems.

Machine Learning for Power Grid Control: A Project for Enhancing Resilience through Data Quality

Maximilian Gräser[1], Oscar H. Ramírez-Agudelo,[2] Michael Karl[3]
1 German Aerospace Centre (DLR) - Institute for AI Safety and Security, Germany, Maximilian.graeser@dlr.de
2 German Aerospace Centre (DLR) - Institute for AI Safety and Security, Germany, oscar.ramirezagudelo@dlr.de
3 German Aerospace Centre (DLR) - Institute for AI Safety and Security, Germany, michael.karl@dlr.de

Abstract

Machine learning methods offer promising capabilities for forecasting, decision support, and automated control, but their trustworthiness in critical infrastructures depends heavily on the quality of the underlying data. This project addresses these challenges by systematically analyzing and integrating data quality considerations into the entire ML lifecycle. The project's outcomes include a dedicated data quality framework that identifies leverage points where interventions can enhance the reliability of ML models. By explicitly embedding data quality into the design and application of AI methods, this project contributes to strengthening trustworthiness and resilience in critical energy infrastructures.

Keywords: Data Quality; Machine Learning; Resilience; Forecasting

Introduction

The transformation of the power system through the expansion of renewable energy has led to higher variability, decentralization, and uncertainty in grid operation. Traditional control mechanisms are increasingly insufficient to guarantee stability and resilience under such conditions. AI and machine learning (ML) are regarded as key enablers for future energy systems, offering advanced forecasting, situational awareness, and automated decision-making capabilities (Strecker et al., 2025). However, the deployment of such methods in critical infrastructures raises fundamental concerns about trustworthiness.

A central factor in this context is data quality (DQ). ML methods are only as reliable as the data they are trained and operated with. Low-quality, incomplete, or biased data can lead to poor performance, unreliable decisions, and, in the worst case, unsafe system states. Recognizing the critical role of data quality in ensuring reliable and safe ML applications, this project explicitly integrates DQ considerations throughout the ML lifecycle.

Project Objectives

The main objective of this project is to enhance the trustworthiness of ML applications in grid operation by explicitly embedding data quality into the entire ML development and deployment process. To achieve this, the project focuses on:

1. Designing a lifecycle-oriented data quality framework to systematically integrate DQ considerations into ML development and deployment.
2. Applying the framework to a representative use case: the prediction of solar irradiance as an important factor for solar energy integration into the grid.
3. Developing a data quality model and robustness analyses that demonstrate how the framework can be used to evaluate and strengthen ML models in practice.

Methodological Approach

The data quality framework developed in this project spans the entire ML lifecycle, from data acquisition to model deployment. It identifies leverage points where data quality issues most strongly affect model reliability and provides guidance on how to address them.

To validate the framework, it was applied to a solar irradiance forecasting task. This use case reflects a highly relevant challenge for renewable energy integration, where variability and uncertainty strongly impact grid operation. LSTM networks and other ML methods have been shown to provide effective and accurate forecasts for energy time series, such as power load (Tang et al., 2019), making them suitable for this use case. Within this context, several data quality measures for sensor data were defined to quantify characteristics such as accuracy, precision, and timeliness. In addition, a robustness analysis was carried out to assess how variations in data quality affect the performance of the ML model.

Results and Contributions

The project provides the following contributions to trustworthy ML in grid operation:

- A data quality framework applicable across the ML lifecycle, with clear leverage points for intervention.
- A validation of the framework through its application to solar irradiance forecasting, demonstrating its practical relevance and showing how ML model trustworthiness is affected by variations in data quality.
- A set of data quality measures tailored to sensor data.

These results contribute to improving the resilience of critical energy infrastructures by enabling more reliable forecasting and decision support based on trustworthy ML models.

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Resilience in Marine RC Infrastructure: Global Structural Performance under Depth-Dependent Corrosion

Rishwanth Darun Annamalaisamy Sannasiraj[1,2 *], Shuangmin Shi[1], Xuemei Liu[1], Konstantinos Gryllias[2], Dirk Vandepitte[2], Dimitrios Chronopoulos[2], Lihai Zhang[1]

[1] Infrastructure Protection and Management, Department of Infrastructure Engineering, The University of Melbourne, Australia

[2] Mecha(tro)nic System Dynamics (LMSD), Department of Mechanical Engineering, KU Leuven, Belgium

[*] Presenting author (rishwanthdarunas@gmail.com, rannamalaisa@student.unimelb.edu.au)

Abstract

Marine Reinforced-Concrete (RC) structures are prone to severe corrosion that demands comprehensive modelling against operational impacts to mitigate risks and enhance structural safety. In this work, the key novelty addressed is to quantify how Depth-Dependent Corrosion (DDC) reshapes dynamic characteristics and service-life margins compared with uniform corrosion assumptions clarifying when traditional practice over- or under-estimates resilience. Industry practices that design the structures considering most corroded splash region, uniformly across the zones is very conservative. It clearly under-estimates the service life of the structure by more than 25%. Implementing and understanding DDC is important to develop inspection/retrofit strategies and identify to provide timely interventions enhancing structural resilience and robustness.

Keywords: Reinforced Concrete pile; Marine corrosion; Vessel Impact; Structural degradation; Service life

Introduction & Motivation

Marine reinforced-concrete (RC) piles are key structural elements in ports and harbours that must absorb frequent, uncertain lateral impacts from tugs, barges and service vessels while they deteriorate in a harsh marine environment (Dacuan et al., 2020; Guo et al., 2018; Shao et al., 2023). Most design checks still adopt uniform or piecewise-constant corrosion allowances (*BS 6349 (Part 4) Maritime Works: Code of Practice for Design of Fendering and Mooring Systems*, 2014; Navarro et al., 2019; Thoresen, 2018) (determined through experience and practice; and as suggested in industry design handbooks) and static, time-invariant sectional properties, which can hide the coupled evolution of mass, stiffness and capacity changes that governs dynamic impact performance. It important to note that depth-dependent corrosion (DDC) which varies along the atmospheric, splash/spray, tidal and submerged zones must be

considered into the dynamic model, to make more meaning when addressing the structural robustness and assessing resilience capacity i.e., maintaining/recovering as berthing impact hazards and ageing which are time-dependent and zone-varying.

Methodology, Objectives & Contribution

A time-dependent multi-degree-of-freedom (MDOF) cantilever model for a circular marine RC pile is developed and proposed that

(i) updates mass and flexural rigidity/effective stiffness with year-by-year, based on zone-specific corrosion.

(ii) Simulates lateral vessel impacts using impulse-force histories and modal superposition; and

(iii) Evaluates global performance/resilience through peak top displacement, base moment demand versus capacity, and modal properties (stiffness, frequency, period) across a 50-year designed service life period.

Figure 1 shows the developed structural service life prediction framework of marine RC structures and presents the developed model for assessing integrity and robustness of the piles against lateral impact loading.

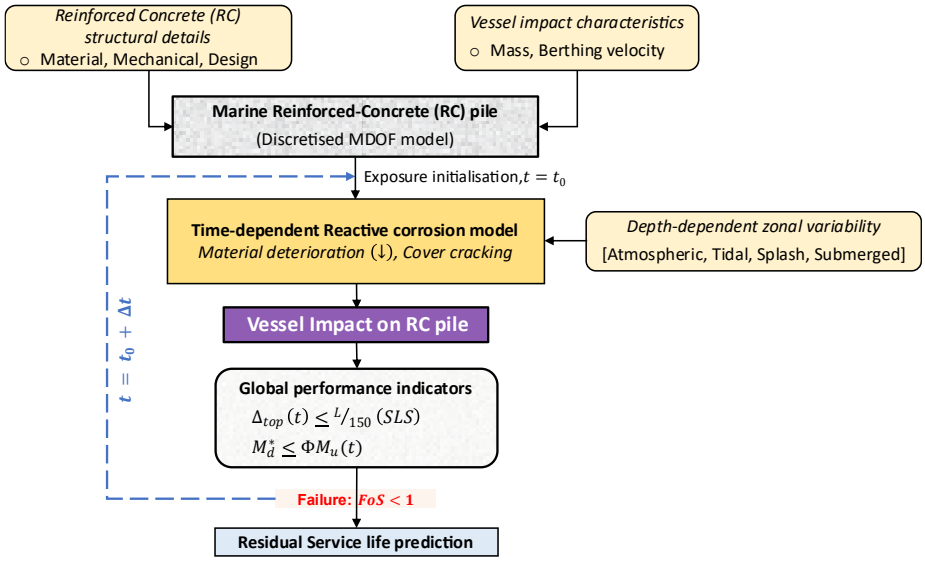


Figure 1: Structural service life framework

MDOF Structural model

A multi-degree-of-freedom (MDOF) cantilever pile column model is developed based on Euler–Bernoulli beam principles with 2 DOF per node (lateral, rotation), assuming fixed base at seabed. Time-dependent global matrices are assembled from element-level $EI_{eff}(y,t)$ and mass per node $m_n(y,t)$ through direct stiffness method (Baxter et al., 2005; Bradshaw et al., 2006). Hydrodynamic inertial mass effect is considered for submerged nodes. Figure 2 provides a graphical representation of the developed discretised MDOF model.

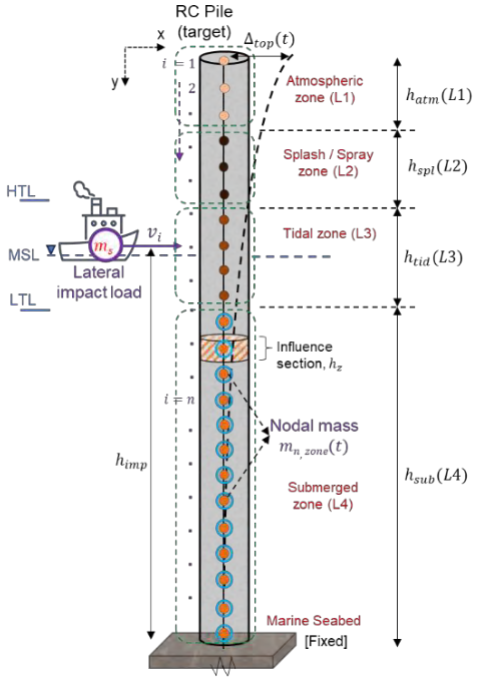


Figure 2: Discretised MDOF dynamic model under lateral vessel impact

Depth-dependent corrosion (DDC)

Depth-dependent corrosion is dependent on the marine exposure environment varying along the zones (atmospheric, tidal, splash, submerged) with changes in surface concentrations of chloride, sulphate available from seawater; carbon-di-oxide, wind, temperature, humidity levels in the coastal atmosphere; and tidal periods at that specific location. A fully coupled multi-ion reactive corrosion model (Annamalaisamy Sannasiraj et al., 2025) is adopted and the corrosion factors influencing the material deterioration of concrete and steel is considered.

Vessel impact loading

The berthing impact of the vessel is represented through a contact force model following half-sine slicing generating impulse across the contact time (Baxter et al., 2005; Chopra, 2022), energy absorption attributes via coefficient of restitution (Yuan et al., 2008; Yuan & Harik, 2008), loads applied at an impact elevation near MSL. Responses are reconstructed by modal superposition using mass-normalized eigenvectors of $[K(t)]$, $[M(t)]$.

Table 1: Impact Vessel parameters

Vessel Type	Mass DWT	Impact Berthing Velocity (m/s)	Contact duration (s)	Coefficient of Restitution COR
Tug/ Harbour Assist / Service Barge	150 – 250 (**200**)	0.4 - 0.8 (**0.8**)	1.2 – 1.5 (**1.2**)	0.15 – 0.3 (**0.20**)

* Adopted value is indicated within ()

(*Guidelines for Design of Marinas (AS 3962)*, 2001; *PIANC - Guidelines for The Design of Fenders System*, 2002; *Planning and Design of Ports and Harbours - Code of Practice - Part 3 Loading (IS 4651 (Part 3) : 2020)*, 2020)

Global Service life performance metrics

Structural resilience capacity is assessed based on the performance against global damage thresholds. Due to time-varying material deterioration due to corrosion there is varying section capacity reduction which alters the flexural rigidity and stiffness parameters.

- **Section capacity:** $M_u(t)$ at the base and zone-weighted average, from corrosion-updates A_s, f_y, f_c'. Reduction of >20% may result in plastic hinge formation.
- **System stiffness/flexural rigidity**: $\sum EI(t)$
- **Top displacement:** $u_{top}(t)$ and its yearly peak due to isolated impacts is compared against serviceability limit state (SLS) (*Guidelines for the Design of Maritime Structures (AS 4997:2005)*, 2005)
- **Base moment demand:** $M_d^*(t)$ generated due to the lever arm of peak impact forces and the dynamic response envelope.

A simple resilience model with ease of interpretability can be denoted through Factor-of-Safety (FoS) metric. The threshold values >1 imply serviceable, capacity-adequate performance under the selected impact scenario, trajectories of map resilience attrition or recovery under mitigation.

Case Scenario

We illustrate the framework with the baseline pile through in-house developed MATLAB implementation (1.0m diameter, 10m Pile depth above seabed, 20mm longitudinal steel reinforcement and 65mm cover; 5m submerged zone, 2m tidal variation, 1m above as spray/splash zone, 2m exposed top) and 50-year marine zonal corrosion histories through our previous depth-dependent corrosion study. Impacts reflect harbour tug/service barge conditions (see Table 1) (Sha & Hao, 2013), with sensitivity tests on impact momentum and COR to explore hazard intensity versus ageing.

Key Findings

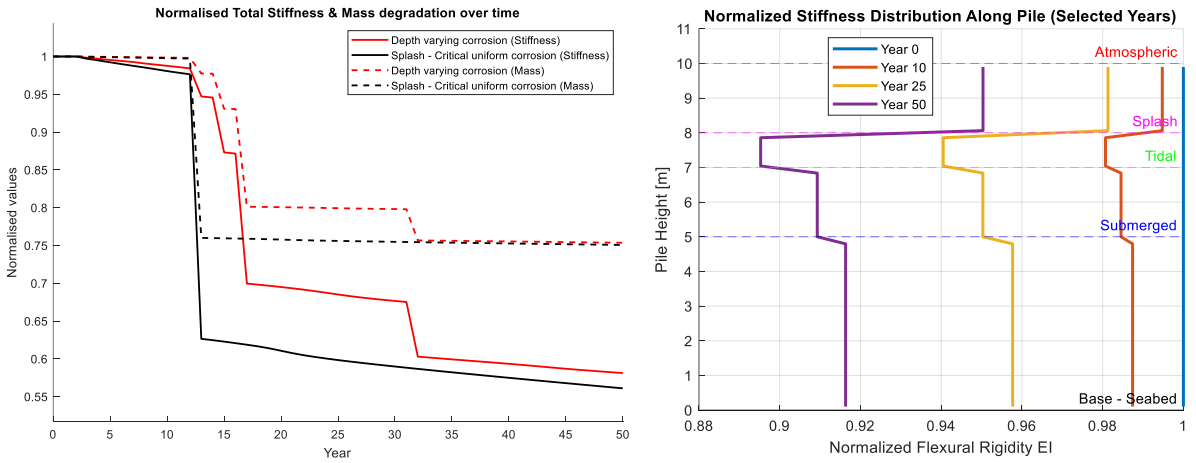


Figure 3. Normalized degradation over time (i) Total Stiffness & Mass (ii) Stiffness distribution across zones for DDC

- **Dynamic softening is zone driven.** Splash/tidal degradation, and especially cover spalling near the impact elevation, accelerate *EI* loss locally (Figure 3), which

propagates to lower modal frequencies and longer periods—increasing amplification under certain contact times.

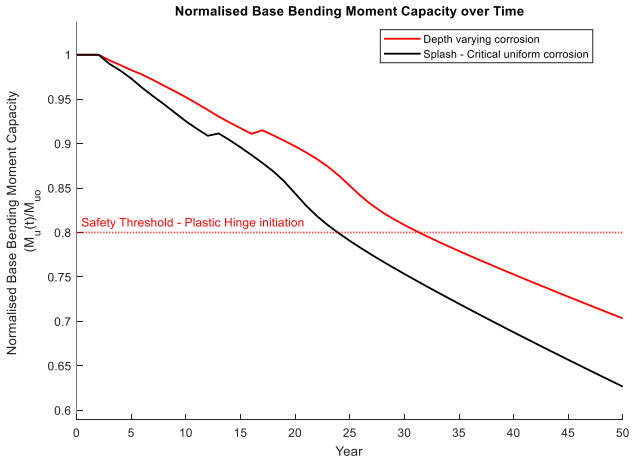


Figure 4: Degradation of Flexural Bending Moment capacity at base over time

- **Uniform corrosion can mislead.** Treating corrosion uniformly tends to over-predict global displacement when deterioration is concentrated near the impact zone (more flexible "hinge" forms) yet may over-predict when loss is mostly submerged (added mass masks stiffness loss).
- **Resilience trajectories matter, not single snapshots.** Often declines non-linearly: periods of rapid drop align with cover cracking/spall transitions and frequency plateaus. These change the graceful extensibility of the system—less margin to absorb higher-momentum impacts without failure—highlighting maintenance windows for timely intervention.
- **Factor of Safety (FoS) & thresholds:** Figure 5 clearly represents RC pile fails in flexure moment before the it reaches the serviceability criteria due to dynamic amplification of vessel force under impact.

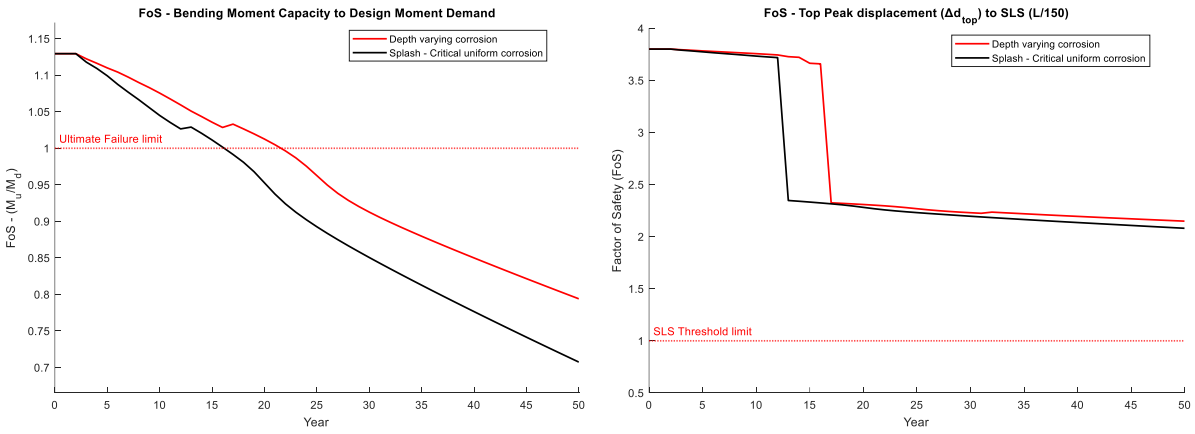


Figure 5: Factor of Safety (FoS) of (i) Flexural capacity to Moment demand (ii) Peak top lateral displacement to Serviceability limit

Discussion & Conclusion - Implications for resilient design & management

- **Why DDC?** Incorporating realistic vertical corrosion profiles into dynamic analysis reveals when and where performance wears down, enabling targeted protective systems (e.g., enhanced splash-zone durability, wrap/fender protection) instead of blunt uniform allowances.
- **Impact-aware ageing curves:** Coupling contact-time spectra (from berthing/traffic return period) with evolving modal properties offers a hazard–age alignment view—key to resilient operations scheduling and inspection prioritization.
- **Simple system-level indicator:** Safety factor provides a transparent resilience check (SLS and ULS) that practitioners can track alongside code limits; it clarifies over-/under-estimation introduced by uniform corrosion assumptions.
- **Transferability:** The formulation generalizes to other marine RC elements (piers, dolphins) and can assimilate field data to update $EI_{zone}(y,t)$ in service.

Acknowledgements

This research is part of the Joint Doctoral project between the University of Melbourne and KU Leuven as part of the KU Leuven Global PhD Partnerships program (GPUM/22/018). Travel fundings from both institutions is gratefully acknowledged.

Expected contribution to ICRS'26

The work contributes to Marine Infrastructure (ageing, shocks, and adaptive design) and to Resilience assessment methodologies (a modelling and indicator framework that integrates environmental degradation with dynamic hazards). We present a workflow (figures/tables of displacement, frequency/period, stiffness histories, and over 50 years) and discuss implications for inspection/retrofit strategies under port-structure-environment specific impact spectra.

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Optimization of temporary and demountable flood protection strategies for resilient infrastructure systems

Fulvio Lopane[1], Richard Dawson[2]
1 Northeastern University London, London, UK and Centre for Advanced Spatial Analysis, University College London, London, UK, f.lopane@northeastern.edu & f.lopane@ucl.ac.uk
2 School of Engineering, Newcastle University, UK, richard.dawson@newcastle.ac.uk

Abstract

Infrastructure systems deliver critical services. Extreme weather events, particularly flooding, can severely disrupt these services. Temporary and demountable flood protection (TDFP) offers a flexible way to safeguard individual infrastructure assets, especially where permanent defenses are impractical. Due to budget constraints, TDFP are typically stored centrally and deployed to multiple infrastructure assets, making warehouse location a critical factor in minimizing costs and maximizing coverage. To address this complex spatial challenge, a Spatial Resource Allocation Optimization (SRAO) framework using a Genetic Algorithm has been developed and tested in the Humber Estuary, UK. The SRAO identifies optimal deployment strategies across various scenarios, achieving up to 50% cost savings and significantly reducing deployment times. It also highlights eight robust "hotspot" warehouse locations that perform consistently well despite model uncertainties. This approach offers immediate value to local authorities, infrastructure operators, and emergency planners—enhancing flood resilience while reducing financial burdens for the communities they serve.

Keywords: spatial optimization; emergency management; resilient infrastructure; temporary flood protection

Introduction

Infrastructure networks—such as power, telecoms, transport, water, finance, and emergency services—are vital to society (Dawson et al., 2018). Flood management often prioritises protecting people, yet damage to infrastructure can disrupt essential services for hundreds of thousands beyond the flood zone (Arrighi et al., 2021; and Merz et al., 2021). Resilient systems anticipate shocks and improve recovery, making investments in resilience more cost-effective and sustainable (Baral and Shahandashti, 2022).

Permanent flood protection for all assets is rarely feasible. Temporary and demountable flood protection (TDFP) offers a flexible, lower-cost alternative (Booth and Gleed, 2024), but presents logistical challenges: it requires advance warning, is bulky to store and transport, and infrastructure assets are widely dispersed with access routes prone to flooding. These constraints create trade-offs for decision-makers, who must balance cost, coverage, and

deployment speed to minimise disruption. Strategic planning is essential to optimise resilience and ensure critical services remain operational during flood events.

Spatial Resource Allocation Optimization

To address this combinatorial problem, a Spatial Resource Allocation Optimization (SRAO) framework has been developed. Initially applied to optimize health resources (Lopane et al., 2023) it has been adapted for infrastructure resilience.

The SRAO comprises six key components: (1) The algorithm first processes input data and generate an initial population of potential solutions. The Iterator (2) includes three components: (2a) Three genetic mechanisms of selection, crossover, and mutation to efficiently explore and evaluate the parameter space; (2b) Problem-specific limitations and rules that ensure only feasible solutions are retained; and, (2c) at each iteration the set of non-dominated solutions, the Multi-Objective Pareto Optimal (MOPO) set is updated and stored. In the final phase (3) the SRAO returns a set of optimal solutions as the result of the search process.

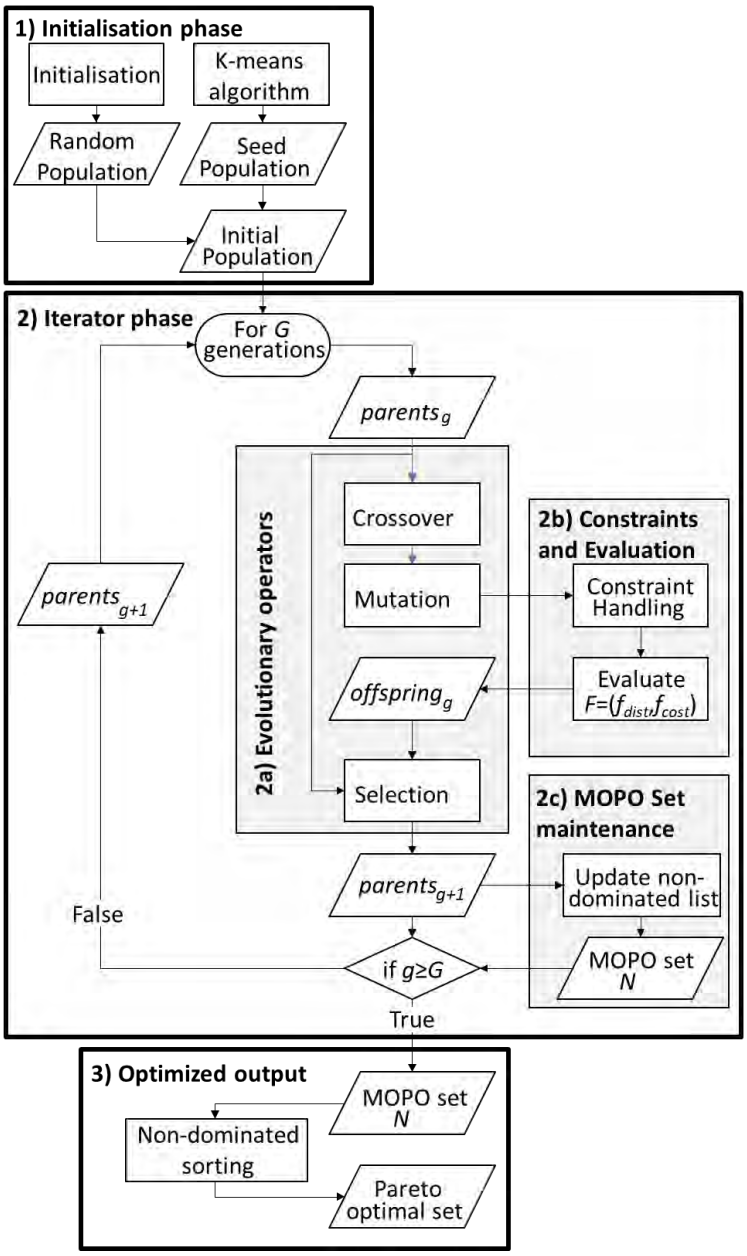


Figure 1. Overview of the Spatial Resource Allocation Optimization framework.

Case Study

The SRAO framework is applied to the Humber Estuary, on the East coast of England. Over 400,000 people live in the region, which also contains 133 strategic infrastructure assets.

The objective of deploying TDFP is to maximise the speed with which it can be deployed at the lowest cost. Here this is achieved through two fitness functions, f, which seek to minimise the time of travel from the storage site(s) to the infrastructure asset(s), f_{dist}, and to minimise the cost of the TDFP storage, f_{cost}. Travel time, f_{dist}, is calculated on the basis of the time taken to travel along the route between the warehouse and infrastructure asset, and the number of lorries available to each warehouse. Travel time therefore increases with fewer warehouses or fewer lorries. The cost, f_{cost}, incorporates the cost of building and operating a warehouse, including personnel costs, fleet costs, and maintenance costs (Ramos, 2017, Mishra, 2021).

A large number of scenarios and assumptions have been tested. These include varying the number of warehouses across the region; the availability of land for development; the number of lorries available at each warehouse to transport TDFP to infrastructure sites; prioritizing infrastructure on the basis of customers served; budget constraints.

Key findings

Figure 2 shows an indicative set of results for a scenario. Analysis of a wide range of scenarios and strategies shows that TDFP offers flexible flood defence for infrastructure assets, especially where permanent solutions or on-site storage are impractical. Shared storage sites that protect multiple infrastructure locations reduce costs but increase deployment time and risk greater disruption from flooding.

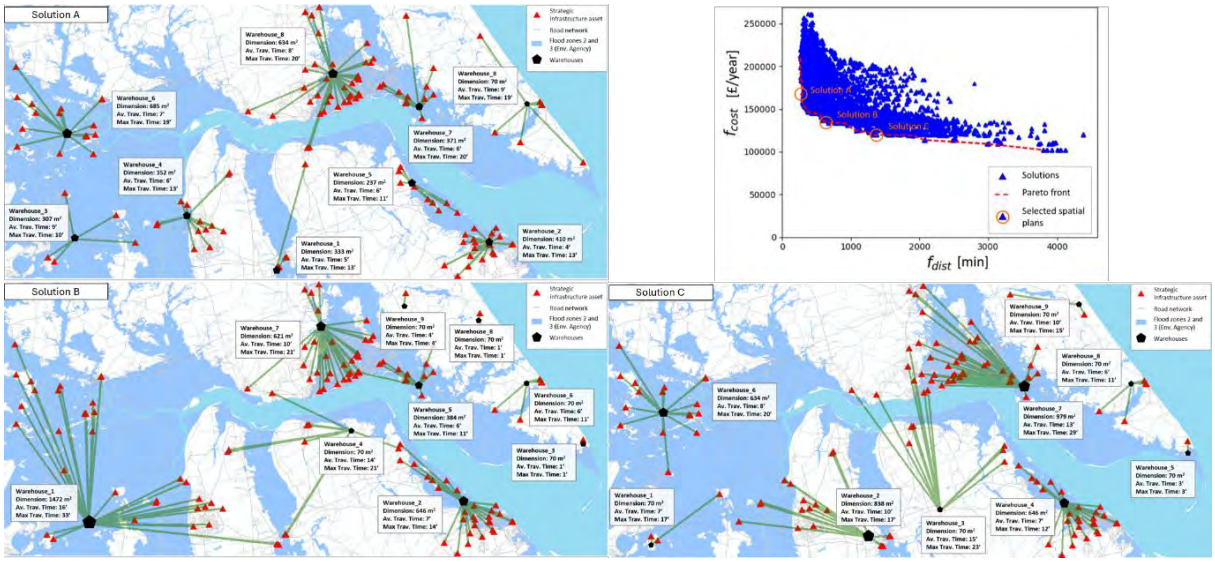


Figure 2. Indicative result for a scenario where each warehouse has one lorry available to it, and all infrastructure sites are weighted with equal importance. Three solutions from the pareto front are visualized showing proposed warehouse sites, their size and assets they cover.

The SRAO identifies strategies that halve costs and cut deployment time tenfold. For scenarios where budgets are critically constrained, limiting the number of assets that can be protected, between 20–37% of people remain susceptible to infrastructure disruption. Analysis of all scenarios demonstrated that eight warehouse locations consistently performed well, demonstrating the ability to identify strategies that are robust to a wide range of assumptions and future conditions.

Future improvements to the SRAO will consider the implications of differential hazards, the dynamics of transport behavior (e.g. using Pregnolato et al., 2016), and incorporation of other costs, impacts and scenarios. Moreover, as decisions on the allocation of flood protection are often taken at national scale further work will also increase the spatial scale of the study.

Acknowledgements

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From Risk to Resilience: Assessing Geophysical and Climate Vulnerability and Adaptation Strategies for Transport Infrastructure in the Middle Corridor

Sadhana Nirandjan1, Elco E. Koks1, C. Colon2, D. Luzzati2,3, E. Espitia4, J. Rozenberg4
Affiliations 1. Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam, 1081HV Amsterdam, the Netherlands 2. International Institute for Applied Systems Analysis, Laxenburg, Austria 3. International Finance Corporation, World Bank Group 4. The World Bank Group, Washington DC, USA

Abstract

The Middle Corridor (MC) is emerging as a strategically important Eurasian transport route, yet its infrastructure faces significant risks from floods, earthquakes, and landslides. This study assesses current and future exposure and risk to railway and road networks using high-resolution hazard, infrastructure, and vulnerability data. This is followed by a corridor-wide cost–benefit analyses (CBA) to evaluate the economic justification of adaptation measures. Results show that pluvial flooding and earthquakes dominate current risks, while landslides are locally critical. Future scenarios indicate increasing flood and rainfall-triggered landslide risks, particularly in Armenia and Georgia. Targeted upgrades and protective measures can substantially reduce damages, highlighting the importance of proactive adaptation to ensure long-term climate resilience and continuity of trade along the MC.

Keywords: Middle Corridor; Climate risks; Adaptation

1. Introduction

The Middle Corridor (MC) has gained strategic importance as a Eurasian trade route, particularly since the Russia–Ukraine war increased demand for alternatives to the Trans-Siberian line. Transport volumes are rising, yet the MC currently handles only 5–10% of the Northern Corridor's capacity (Vasa & Barkanyi, 2023; Walter, 2022), reflecting persistent infrastructure, operational, and geopolitical constraints that require sustained investment and cooperation (Rentschler et al., 2025). At the same time, the impacts of natural hazards on the MC remain unaddressed, though they are critical to consider as today's infrastructure decisions will lock in risks for decades to come.

This study evaluates the exposure and risk of the MC's road and railway infrastructure to climate-related and geophysical hazards, combining asset-level data with hazard and vulnerability information. We then conduct a CBA for the MC, identifying network sections where upgrading is economically justified based on avoided direct damages.

2. Methodology

We conduct a comprehensive assessment of the current and future exposure and risk of the transport networks in the ECA region to floods, landslides and earthquakes. Using detailed railway data and hazard datasets combined with vulnerability datasets, we quantify risk in

terms of Expected Annual Damage (EAD), derived from exceedance probability curves linking damages to hazard probabilities.

Flooding is represented by the Fathom V3.0 dataset, including eight return-period maps (1/5–1/1000) at 30 m resolution, with defended historical conditions and two future scenarios (SSP3, SSP5) for 2050 and 2080. Earthquake hazard follows the GIRI maps (Palau et al., 2023), expressed as Peak Ground Acceleration for five return periods (250–2,475 years, ~500 m resolution), combined with liquefaction susceptibility classes (Zorn & Koks, 2019). Landslide is based on GIRI's susceptibility maps (~90 m resolution) for current rainfall and earthquake-triggered landslides, and future rainfall-triggered landslides under SSP1-2.6 and SSP5-8.5, in combination with information on hazard-triggering conditions.

The transport network is derived from OpenStreetMap (OSM) in combination with internal data. Vulnerability estimates (Nirandjan et al., 2024) and construction values from the World Bank and Asian Transport Outlook underpin the risk modeling, expressed in constant 2020 USD.

Investing in the improvement and maintenance of infrastructure can significantly reduce the probability of damage. In this extended abstract, we present preliminary CBA results for railways in Georgia, with plans to extend the analysis to the entire MC. For flooding, we assume that the damage probability for railway tracks can be reduced from 3% to 1% through railway track upgrades.

3. Preliminary results

The MC railway is exposed to multiple hazards, with pluvial flooding accounting for the largest share (43.5%), followed by earthquakes (37.3%) and fluvial flooding (15.1%). Landslides and coastal flooding contribute only marginally. The estimated annual risk amounts to USD 34.7 million for railways and USD 92.7 million for roads (Figure 1). At the national level, flooding dominates risk in most countries, while earthquakes are the primary hazard in Uzbekistan and a major contributor in Kyrgyzstan. Landslide risk is also highest in these two countries, and is the main contributor to road risk in Kyrgyzstan.

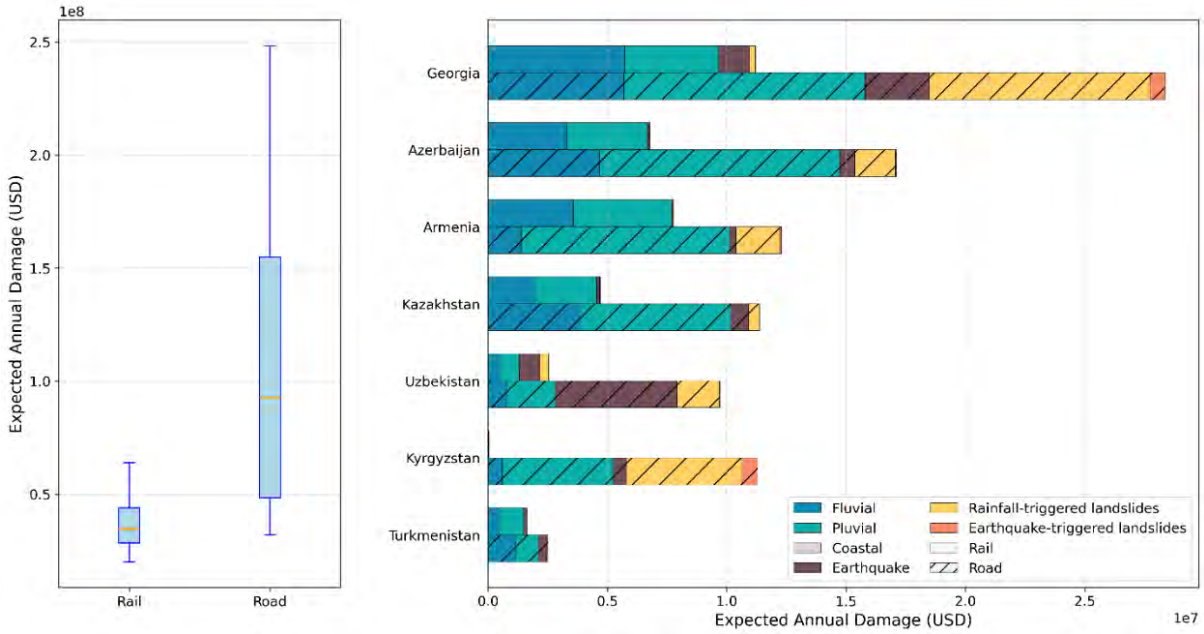


Figure 1. The EAD to the MC railway and the road network relevant for the MC from multiple hazards per country is shown in panel A. Panel B shows the absolute median risk from these hazards.

Flood-related risks, particularly due to pluvial and coastal flooding, to the MC are projected to rise under future climate scenarios. Combined road and rail flood risk amounts to USD 92.3 million under historical conditions, increasing to USD 106–111 million by 2080 under both SSP3-7.0 and SSP5-8.5. The distribution of this risk varies widely across countries and flood types (Figure 2). Rainfall-triggered landslide risks also increase. Total damages rise from USD 20.6 million historically to USD 22.0 million under SSP1-2.6 and USD 25.4 million under SSP5-8.5.

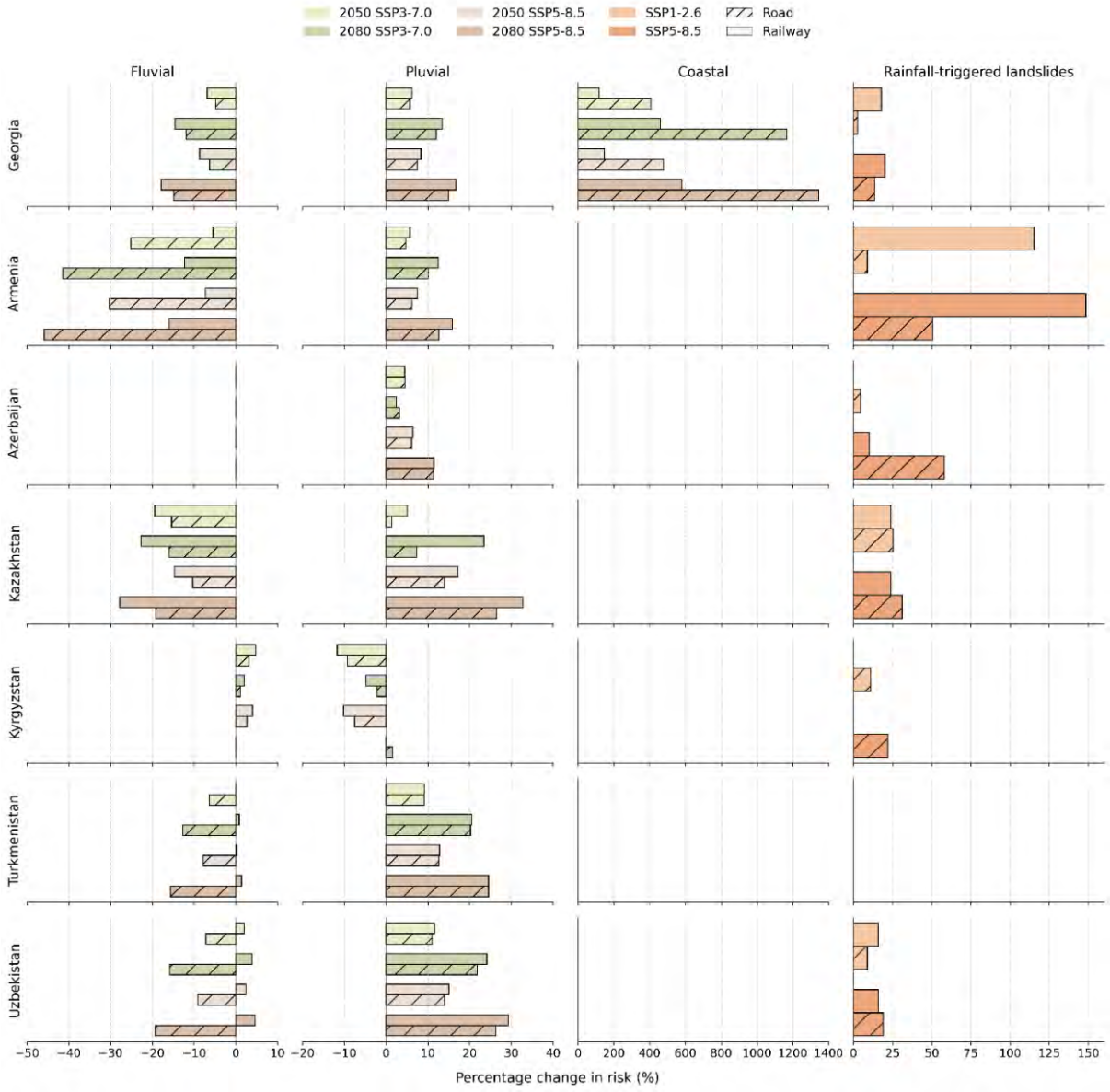


Figure 2. The relative change (%) in road and rail risk for the MC due to fluvial, pluvial, and coastal flooding, as well as rainfall-triggered landslides, across Middle Corridor countries under various future climate scenarios.

Upgrading proves economically viable for 33.4% of the Georgian railway network exposed to flooding (Figure 3). Upgrading 838 km of the railway network, where Benefit-Cost Ratio (BCR) values indicate a positive return, would require an investment of approximately USD 25.2 million and is expected to reduce annual flood-related damages to USD 10.7 million. The total discounted benefits over 15 years is USD 103.7 million.



Figure 3. Spatial distribution of railways in Georgia prioritized for improvement based on economic viability, assuming an investment of 3% of the construction costs, 6% discount rate and a lifetime of 15 years.

4. Discussion and conclusion

The MC railway and road infrastructure face substantial risks from floods, earthquakes, and landslides. Current exposure shows that pluvial flooding and earthquakes dominate the profile, while landslides are highly localized but can be critical for specific segments, particularly in Kyrgyzstan and Uzbekistan. Future climate scenarios indicate a clear upward trend in flood- and rainfall-triggered landslide risks across the MC, whereas the distribution of this risk varies widely across the countries and hazard types. Our study highlights the importance of incorporating hazard assessments into infrastructure planning, as neglecting hazard exposure and risk can lock in long-term vulnerabilities. The CBA suggest that targeted upgrades and protective interventions can substantially reduce risk, offering an economically justified path to enhancing corridor resilience. Overall, risk varies significantly across countries and hazard types, requiring context-specific strategies for effective risk management.

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Climate Risks for Inland Ports: A Two-Level Analysis in the Upper Rhine Region

Klose, Anna[1], Albiez, Daniela[1], Lückerath, Daniel[1], Hömberg, Jakob[1]
1 Fraunhofer IAIS, Germany, anna.klose@iais.fraunhofer.de, daniela.albiez@iais.fraunhofer.de, daniel.lueckerath@iais.fraunhofer.de, jakob.hoemberg@iais.fraunhofer.de

Abstract

Inland ports are essential infrastructure hubs connecting waterway, railway and road. Climate hazards pose severe threats to ports and will intensify over the coming decades. This paper presents the co-development and application of a risk analysis for upper Rhine ports. Risks are analysed for single infrastructure elements and whole port processes. This is a key element for adaptation planning as it allows prioritizing the adaptation of a system element not only based on its own risk, but also on its importance for port operations.

Keywords: inland ports; climate risk analysis; upper Rhine region; EU taxonomy

Introduction

Climate change is a significant threat to the stability and functionality of critical infrastructure systems. Inland ports are of vital importance for transport networks as they connect waterways, railways, and roads. Their positioning and operational dependencies make them particularly vulnerable to impacts from climate change and extreme weather events, including flooding, drought, infrastructural degradation, and disruptions to logistical networks. Consequently, there is a need to systematically identify how climate hazards threaten port operations and develop evidence-based adaptation strategies allowing to increase resilience. There is a need for a viable analysis method for port operators as existing assessment frameworks fall short in considering the specifics of ports.

This project develops such a method with seven ports from France, Germany and Switzerland in the Rhine region. The approach is adapted from methods of the German Environment Agency (Dorsch, 2023) and compliant with the EU taxonomy.

Risk Analysis

The risk analysis is structured in three main steps (Figure 1) to systematically evaluate risks on different levels, thereby incorporating co-created expert estimates as well as climate projections. The method was developed in two-phases: (i) prototype development with a first group of three ports and (ii) validation with the remaining four ports. The analysis started out with a co-identification step, in which port staff identified: 1) relevant system elements (resulting in 49 elements), 2) key port processes (18 processes; not all relevant for all ports), and 3) relevant climate hazards (heatwaves, droughts, low water, floods, storms, heavy

precipitation, land subsidence). Climate profiles were created for each port that depict hazard indicators and their future development in three timesteps based on climate and hydrological projections under the RCP8.5 scenario. Risk was analysed on two levels. First, present and future risk levels for individual system elements were assessed under different hazards, resulting in risk matrices combining vulnerability and climate hazard. Second, risks to port processes were assessed by combining system element criticality for processes and the element's risk level. The result is a process model indicating process risk and interdependencies between processes.

Risk Analysis Results

At the system element level, heatwaves, low water, floods, and heavy rainfall cause the majority of "high risk" classifications. Across all ports *heatwaves* lead to high risks for rails and switches due to deformations. Technical installations (e.g. signals) are at high risk from heatwaves due to insufficient insolation. Personnel are also at risk from heatwaves, especially outdoor workers. The Rhine and its tributaries are at high risk from *low water*: restricted navigability means ships cannot reach or leave ports. Similar high risks arise from *floods*, damaging equipment located in basements or on ground floors and subsequently disrupting operations. Dangerous goods transhipment facilities are also at high flood risk due to disruptions. *Heavy rainfall* causes high risks for older buildings and stored equipment, e.g. from water leakages through roofs. In addition, sewage disposal systems are at high risk due to insufficient capacity or clogging. Apart from these common system element risks, several elements feature high risks in individual ports based on the local situation, e.g. an element's location relative to the Rhine or its constructive details.

Based on the system element risks and their criticality for port processes, some processes commonly at high risk in all ports can be identified. First, "arrivals and departures via ship" are at high risk due to low water and flood. Both hazards lead to limited accessibility of the ports. Furthermore, handling of dangerous goods emerges as a high-risk process due to floods, resulting from high risks to dangerous goods transhipment facilities. Handling of cars, machines and vehicles is at high flood risk, based on risk and criticality of the in-port transport facilities (roads, railways, waterways). A medium risk level is reached in all ports for cross-cutting processes (e.g. emergency management, maintenance and services) from heatwaves, droughts, low water, and land subsidence due risks to staff and technical installations.

Although system elements exhibit high risks from heavy rainfall, this does not trace to the process level. This is because the ports let most of their property for rent to industry. Subsequently, while system elements have a high heavy rainfall risk, they do not exhibit a high criticality for port processes and thus exhibit no high process risks – even if they are vital for the tenant.

Conclusion

The risk analysis for inland ports focusses on two levels, the system element and the process level, and is compliant with the EU Taxonomy. The approach allows the identification and prioritisation of risks based on their relevance for port processes. Although there are

considerable differences among the ports due to local settings, system elements and processes commonly at high risk, now and in the future, could be identified.

The implementation of adaptation measures is of vital importance to build resilient infrastructure that can cope with the effects of climate change. Given limited personnel and financial resources, the results of the risk analysis will be used in the next project phase to prioritise and plan adaptation measures, helping the ports to ensure their continued contribution to economic, societal, and environmental objectives in a rapidly changing climate.

Figures

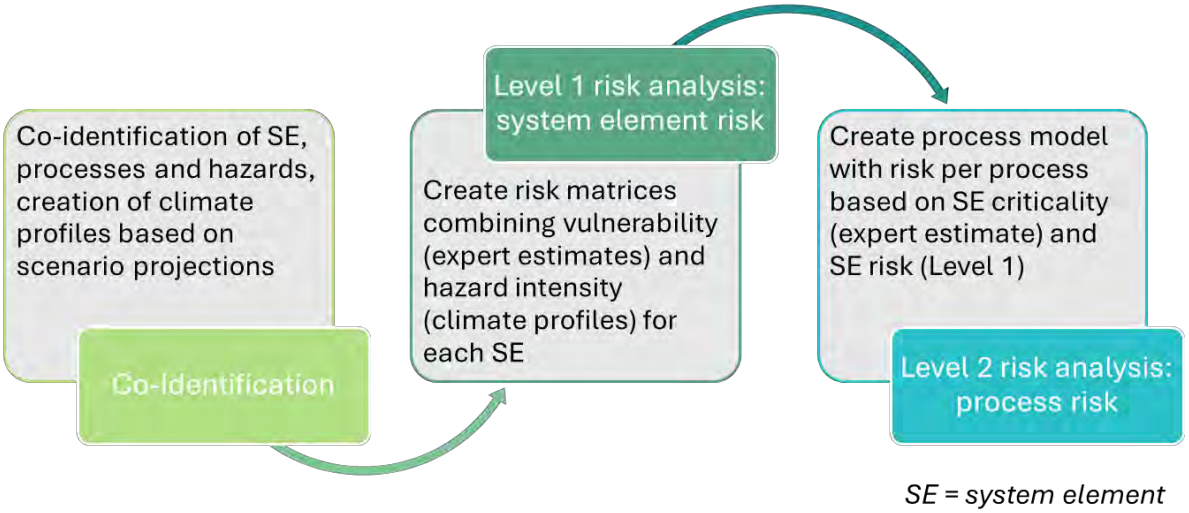


Figure 1: Main steps of the two-level risk analysis method

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Quantifying System Limits: Flood-Oriented Stress Testing for Adaptive Risk Governance

Jens Reinert, Paul Christian Hassenjürgen, Alexander Menz, Elena-Maria Klopries
Institute of Hydraulic Engineering and Water Resources Management, RWTH Aachen University, Germany,
reinert@iww.rwth-aachen.de

Abstract

As climate change speeds up the frequency and intensity of short-term extreme rainfall events across Central Europe, traditional flood risk management methods based on historical return periods and fixed design thresholds are becoming less effective. The July 2021 flood disaster in Germany exposed the failure of infrastructure under multiple stressors, including saturated soils, blocked culverts, and delayed responses. This situation calls for a shift toward more dynamic, diagnostic, and proactive assessment methods. In this context, Flood-Oriented Stress Testing (FLOOD-ST) is introduced: A scenario-based stress testing framework to evaluate system limits and identify hidden vulnerabilities in flood-prone areas.

Keywords: Stress testing; flood risk management; hydraulic modeling; compound scenarios; system resilience

Introduction

Traditional flood risk assessments are grounded in the assumption of stationary hydrological behavior and focus on compliance with regulatory thresholds (such as HQ_{100} design flood). However, recent flood events across Central Europe illustrate the failure of systems even when water levels remain within design parameters (Lehmkuhl et al. 2022). Systemic vulnerabilities, such as cascading failures from power outages, undersized culverts, or delayed pump activations, are rarely captured in conventional hazard maps and management plans (?). As recent research suggests, resilience must be understood not just as resistance to hazard levels, but as the ability to sustain system functionality under compound and uncertain stressors (Kreibich et al. 2022).

In this context, scenario-based stress testing offers a promising approach. Borrowed from sectors such as finance and energy, operational stress testing seeks to uncover limits in real-world performance rather than theoretical thresholds (Tsionis et al. 2016; Linkov et al. 2022). Applied to flood risk management, this approach enables a realistic diagnosis of system

behavior under combined loads, shifting the focus from deterministic protection to systemic foresight.

Framework and Methodological Structure

FLOOD-ST (Flood-Oriented Operational Stress Testing) is a modular, platform-independent framework that combines synthetic rainfall archetypes, soil moisture classes and infrastructure parameters to simulate critical stress conditions. Its methodological core comprises four components: (i) selecting regionally plausible rainfall scenarios based on evolving European storm patterns; (ii) modeling catchment states under different antecedent soil moisture conditions (dry, average, wet); (iii) incorporating operational stressors such as pump failures, culvert blockages or retention basin overflows; and (iv) system diagnostics using impact indicators like flood extent, peak discharge and failure triggers. The framework features two simulation stages: a baseline system run without infrastructure failures, and a detailed run that includes key operational stressors and operational logic. This enables users to distinguish between topographic runoff patterns and infrastructural bottlenecks. Use cases include modeling local backwater effects caused by undersized culverts, timing emergency pumping operations, and assessing the response of retention systems near failure. In practice, the diagnostic strength of FLOOD-ST lies in its capacity to identify system tipping points across a range of complex scenarios, rather than focusing on single-event exceedances.

Application, Policy Relevance, and Future Directions

FLOOD-ST has been tested in various urban and peri-urban areas across Central Europe. For example, in a densely populated tributary catchment of the Emscher River, stress tests simulated severe events combining stationary cloudburst (120 mm in 6 hours) with wet conditions beforehand, pump failure, and culvert blockage. Each scenario revealed different weaknesses: pump failure increased surcharge risks, upstream blockages caused overtopping, and downstream congestion led to extensive backwater effects. These insights are directly useful for civil protection planning, infrastructure investments, and local flood management discussions.

Notably, FLOOD-ST promotes cross-sector collaboration. Stakeholders from engineering, emergency services, urban planning and public utilities can work together to develop stress scenarios and assess risks from multiple perspectives. This aligns with current policy frameworks, such as the EU Floods Directive and the UNDRR’s call for systems-based resilience governance (United Nations Office for Disaster Risk Reduction 2025). FLOOD-ST complements probabilistic models by providing a diagnostic perspective focused on practical failure pathways.

Moving forward, integrating FLOOD-ST into routine flood risk management cycles can help identify areas that need redundancy, design improvements or adaptive measures. Its flexibility allows use in both data-rich and data-scarce environments. As climate extremes become more common, tools like FLOOD-ST can enhance preparedness without necessarily predicting the next event.

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Integrating Extreme Event Attribution for the Resilience of Infrastructure Networks in the Hot Climate Conditions

Mohammed M. Al-Humaiqani[1], Mohammad Zaher Serdar[1], and Eyad A. Masad[1]
1 College of Science and Engineering, Hamad Bin Khalifa University (HBKU), Education City, Doha, Qatar

Abstract

Extreme climate and natural disasters have intensified globally, causing escalating damage and highlighting the urgency of resilient infrastructure. This challenge is particularly critical in hot regions like the Gulf Cooperation Council (GCC) Countries and the broader MENA region, where extreme and unusual events are becoming more frequent. Extreme Event Attribution (EEA) has emerged as a powerful scientific tool to quantify the influence of anthropogenic climate change on the intensity and frequency of extreme weather and climate events. While EEA offers valuable insights for forward-looking resilience strategies, its integration into civil infrastructure adaptation planning, particularly in interdependent critical infrastructure networks (CINs), remains limited. Most CIN models still rely on assumptions based on historical recurrence intervals, overlooking attribution-informed evidence of shifting hazard probability. The omission of such integration risks may lead to underestimating systemic vulnerabilities, particularly in hot climates such as in the GCC and MENA regions, where extreme stress puts infrastructure systems to their maximum operational capacity. This study explores this gap by synthesizing recent advances in EEA methodologies, examining their relevance for resilience modeling of CINs, and identifying approaches to include climate-informed adaptation. It also discusses the embedding of EEA outputs into CIN frameworks by synthesizing current knowledge on EEA methods, their applications in the infrastructure context, with a focus on hot climate conditions. The contribution of this paper lies in explicitly linking EEA science with infrastructure network-based resilience assessment in hot climate regions, providing a roadmap for researchers and policy development.

Keywords: Extreme Event Attribution; Extreme events; Climate Resilience; Critical infrastructure networks; Hot climate conditions

Introduction

Critical infrastructure networks (CINs), including energy, water, transportation, communications, drainage distribution networks, and gas distribution networks, form the lifelines of modern societies and are an essential propellant for economic stability [1]–[3]. Hence, the resilience of CINs against climate and weather extremes is essential for their survivability [4], [5]. This ensures they maintain their capacities and prevent destructive

cascades that affect interconnected systems such as the environment, economy, safety, security, and public health [3], [6]. The CINs are deeply interconnected; as such, the continuous provision of potable water, communication, and wastewater treatment cannot be sustained without an uninterrupted supply of energy. Electricity is the main driver of water supply, including desalination and pumping processes. Telecommunication systems require uninterrupted power to operate, while drainage systems are necessary for moving wastewater to treatment facilities or designated disposal sites. Furthermore, all modes of transportation systems depend on energy to ensure efficient mobility across the network. Similarly, the gas distribution network is also crucial for cities as part of the life support systems [7]. A failure in one sector can trigger cascading failures across other sectors, causing overall disruption on a large scale [8], [9]. In the GCC, this vulnerability is especially evident, as electricity consumption is heavily driven by cooling requirements and water security depends almost entirely on energy-intensive desalination [10].

Extreme Event Attribution (EEA) has emerged as a scientific approach to quantify the influence of anthropogenic climate change on climate and weather events [11]. EEA contributes to estimating how humans are influencing the likelihood and intensity of such climate and weather events. For example, attribution studies showed that climate change caused the 2022 European drought [12] and made the 2021 Pacific Northwest heatwave at least 150 times more likely [13]. These insights provide practical guidance for infrastructure planning by shifting from fixed design thresholds to probabilistic risk measures that account for a changing climate.

This paper examines current initiatives and efforts aiming to incorporate forward-thinking climate information into national building codes in the GCC and MENA region. The review will discuss the obstacles to the interpretation of climate model uncertainties into practical engineering design methods and establish approaches that utilize the projections to enable regular updating of design values and hazard maps. Furthermore, it will explore the formulation of standards for extreme events that are currently not reflected in existing design codes (Figure 1).

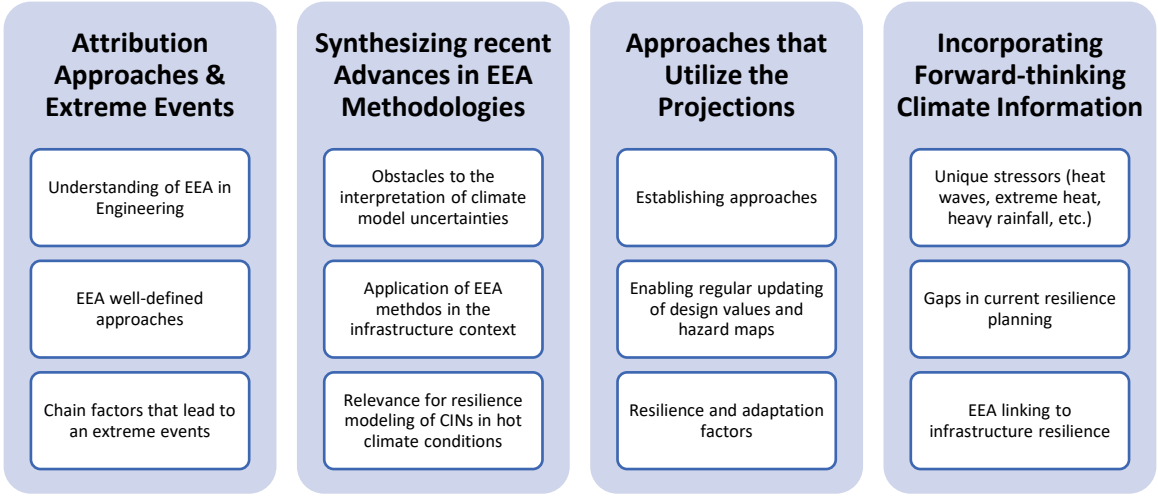


Figure 1. Systematic overview of the review conducted in this study.

EEA Methodological Approaches

EEA is generally based on comparing climate model simulations conducted with and without anthropogenic forcings [14]. EEA generally employs two complementary approaches: the risk-based approach and the storyline approach [13]. The risk-based approach employs probabilistic models that assess the likelihood of an event occurring under a counterfactual climate. Then it evaluates the anthropogenic influence by comparing simulations of a "factual" world [13]. The storyline approach, also known as the mechanistic or process-based approach, focuses on physical mechanisms [13], [14]. It identifies the chain factors that lead to an extreme event. It relies on the sensitivity experiment of the climate model to separate the role of each causal factor [13], [15].

Linking EEA to Infrastructure Resilience in Hot Climates

Infrastructure systems in hot climates are exposed to unique stressors, including heat waves, heavy rainfall, etc., that make them highly sensitive to extreme events [16]–[19]. Extreme climate and weather events can cause damage and disruption over time [20]. Electricity systems are stressed to their maximum limits during prolonged heatwaves, due to the increment in cooling demand [17], [21]. On the other hand, water desalination is the primary source of potable water in all GCC countries, which in turn requires uninterrupted electricity, creating a tight energy–water nexus [21], [22]. Transportation systems face progressive degradation from extreme heat, unusual flooding, and sandstorms, while telecommunications are increasingly exposed to cascading failures [23]–[26].

Gaps in Current Resilience Planning

Traditional resilience frameworks often overlook the evolving nature of climate hazards. Engineering codes typically incorporate the use of fixed return periods (also known as repeat or recurrence interval), despite evidence from EEA that hazard probabilities are changing significantly over time [27]. For example, an extreme heatwave historically expected once in a century could now recur every decade or more under the current trends of climate change [28]. Key climate event types relevant to hot climates are synthesized alongside the attribution confidence for observed changes and the infrastructure vulnerabilities most likely to be affected, as highlighted in Table 1 [29]. This framing links evolving climate signals to practical points of system stress, particularly across electricity networks, water supply, transport, and public health, where cascading impacts can amplify disruption. Recent regional evidence from the GCC is then incorporated by summarizing heat extremes observed from May 2024 to May 2025, presented in Table 2, and providing examples of notable extreme heatwave events affecting the region during the same period, Table 3. To ensure comparability, anomalies and likelihood-related metrics reported in both tables are evaluated against the 1991–2020 reference period.

Table 1. Event type, attribution confidence of observed changes, and infrastructure vulnerabilities in hot climates (sourced from the special report of working groups I and II of the Intergovernmental Panel on Climate Change, IPCC [29]

S. No.	Event type	Attribution confidence	Infrastructure vulnerabilities in hot climates

1	Heatwaves	High	Grid overload, transformer failure, water shortage, health crises, etc.
2	Extreme rainfall	Medium–High	Transport disruption, drainage failure, substation flooding, etc.
3	Droughts	Medium–Low	Water scarcity, energy stress, reduced food production, agricultural loss, etc.
4	Wildfires	Low–Medium	Telecom outages, power line damage, and emergency access constraints, etc.
5	Tropical cyclones	Low–Medium	Seaport disruption, coastal flooding, damage to energy and telecom assets, etc.

Table 2: The heat extremes suffered in the GCC countries over the past 12 months. These data are referenced against 30 years of data, ranging from 1991-2020. These were based on the report by J. Giguere et al.(2025)[30]

Country	**May 1, 2024 - May 1, 2025**		
	Mean temperature anomaly (°C)	**Days of temperatures above the 90th percentile**	**Days of temperatures above the 90th percentile, added by climate change**
Bahrain	0.6	80	60
Kuwait	0.7	77	64
Oman	1	66	39
Qatar	0.7	70	57
Saudi Arabia	0.9	80	72
United Arab Emirates	1.1	65	52

Table 3: Extreme heatwaves in the region over the last year. Other countries outside the GCC were impacted by these heatwaves, but are not presented. The likelihood and anomalies are measured against 30-year reference periods between 1991 and 2020. The data was adopted from J. Giguere et al.(2025) [30]

Start date of heat event	**End date of heat event**	**GCC countries affected by the heat event**	**Increase in likelihood due to climate change (times more likely)**	**Mean temperature anomaly (°C)**
31-May-2024	5-Jun-2024	United Arab Emirates, Oman, Kuwait	4	2.6
5-Jun-2024	10-Jun-2024	Saudi Arabia	11	2.3
11-Jul-2024	16-Jul-2024	Saudi Arabia, Kuwait, Bahrain	14	2
27-Jul-2024	1-Aug-2024	United Arab Emirates, Oman, Saudi Arabia	9	1.3
1-Oct-2024	6-Oct-2024	Saudi Arabia	5	2.2
10-Oct-2024	15-Oct-2024	Saudi Arabia	10	3
3-Nov-2024	8-Nov-2024	Kuwait, United Arab Emirates, Oman, Bahrain, Saudi Arabia, Qatar	5	1.8
20-Feb-2025	25-Feb-2025	Saudi Arabia, United Arab Emirates, Oman	3	0.1
23-Apr-2025	28-Apr-2025	Saudi Arabia	5	2.5

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Experimental Validation of Design and Operation Concepts for Resilience in Water Distribution Systems

Kevin T. Logan [1] Peter F. Pelz [2]
1 Chair of Fluid Systems, Technische Universität Darmstadt, Germany, kevin.logan@tu-darmstadt.de
2 Chair of Fluid Systems, Technische Universität Darmstadt, Germany, peter.pelz@tu-darmstadt.de

Abstract

Most resilience approaches to water distribution are developed for simulation models of water distribution systems (WDSs). The presented work applies resilience engineering concepts to a physical model of a WDS using a test rig. Central, decentral and decentral-coupled topological configurations as well as augmented control strategies based on signal analysis, statistical modelling and analytical modelling respectively are implemented on the test rig. Subsequently, they are tested against leakage, blockage and pump failure disruptions. The resilience of each system setup is assessed by evaluating existing resilience metrics to determine the resilience of each setup and to reveal the metrics' usefulness.

Keywords: water distribution systems; resilient design; resilient operation; experimental validation; resilience assessment

Introduction

Urban populations rely on water distributions systems (WDSs) to satisfy fundamental needs. Accordingly, WDSs are considered critical infrastructure and their reliable operation is a major concern faced with challenges such as progressing urbanisation, natural hazards or malicious activity. Resilience of WDS has been the subject of a growing body of research.

Resilience has multiple definitions across several domains. This paper follows a definition from the engineering domain, in which a resilient technical system "guarantees a predetermined minimum of functional performance even in the event of disturbances or failure of system components, and a subsequent possibility of recovering at least the setpoint function." (Altherr et al., 2018) Several concepts have been proposed for engineering resilience both in the design and in the operation of WDSs, though they have been predominantly applied to virtual models of WDSs, either generic or derived from real-world networks. A multitude of metrics for evaluating resilience of WDSs has also been proposed, though individually they offer limited informative value (Leštáková et al., 2024).

The presented work aims to experimentally validate design and operation concepts for resilient WDSs, using several established metrics. It builds on previous work by Leise and Altherr (2021), and Leise et al. (2020). The main contribution consists of demonstrating how design concepts can be put into practice in a physical system both for system topology and control. Furthermore, the system setups are exposed to disruptions. Their performance is assessed by applying established resilience metrics, revealing the metrics' practical usefulness and limitations.

Methods

This section presents the chosen resilience design concepts, their implementation in the experimental setup, the modelling of disruptions, as well as the resilience assessment.

Resilience design concepts

The design concepts selected from literature for validation are *redundancy* (Michel Bruneau et al., 2003) and *decentralisation* (Mohebbi et al., 2020) with regard to topology and adaptivity (Shin et al., 2018) during operation. Furthermore, the four resilience functions *anticipating*, *monitoring, reacting and learning* (Hollnagel, 2011) are implemented.

Experimental setup

Test rig – The test rig used for experimental validation is shown in Figure 1, incl. scale and technical specifications. Its hydraulic schema is shown in Figure 2. It represents a generic WDS using gravity supply supported by pumping (cf. Figure 3.48 in (Trifunović, 2006)) with two pumps feeding water into two tanks from where it flows out through two pipes each fitted with a valve, representing the supplied consumers.

System function - The function of a WDS is to deliver volume flow at a required pressure. Accordingly, the function of the test rig system is to maintain a given pressure in the tanks despite continuous outflow through the consumer valves (water consumption).

Topologic configurations – The test rig allows implementing various topologic configurations. Three configurations are considered in the scope of this work: centralised, decentralised and coupled, Figure 3. In the centralised configuration, a pumping station of two parallel pumps (reflecting the design concept *redundancy*) supplies flow at constant pressure, while the pressure in each tank $p_i(t)$ is controlled with a separate PID controller acting on a valve by setting the valve opening $z_i(p_i)$. In the decentralised case, the system is fully separated into two subsystems (*decentralisation*) and the tank pressure is controlled with a PID controller manipulating pump speed $n_i(p_i)$. The coupled configuration is the same as the decentralised configuration, except that a valve can be opened between the two tanks (*adaptivity*) to allow feeding one subsystem from the other in case of a disruption (*anticipation*).

Control strategies – Systems using real-time feedback control already implement the resilience functions monitoring and reacting, since a system output is measured (*monitoring*) and compared to a setpoint. The reacting function is fulfilled in a control system as the control variable is manipulated to minimise deviations from the setpoint. In this work, control strategies are used that augment basic PID control by a fault detection (*monitoring*) module and a module for adapting PID setpoints in case of disruptions (*reacting, adaptivity*). The control loop is further extended by a module for learning from past disruptions (*learning*). The control loop schematic is shown in Figure 4. Three control strategies are implemented, based on signal analysis, statistical modelling, and analytical modelling, respectively. The signal-based strategy uses dynamic time warping (DTW) for fault detection and the largest past deviation for calculating a required reserve pressure for the tank. The statistical modelling strategy uses an ARMA model for fault detection and an ARIMA model for forecasting the drop in tank pressure to calculate the required reserves (*anticipating*). The analytical modelling

strategy uses an analytical model simulated in parallel to the running system for fault detection and model-predictive control (MPC) for reacting to detected disruptions.

Disruptions – Three disruption scenarios are applied to each of the system setups, a leakage, a blockage and a pump outage. The leakage is of gradually increasing intensity, the blockage has the shape of a harmonic oscillation and the pump outage occurs abruptly.

Resilience assessment – We evaluate the Todini Index (Todini, 2000) and the Buffering Capacity (Altherr et al., 2018) to assess the topological configurations before operation to show how well the systems are prepared for disruptions (*anticipate*). To assess the *monitoring* function, we evaluate delay in detecting a disruption, time ratio of detected disruption to actual disruption and false detection ratio. The reacting function is assessed using the performance-based metrics maximum performance loss, integral service loss and time to recovery. The performance loss behaviour and recovery behaviour according to Cassottana et al. (2021) are also evaluated. The learning function is assessed by improvements on resilience metrics for consecutive disruptions. The energy consumption of the system is evaluated to quantify the effort required for resilience.

Conclusion

The presented work proposes an approach for systematically testing the practical applicability of resilience design and assessment concepts in the context of WDSs. System setups varying in topology and operation are tested against various disruptions. Established resilience metrics are evaluated and compared to showcase their informative value. The work contributes to transferring resilience from concepts and system models to physical systems and thus operationalising resilience.

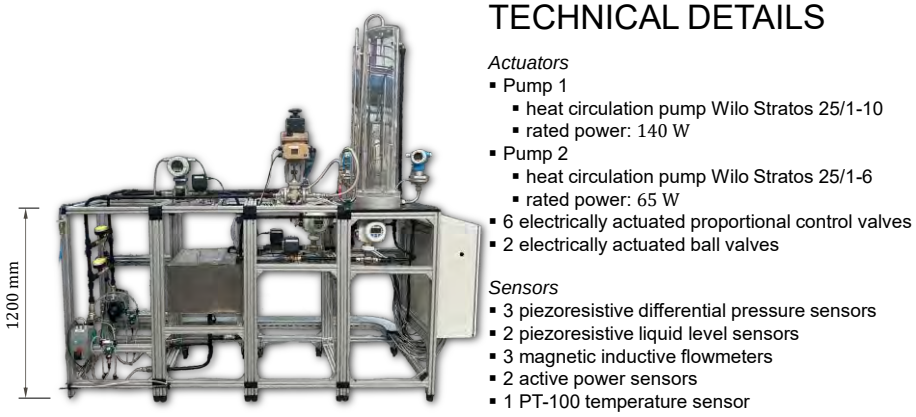


Figure 1. Test rig with scale including technical specifications.

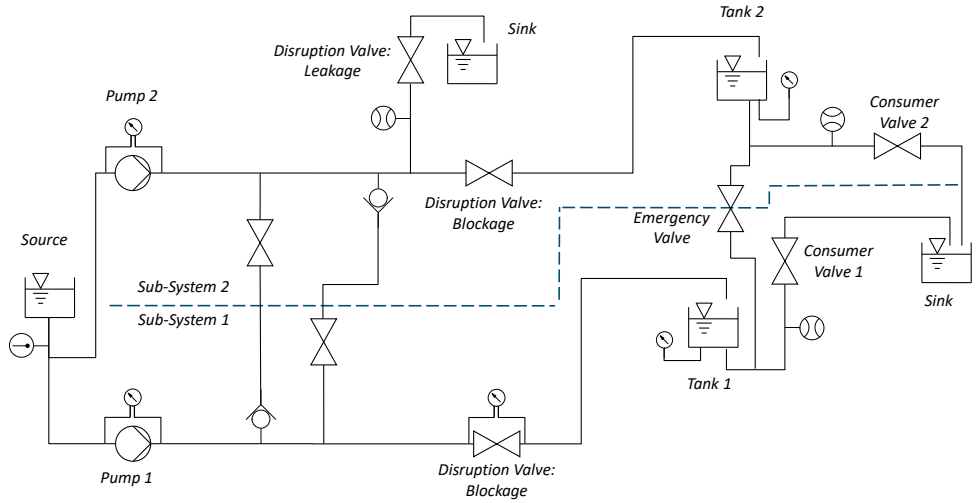


Figure 2. Hydraulic schema of the test rig.

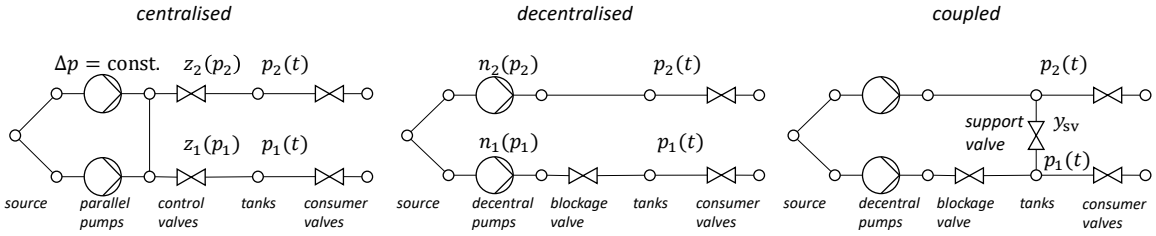


Figure 3. Hydraulic schemata of centralised, decentralised and coupled topologic configurations.

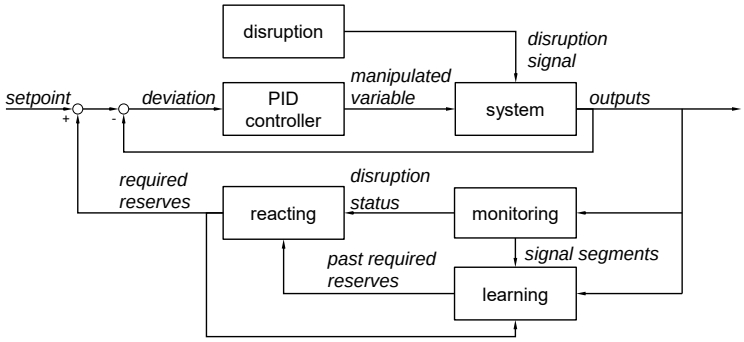


Figure 4. Schematic of the implemented control loop.

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Requirements Analysis for a Modern Crisis Communication System Involving Multiple Stakeholders

Thomas Müller[*], Jakob Reitmeier[**], Viveca Reißig[***], Stefanie Schubert-Polzin[****]
[*] Hochschule Magdeburg-Stendal, Germany, Thomas.mueller@h2.de
[**] Johanniter-Akademie-Mitteldeutschland, Germany, Jakob.reitmeier@johanniter.de
[***] Hochschule Magdeburg-Stendal, Germany, Viveca.reissig@h2.de
[****] Hochschule Magdeburg-Stendal, Germany, Stefanie.schubert-polzin@h2.de

Abstract

As part of the research project *"Autonomous, Failure-Protected and Integrated Crisis Communication in the District of Meißen"* ("KriKom-LK-MEI"), a communication system is being tested in the model region Meißen to ensure crisis communication in the event of a major incident. The aim is to maintain a functional exchange of information and communication even in the event of a failure of the digitally based primary infrastructure, for example, as a result of a widespread, long-lasting power outage (blackout). The holistic system particularly addresses alerting, emergency call forwarding, supply security, and public warning. The focus is on facilities other than authorities and organizations with security tasks (BOS), which cannot rely on the hardened TETRA-BOS radio communication in the event of a power failure. The basis for developing a requirements analysis is a comprehensive vulnerability assessment of existing crisis communication systems.

The knowledge gain lies in the combined application of qualitative and quantitative research methods as well as the derivation of technical[1] and organizational[2] optimization measures. For this purpose, national and international specialist publications, theses, and incident reports of past crises and disasters were analyzed according to keywords such as "crisis communication," "incident command system," "interdependence," "vulnerabilities," and "communication disruption." In addition, structured expert interviews and workshops with stakeholders of the research project „KriKom-LK-MEI" from the sectors BOS, critical infrastructures, and public administration were conducted. Furthermore, operational logs of the district administration staff of Meißen from real large-scale incident and disaster events since 2002 were systematically evaluated. These events include, for example, flood situations along the river Elbe in 2002, 2006, 2010, and 2013, a drinking water disruption in 2023, and the forest fires of 2022 and 2023.

[1] **Technical vulnerabilities** include system reliability, disruptions at the interfaces with other communication or data processing systems, as well as the capacity limitations of the communication systems.
[2] **Organizational vulnerabilities** primarily arise in the organizational structure, established workflows, and the hierarchical structures of the crisis management staff.

The identified weaknesses were categorized into technical and organizational groups and form the basis for the design of the new redundant system in the model region. The requirements analysis developed in this context clusters thematically and substantively similar weaknesses into overarching categories, thereby consolidating comparable features to derive optimization recommendations for the applications to be implemented.
In November 2024, an initial demonstration project was carried out in which an autonomous message transmission system between crisis staff was tested. Both technical functionalities and organizational processes were practically reviewed and evaluated. The project results provide the foundation for further research and the nationwide transferability of the findings as recommendations for action for other districts and federal states.

7. Progressing Climate And Disaster Resilience

An Integrated Modelling Framework for Assessing Climate Risks and Adaptation Options for Urban Transport Infrastructure

Dr Alistair Ford

Abstract

Urban transport systems face growing risks from extreme weather, especially pluvial flooding, which causes approximately 39% of transport infrastructure damage globally. This study presents a UK-based modelling framework that integrates climate projections, a flood model, and an agent-based transport model to simulate the impacts of extreme rainfall. It captures both direct infrastructure disruptions and indirect effects on users, including delays and journey cancellations. Even for a modest 1 in 30 rainfall event, more than 1 in 10 roads are affected by floodwaters, with 1% closed. If this were to occur during the evening rush hour it would negatively impact 1 in 5 trips - including critical journeys for work, education (10% of trips), and healthcare (17% of trips). Adaptation strategies - green, grey, and soft - are tested to reduce disruption. This approach enables decision-makers to assess transport resilience and compare the effectiveness of adaptation options under future climate and socio-economic conditions.

Keywords: transport; modelling; impact assessment; adaptation; infrastructure

Introduction

Transport networks are critical infrastructure for urban areas, providing the means to move people and goods, underpinning urban economies and society. Urban transport networks, however, are also exposed to extreme weather events, with events like heavy rainfall and extreme temperatures causing a reduction in performance, or even loss, of infrastructure. Lu et al. (2022) reported that urban floods account for approximately 39% of annual transport infrastructure damage worldwide. Urban decision-makers therefore require tools and approaches to quantify the risks posed to transport infrastructure during extreme weather events and to assess potential adaptation options to improve the resilience of transport systems.

The risks posed by extreme weather events are a complex combination of hazard (e.g. the spatial footprint of extreme rainfall and resultant pluvial flooding), exposure (e.g. the intersection of hazard footprints with transport infrastructure), and vulnerability (e.g. the ability of infrastructure to cope with a given severity of hazard). In order to assess the risk posed to the transport system, a spatial approach that combines hazard models and transport models is required, assessing both the direct impacts on infrastructure and indirect impacts that play out through the users of the transport system.

This paper presents an integrated modelling framework developed to simulate extreme weather impacts on urban transport systems in the UK. The approach combines a hazard model (demonstrated here with surface water flooding), and an agent-based transport model (MATSim) to simulate the response of transport users and quantify impacts.

Methodology

The framework (Figure 1) considers both future climate (bottom row) and future socio-economic (top row) conditions. UKCP18 climate model outputs (Kendon et al., 2021) are used to simulate rainfall events to generate scenarios that capture the intensity, duration, and spatiotemporal distribution of heavy rainfall. These outputs feed into the CityCAT urban flood model (Glenis et al., 2018) to produce dynamic high-resolution surface water flood depth maps that capture the temporal evolution of flood conditions over the course of the rainfall event.

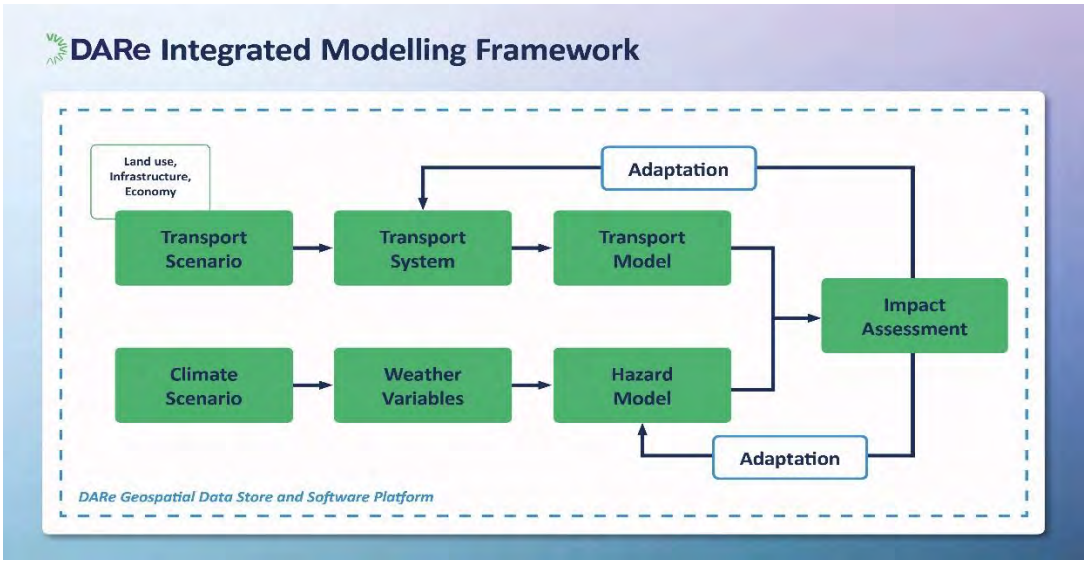


Figure 1: the integrated modelling framework employed in this study

The urban transport system is defined for a future socio-economic transport scenario (top row), considering transport decarbonisation (e.g. electrification, mode shift) policies and future travel demand. This demand is fed into the MATSim agent-based transport model (Axhausen et al., 2017) to simulate the movement of synthetic individuals, through the multimodal urban transport network. Simulated modes include walking, cycling, private car, bus, metro, and rail. The agent-based model is calibrated and validated for a normal working day using a range of data sources (Alvarez Castro et al. 2024). An output from the MATSim model used in this study is shown in Figure 2.

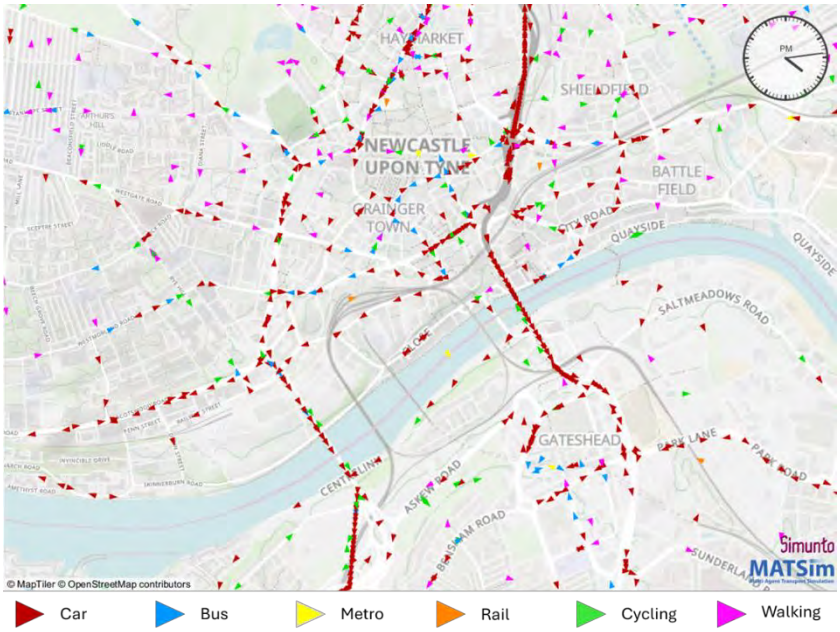


Figure 2: Sample output from MATSim agent-based model

The framework then integrates the hazard model and transport model to quantify climate risks to the urban transport system. In this example, the flood depth maps from CityCAT inform vehicle travel speeds by identifying road segments affected by inundation and simulating the adaptive behaviour of individual agents. A depth-speed curve (Pregnolato et al., 2016) is used to adjust maximum speeds on the road network, whilst depth thresholds impact active travel and public transport links. This simulation captures emergent travel disruptions caused by flooding, such as journey delay and cancellation, which are then evaluated through a performance metric framework spanning physical, operational, environmental, social, and economic dimensions of transport resilience.

Once impacts have been assessed, adaptation options can be explored to assess their effectiveness in reducing disruption to transport users. The framework allows simulation of multiple forms of adaptation. Green interventions (e.g. SUDS, green roofs) can be simulated in the CityCAT model to assess their impact on reducing the flood hazard. Grey interventions (e.g. improved drainage) can be simulated in the transport model, by reducing the impact of flood water on transport performance. Soft adaptations (e.g. early warnings, work-from-home instructions) can be captured through the agent-based simulation, exploring how reduction in demand or avoidance of flood risk areas can reduce the scale of the disruption.

Key Findings

The number and length of road links affected by flooding are captured during the rainfall event. For example, in the first two hours of rainfall of a relatively modest 1 in 30 year event of 48,844 road links experience at least 0.01m of water depth, accounting for 15.3% of the total network. At the peak of this event, the number flooded roads with water depth above or equal to 0.3m is 2,645 road links, leading to these links being closed and accounting for 0.8% of the total. This equates to 3,433km of roads affected by flood water (13.2% of the total) and 226km (0.9%) are considered closed due to a depth over 0.3m.

The performance loss resulting from the flooding is measured through delay to transport users and journey cancellations. In this demonstration, the worst-case scenario of a flood in the morning rush hour (07:00-09:00) leads to 126,656 journeys being cancelled (21% of the total simulated trips) due to users returning home or becoming stranded in the transport system. This includes 17.0% of all simulated medical journeys, 15.5% of work journeys, and 9.8% of education journeys, with the agent-based model able to identify potential disruptions to different trip types in the event of heavy rainfall.

The framework can also be used to assess social (e.g. missed medical trips), environmental (e.g. increased greenhouse gas emissions and air pollution during disruption) and economic (e.g. productivity loss) during the simulated event. The implementation of adaptation options allows for the assessment of loss reduction and comparison of costs and benefits of different adaptation approaches.

Acknowledgements

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Impact of large-scale pluvial flooding on an interdependent electricity and road network: do we need to adapt?

Edgar Daniel Peregrina Gonzalez [1], Lieke Meijer [2], Margreet van Marle [3], Kees van Ginkel [4], Elco Koks [5]
[1] Deltares/VU Amsterdam (IVM), the Netherlands, daniel.peregrinagonzalez@deltares.nl
[2] Deltares, the Netherlands, lieke.meijer@deltares.nl
[3] Deltares, the Netherlands, margreet.vanMarle@deltares.nl
[4] Deltares, the Netherlands, kees.vanGinkel@deltares.nl
[5] VU Amsterdam (IVM), the Netherlands, elco.koks@vu.nl

Abstract

Critical infrastructure (CI) systems of interdependent networks rely on each other to function as intended, both during regular operation, and during emergency recovery. Extreme weather events such as pluvial flooding may damage and disrupt CI systems, including electrical substations and road networks, leading to power outages and disrupted traffic routes. Climate change increases the likelihood of large-scale pluvial flood events. However, there is limited understanding of how pluvial flooding of such scale may lead to electricity outages, and therefore of how to adapt to this threat. In this paper, we investigate the potential for adaptation and disaster risk reduction measures through a case study in the province of South-Holland in the Netherlands. The case considers the consequences of an extreme rainfall event, leading to consecutive days of large-scale pluvial flooding on the electricity and road networks. We additionally model how road disruptions pose accessibility constraints that are also relevant for the recovery process of the electrical distribution network. In our evaluation of adaptation options, we consider the interconnectedness of these two networks and dynamic recovery over time. The adaptation options that may reduce risk and improve resilience work in very different ways, making it difficult to choose between investing in polder pumping capacity to drain water more quickly, protecting electrical substations, or ensuring specific routes remain transitable to reach disrupted substations for repairs. The heavily urbanized, below-sea level, polder situation (with many roads on top of canal embankments) comes with some unique challenges, such as: will faster pumping of the polders exceed the discharge capacity of the canals, leading to even more road closures? We use different impact metrics (population affected, service disruption, and repair costs among others) to evaluate the effectiveness of various operational and structural measures. We aim to answer: do we need to adapt?

Keywords: infrastructure adaptation; risk reduction; pluvial flooding; electricity distribution; road accessibility

Introduction

In July 2021, a large-scale precipitation event caused flooding and widespread destruction of critical infrastructure (CI) in Germany, Belgium, and the Netherlands (Koks et al., 2022). This raised the question: if a similar event happens elsewhere, what would be the consequences? Is it necessary to adapt, and if so, how?

Based on this event, this case study investigates what would have happened to the electricity network in the Dutch province of "South Holland", if the 2021 rainfall had occurred here. Most of the province consists of low-lying land which is strongly urbanized with cities like Rotterdam, The Hague, and Delft surrounded by intensive greenhouse horticulture and dairy farming. The province is largely composed of polders, areas of reclaimed land that are constantly drained with pumps into a system of interconnected canals. The drainage capacity is therefore not only constrained by the capacity of pumps but also by the discharge capacity of the canals (van Ginkel et al., 2023).

Here we explore how this rainfall would disrupt society with an interconnected road and electricity model and use it to evaluate different adaptation options and recovery strategies. We incorporate uncertainty by considering different fragility curves for the substations and repair crews that are in different locations of the study area when the flood occurs.

Method and Data

A time-explicit disruption and recovery model of the electricity and road networks is used to explore the consequences of pluvial flooding and the benefits of climate adaptation. In our approach, we overlay a synthetically generated timeseries of flood maps with electricity and road assets. Through this overlay, we first determine the damage to electrical substations using a depth-damage curve. Following, we estimate the time required to restore operations (Movahednia et al., 2022). This allows us to identify the potentially disrupted substations. At each timestep, the (flooded) road network is analysed to determine whether disrupted substations can be reached to be repaired; when the substation is reachable and there are repair crews available, they are assigned a repair task, remaining unavailable until the substation is fully repaired and returned to operation.

The flood maps are high-resolution, daily inundation depth maps produced by simulating a large-scale precipitation event of 200 mm in 48 hours under initially wet soil conditions, considering the capacity of the drainage and pumping systems (De Bruijn et al., 2022). The electricity substations considered are the medium-low and low voltage substations of the local operator (Stedin, 2024), while the road network is retrieved from OpenStreetMap (OpenStreetMap contributors, 2025).

The outputs of the model are evaluated through different impact and resilience metrics (Argyroudis et al., 2020) – the number of days substations remain flooded, population affected, total hours of service disruption, economic losses caused by lack of electricity, total repair cost, and repair effort hours. The effect of different adaptation options and response strategies on these metrics is assessed to determine which options should be pursued. The structural options considered are increasing drainage capacity in an area, elevating substations, and guaranteeing certain roads remain transitable, while operational measures focus on the order in which repairs are prioritised.

Results

Our results indicate that a large-scale precipitation event of these characteristics would cause flooding in several electricity substations. In the case of medium-low voltage stations, 198 are flooded above a depth of 0.2 m, representing 3.4% of the substations in the area. In the case of low voltage stations, 142 are flooded, 2.8% of all stations. On average, assets remain flooded for 3.3 days, however, some remain flooded for up to 5 days (Figure 1).

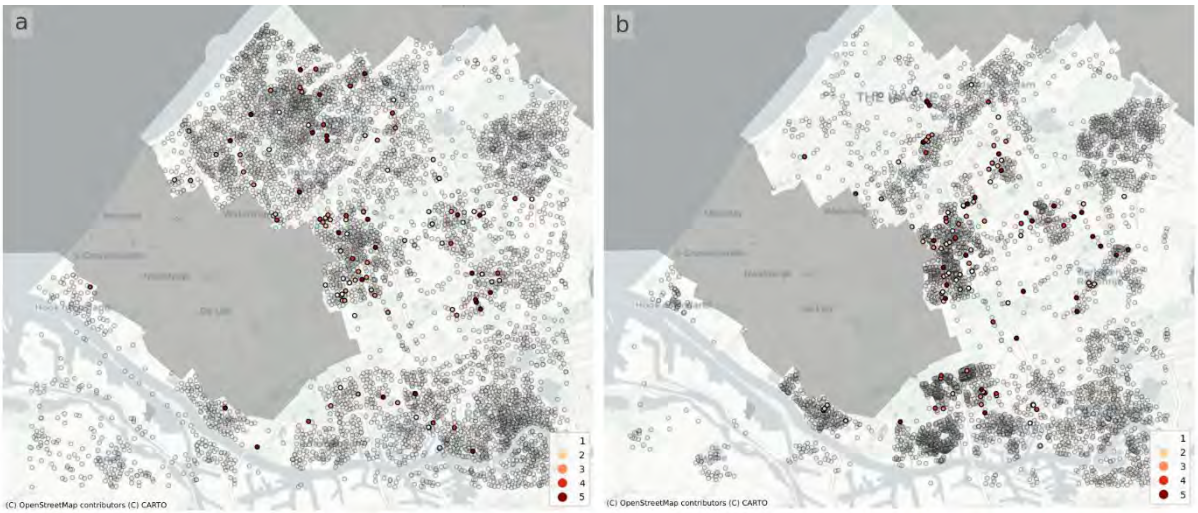


Figure 1. Flood duration (in days) for electricity substations in South Holland, the Netherlands. (a) Medium-low voltage substations; (b) low voltage substations. Zones outside the study area are greyed out.

The depth to which substations are submerged is generally low; during peak flooding (day 2, hours 48-71), the median flood depth is 0.36 m. This is not much higher than the assumed damage threshold of 0.2 m, under which no damage is considered. Given the relatively low flood depth, repairs can be quickly carried out when the flood recedes and the substation becomes reachable, making it possible to finish all repairs ~60 hours after the flood has fully receded, with most repairs finishing within 24 hours after the flood recedes (Figure 2).

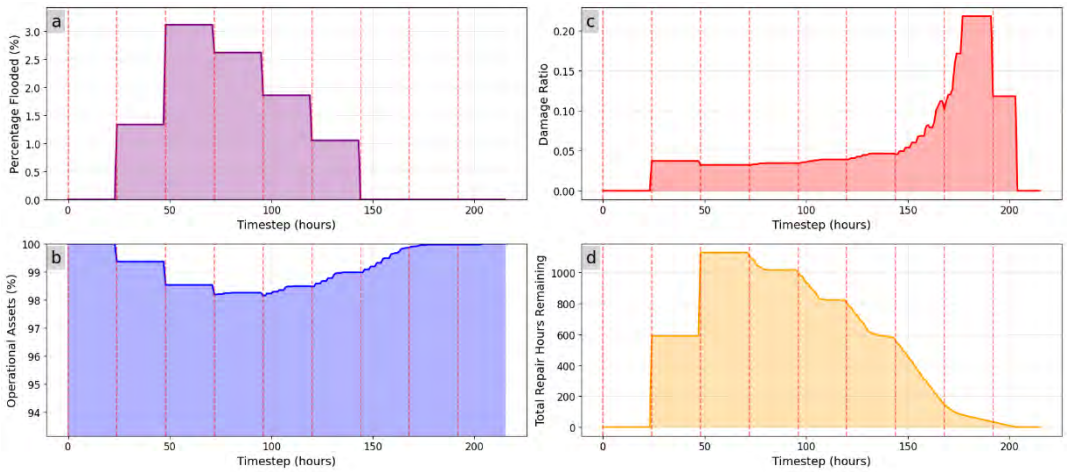


Figure 2. Damage and recovery process for electricity substations. (a) Percentage of assets flooded above 0.2 m; (b) percentage of assets that are operational; (c) average damage ratio across all damaged substations; (d) total backlog of repair hours across all substations.

During the flood, approximately 100 segments of the road network get isolated: completely disconnected from the rest of the road network (Figure 3). Since electrical substations located within these "islands" are impossible to reach, they are often among the last to be repaired.

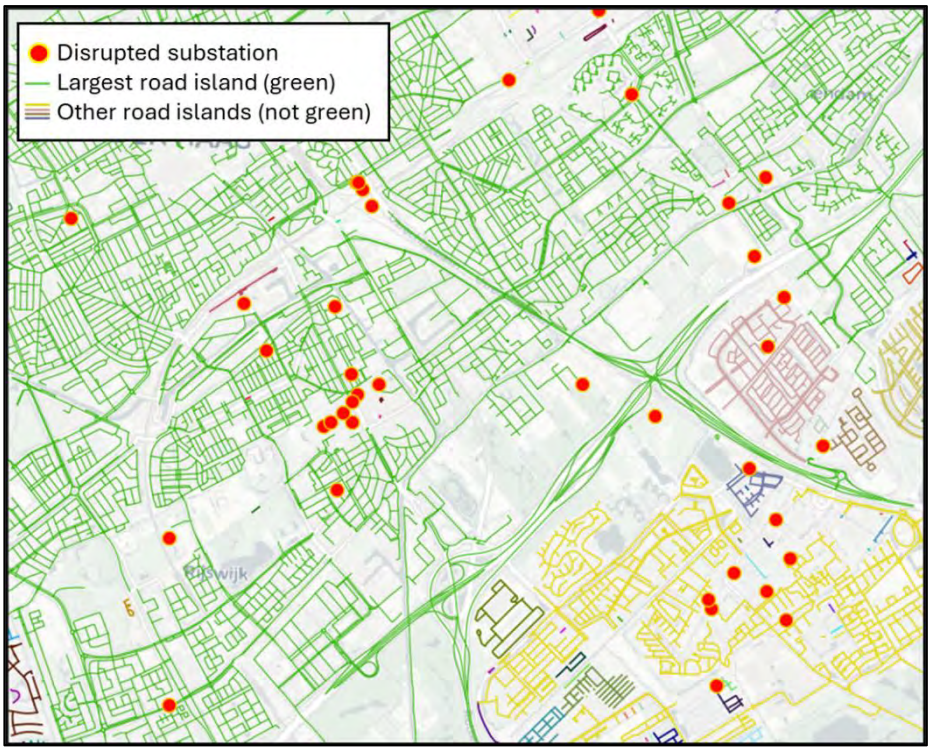


Figure 3. Disrupted substations in the southeastern area of The Hague and isolated sections of the road network (islands) in different colours; the largest connected component is coloured green. Transit between sections of the road network of different colours is not possible due to flooding.

The chosen recovery and adaptation strategies play an important role in the impact observed. For example, prioritising substations with low damage allows them to return to operation more quickly, leading to the lowest total substation outage time; however, these stations may only service a small number of people or areas with low economic productivity, so this is not necessarily the lowest impact in terms of societal disruption.

Regarding adaptation options, since the flooding for most stations is quite shallow, reducing the amount of water present (by increasing pumping) or elevating the threshold from which damage begins by 10 cm greatly reduces the number of stations affected (Table 1), making these attractive general and targeted adaptation options, respectively. Since the drainage system may be too full during extreme precipitation events to receive additional pumped water (van Ginkel et al., 2023), elevating the substations is the more feasible alternative.

Table 1. Percentage of substations affected when different flood thresholds are considered.

Flooding threshold [m]	Medium-low voltage stations affected [%]	Low voltage stations affected [%]
0.1	5.2%	4.8%
0.2	3.4%	2.8%
0.3	2.3%	1.9%

Key Insights and Conclusion

Our study reveals that localised disruptions to power supply would be expected; while the severity of the damage to substations is relatively low, the outage duration in some areas is much longer than the required repair time due to persistent flooding and limited access. This indicates it is especially important to adapt in areas that become inaccessible during flooding.

Furthermore, we learn that prioritising based on criticality (number of people affected) and multiple impact metrics is a way to inform both recovery and long-term adaptation planning, and that considerations should be made for equitable adaptation, repair, and restoration of service. Otherwise, when considering economic losses due to service disruption, high monetary value areas may be prioritized over housing areas with low economic productivity. Further research should fully incorporate equity considerations into adaptation and recovery planning.

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The impact of climate change on critical services accessibility during flooding

Zizhen Xu^1, Jie Liu*^1, Li Wan^2, Kristen MacAskill^1
^1 Department of Engineering, University of Cambridge, Cambridge, UK, CB2 1PZ
^2 Department of Land Economy, University of Cambridge, Cambridge, UK, CB3 9EP

Abstract

Climate change is expected to increase flood risk across England, threatening access to critical services such as healthcare and fire-rescue. This study provides a national-scale assessment of how future flooding may affect neighbourhood-level accessibility in England. While the overall average impact of climate change appears modest, resulting in only a 2.4% reduction in accessibility compared with current climate, the results reveal spatial disparities, with some councils experiencing significantly greater losses. Importantly, there is no clear correlation between current flood-related accessibility and future climate-driven reductions, indicating that reliance on historical baselines may be insufficient for future planning. The analysis also shows that climate change may shift the dominant source of flooding in some councils—from surface water to rivers and sea—requiring prospective response strategies. Marginal accessibility loss caused by climate change is more pronounced in extreme, low-probability flood scenarios, with the longer time window for accessibility (15mins vs. 7mins) showing greater loss despite higher tolerance under frequent flood scenarios. These findings highlight the need for localised adaptation strategies that account for flood source, infrastructure interdependencies, and sensitivity to changing flood risk due to climate change. The approach supports planners and infrastructure operators in considering benefits of intervention strategies to ensure the critical service accessibility under current and future flood conditions.

Keywords: accessibility; critical services; flooding; climate change

Introduction

Shifting precipitation patterns are expected to induce more flooding events in many regions (Hirabayashi et al., 2013; Tabari, 2020), including the UK (Environment Agency, 2025). While timely early warning and preparation such as personal emergency supplies could effectively mitigate a substantial level of impact, essential services are highly vulnerable during the flooding events, such as healthcare and fire-rescue, which are identified as the most time-critical (Girardet, 2020; Parmesan et al., 2022). Research on essential services has often discussed the accessibility under normal situations (Balsa-Barreiro et al., 2025; Carr et al., 2009; Van Wee & De Jong, 2023). More recent studies start to bring attentions to accessibility under disaster conditions, where the vulnerability and bottlenecks expose additional loss (O'Hara & Toussaint, 2021), and specifically explored the emergence response during flooding

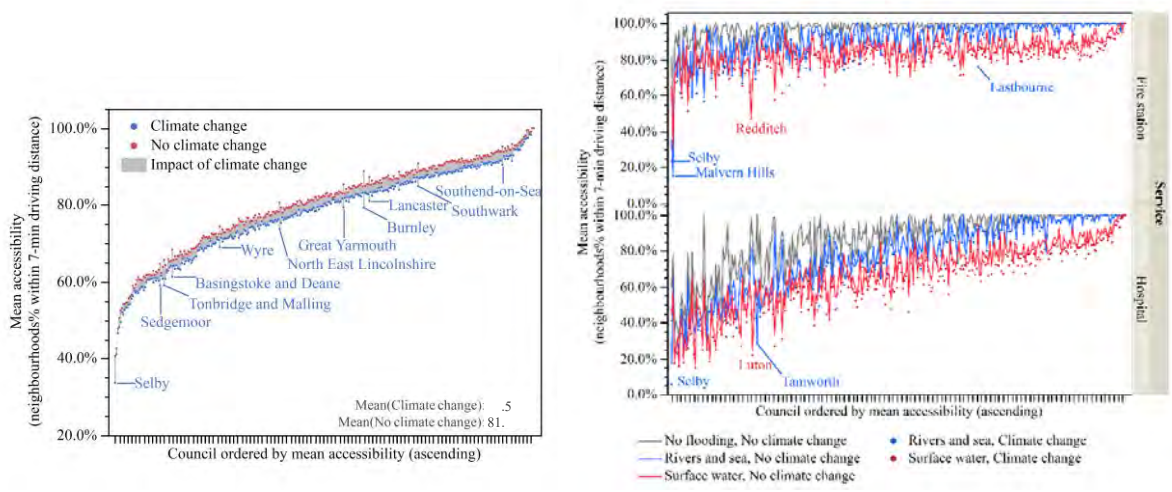
(Gangwal et al., 2023; Gangwal & Dong, 2022; Yu et al., 2020). With climate change, population exposure to risk may further increase in some regions, exacerbating vulnerabilities in infrastructure and coverage of services (Forero-Ortiz et al., 2020; Othman et al., 2023; Tellman et al., 2021). Therefore, this paper takes a step further to understand how climate change is going to exacerbate the accessibility loss during flooding in terms of healthcare and fire-rescue services at neighbourhood levels, as a national case study for England. Our study provides a high-level view of spatial disparities in flooding-induced service accessibility loss and the marginal impact of climate change, as well as the risk pattern changes due to climate change.

Methods

A macroscopic, national-scale approach is adopted in this paper to quantify accessibility loss to healthcare and fire-rescue services under different flood risk scenarios across flood risk sources (surface water vs. rivers and sea), scenario probabilities (probability/return periods), climate change (Environment Agency's risk projection based on UKCP18 RCP8.5), and types of critical services (healthcare vs. fire-rescue). Accessibility is evaluated using the least drive time between neighbourhoods and service spots, which involves the modelling of the road network and accounting for the passability of roads under flood conditions. The water thresholds for passibility were chosen based on wading depth of ambulances or general private cars (0.3m) and fire trucks (0.6m). This research utilises the flood risk maps (Risk of Flooding from Rivers and Sea, Risk of Flooding from Surface Water) produced by the Environment Agency (UK). Flood risk is understood as annual hazard probability (P) correspond to High (P>3.3%), Medium (1%<P<3.3%), Low (0.1%<P<1%), and Very Low (P<0.1%). The data sets include a map of 33,755 neighbourhoods, 1,225 NHS hospital/infirmary sites, 1,398 fire stations, and the road network, all specific to England.

Results

This study demonstrates the impact of baseline risk and changes in climate on neighbourhoods accessibility to healthcare and fire rescue services. As show in **Figure 1a**, National trend has shown that the overall average impact from climate change is relatively small (2.4%). However, this masks regional disparities in climate change impact with some councils experiencing significantly greater reductions. This highlights that national averages may be of limited value when designing interventions, and that local context must be at the forefront of planning. Also, **Figure 1a** shows that poor accessibility during flooding in the past does not suggest high impact from climate change in the future. This absence of correlation challenges common assumptions that past and present vulnerabilities are good proxies for future exposure. It suggests that reliance on historical data alone could mislead planning efforts, and that projections under changing climate conditions must be integrated into the planning and decision processes. Interesting evidence from **Figure 1b** is that, in some areas, climate change shifts the dominant source of flooding from surface water to rivers and sea. These shifts, as seen in councils like Eastbourne, may require a reassessment of infrastructure priorities and response strategies. Other councils, such as Selby, are likely to face exacerbation of already significant flood risks.



(a) (b)

Figure 1. Council-level average impact of climate change on accessibility to fire-rescue and healthcare services during flooding. (a) the overall impact of climate change, averaged across all eight flooding scenarios and both services. Councils estimated to be more heavily impacted are labelled. (b) climate change impacts by flooding source and service type.

Climate change introduces varying additional accessibility loss in flooding scenarios at different probability levels. The marginal impact of climate change is found greater in lower-probability (more extreme) scenarios, as illustrated in **Figure 2**. The 7-min and 15-min time windows both have increasing marginal impact of climate change, while 15-min curve has greater curvature. As the marginal impact of climate change reflects climate resilience, the results imply that the 15-min time window may offer resilience under frequent or moderate flooding scenarios but become more vulnerable under severe flooding.

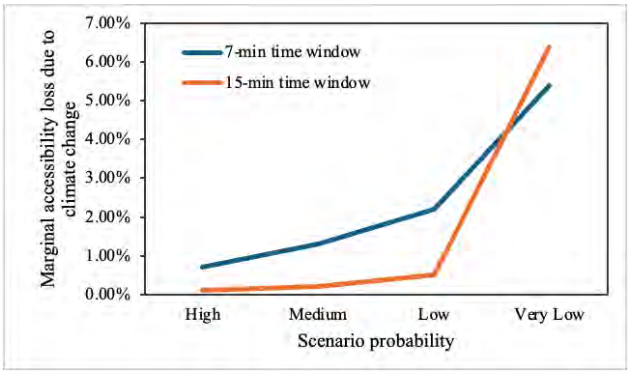


Figure 2. Marginal impact of climate change across different probability scenarios.

This research is part of an ongoing project, and additional analyses will be presented upon acceptance of this contribution.

Acknowledgements

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Seismic Resilience of Critical Urban Infrastructure: Lessons Learned from the 2023 Türkiye Earthquakes

Derya Deniz[1]*, Gulsah Sagbas[1], Ramin Sheikhi[1], Nisa Seyra Ayhan[1], Milad Roohi[2], Milad Cheraghzade[3].
1 Ozyegin University, Türkiye *derya.deniz@ozyegin.edu.tr
2 Univ. of Nebraska-Lincoln, USA
3 Univ. of Science and Technology, Hong Kong, China.

Abstract

The 2023 Türkiye earthquake sequence, which included Mw 7.8 and 7.5 mainshocks followed by a Mw 6.4 aftershock, severely impacted critical urban infrastructure across multiple provinces. This study presents a comparative assessment of the post-earthquake performance and one-year recovery of hospital networks and industrial buildings in regions such as Hatay and Kahramanmaraş. A total of 30 hospitals and 131 industrial facilities were evaluated through field inspections and stakeholder interviews. Widespread non-structural damage and structural failures—particularly in older or non-retrofitted buildings—led to major service disruptions. Hatay's hospital bed capacity dropped to 14% but recovered to 83% within a year. Industrial functionality declined to 11% immediately after the disaster, increasing to 76% over the same period. Recovery trajectories were influenced by construction year, structural design, financial capacity, and access to alternative facilities. These findings highlight the urgent need for resilient infrastructure design, proactive risk mitigation, and continuity planning in seismically active regions.

Keywords: 2023 Türkiye earthquakes; critical infrastructure; recovery; seismic damage; seismic resilience

Introduction

On February 6, 2023, a sequence of powerful earthquakes with moment magnitudes (Mw) of 7.8 and 7.5, followed by a Mw 6.4 aftershock two weeks later, struck southern Türkiye. These events impacted more than 15 million residents and caused widespread destruction across multiple provinces. Critical infrastructure systems—particularly in the healthcare and industrial sectors—suffered significant structural and non-structural damage, resulting in both immediate service outages and long-term operational challenges (Sagbas et al., 2024; Roohi et al., 2025).

This study aims to assess the seismic performance and one-year recovery of two key urban infrastructure systems: hospital networks and industrial buildings. Field investigations, site assessments, and stakeholder interviews were conducted at various intervals (10 days, 6 months, and 1 year after the earthquakes) in the hardest-hit regions, including Hatay and Kahramanmaraş. A total of 30 hospitals from the Hatay hospital network and 131 industrial buildings were evaluated to analyze the extent of damage, loss of functionality, and the strategies adopted for recovery. This comparative analysis provides valuable insights into resilience factors and informs future risk mitigation and infrastructure planning efforts in earthquake-prone areas.

Findings

The evaluation revealed key differences and common patterns in the damage and recovery of healthcare and industrial facilities following the 2023 Türkiye earthquakes. In the healthcare sector, among the 30 hospitals assessed in Hatay, more than 20 experienced non-structural damage, including ceiling collapses, wall cracks, and displaced equipment. Structural damage was less common but still significant, affecting seven hospitals with issues such as soft-story failures and compromised beam-column joints. Notably, only one hospital was equipped with a base-isolation system, and it maintained uninterrupted functionality throughout the disaster period, highlighting the critical role of seismic design in ensuring service continuity. Hospital bed capacity dropped drastically—falling to 31% after the initial earthquakes and further to 14% following the Mw 6.4 aftershock. However, through emergency expansion and new construction, capacity was restored to 83% within one year (Roohi et al., 2025).

In the industrial sector, the assessment of 131 buildings showed that older facilities—particularly those constructed before 2000—suffered the most severe structural damage, often due to inadequate beam-column connections in precast concrete systems. Non-structural components such as cladding, piping, and machinery were also highly vulnerable, even under moderate seismic intensities. Immediately after the earthquakes, the average operational functionality of these industrial buildings dropped to just 11%. Over the course of one year, functionality recovered to 76%, although full recovery was influenced by several factors, including the extent of damage, financial stability, workforce retention, and availability of alternative operational sites. Across both sectors, recovery speed and overall resilience were shaped by seismic intensity, structural typology, construction year, and the presence or absence of continuity planning (Sagbas et al., 2024).

Conclusions

The 2023 Türkiye earthquakes provided a real-world test of the resilience of critical infrastructure systems in developing countries such as Türkiye. In both healthcare and industrial sectors, the earthquakes exposed significant vulnerabilities, particularly in older or non-retrofitted buildings. However, the observed recovery also demonstrated the impact of proactive design measures, such as base isolation, and the importance of coordinated emergency response and recovery planning.

Hospitals and industrial facilities followed distinct but overlapping recovery trajectories influenced by structural integrity, functional dependencies, and resource availability. The hospital equipped with a base-isolation system exemplified how resilient design can ensure uninterrupted service delivery during seismic events. Meanwhile, the recovery of industrial buildings highlighted the need for not only structural resilience but also organizational adaptability.

The empirical findings and recovery models developed in this study offer practical insights and tools for stakeholders—including engineers, policymakers, insurers, and facility managers—to strengthen seismic resilience and inform disaster preparedness strategies in Türkiye and other seismically active regions.

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Developing Resilience Strategies for Ports Against Extreme Weather Events

Gabriel Chikelu*, Osiris Valdez Banda

Marine & Arctic Technology, Energy & Mechanical Engineering, Aalto University, Espoo, Finland

Abstract

Ports are critical hubs for global trade and economic stability, yet they face increasing challenges due to extreme weather events such as hurricanes, flooding, storm surges, drought, high wind, heatwaves and rising sea levels. My research focuses on developing resilience strategies to enhance port preparedness, ensuring operational continuity, and minimizing infrastructure damage during severe weather conditions. The study is structured into three key phases, each addressing a crucial aspect of port resilience. The first phase focuses on vulnerability analysis to understand what climate scenarios the ports are most exposed to. These assessments will help define climate risks, identify critical assets, and evaluate operational sensitivities at each case study port. Establishing the extent of potential threats will lays the foundation for designing targeted resilience strategies. The second phase involves a comparative analysis of climate governance frameworks to assess whether scientifically recommended mitigation and adaptation measures are reflected in port policies. This analysis will examine existing regulations, climate policies, and port management strategies to identify areas where policies align with or deviate from best practices in climate resilience. The third phase focuses on simulating port operations under extreme weather conditions to quantify their impact on port infrastructure and operational capacity. The objective is to model disruptions caused by adverse weather and test recovery strategies aimed at maintaining at least 80% operational efficiency during extreme weather events. This simulation will help port authorities understand bottlenecks, vulnerabilities, and the effectiveness of emergency response measures, leading to better preparedness and strategic decision-making in real-world scenarios. My study aims to provide insights for policymakers, port operators, and maritime stakeholders to enhance port safety, reduce economic losses, and improve climate adaptation strategies

Keywords: Port Resilience; Port Operations; Climate Change; Extreme Weather Impact; Climate Adaptation

Flood Impact Assessment through Machine Learning: Effectiveness of Government Interventions on Economic Loss Reduction in Spain

Matheus Puime Pedra[1], Nazli Aydin[2], Omar Kammouh[2], Josune Hernates[1], Leire Labaka[1]
1Industrial Management Department, TECNUN, University of Navarra, Spain, {mpuime, jhernates, llabaka}@unav.es
2Faculty of Technology, Policy and Management, TU Delft, Netherlands, {N.Y.Aydin, o.kammouh}@tudelft.nl

Abstract

Floods represent a significant threat to human lives, critical infrastructure, and economic stability, with their impacts intensified by climate change, urban expansion, and land-use changes. This study develops a data-driven framework utilising machine learning (ML) and Explainable AI (XAI) to evaluate the effectiveness of governmental interventions in reducing economic losses and enhancing resilience. By analysing a comprehensive dataset of flood events that occurred in Spain, along with socioeconomic factors and intervention measures over several years, the approach identifies key drivers of economic loss. It quantifies the impact of various intervention strategies. The framework enables the simulation of intervention scenarios across regions, providing transparent and interpretable insights that support informed decision-making and the optimisation of flood preparedness policies. This methodology provides robust decision-support information for enhancing disaster resilience and informing investment in effective flood risk reduction measures.

Keywords: machine learning; disaster resilience; loss estimation; floods; governmental interventions

Introduction

Floods are one of the most devastating disasters, posing a significant threat to human lives, critical infrastructures, economic stability, and overall disaster resilience (Cea & Costabile, 2022). Their disruptive potential is being exacerbated by the increasing frequency and intensity of extreme weather events, primarily driven by the effects of climate change, rapid urban expansion and land-use changes (Cea & Costabile, 2022; United Nations, 2023).

Multiple countries are commonly vulnerable to floods. The climate, combined with intense rainfall and a complex hydrological landscape, makes them susceptible to flooding. The importance of effectively managing disasters is highlighted in the European Union and the United Nations guidelines, which emphasise the necessity of enhancing resilience (European Commission, 2024; United Nations, 2023). A notable example of this vulnerability is the 2024 flood in the Spanish province of Valencia, which disrupted public services, caused environmental damage, and resulted in economic losses exceeding four billion euros. (European Commission, 2024). These circumstances underscore the imperative need for implementing more robust flood management strategies.

To attenuate flood impacts, the Spanish government has implemented interventions targeting vulnerability, resilience, and economic loss mitigation (MITECO, 2025). These initiatives include flood defences, drainage, early warning systems, and education programs (MITECO, 2025). Despite this proactive approach, the effectiveness of these measures in lowering economic losses remains unassessed, with no studies evaluating their contribution to regional resilience.

Assessing these actions is crucial for understanding the resilience. This allows end-users to enhance existing interventions and better prepare for future events (Ghaffarian et al., 2023). Without such analysis, policymakers lack the empirical evidence needed to identify key interventions or underperforming measures that require revision (Akbulut-Yuksel et al., 2023). This research aims to evaluate the evolution and impact of Spanish government intervention efforts on flood-related economic losses using a data-driven workflow supported by machine learning (ML). ML models are increasingly used in disaster research due to their ability to handle complex data and find hidden patterns.

Methodology

In this work, a comprehensive dataset was compiled, comprising more than 6,000 flood events that occurred across Spain between 2015 and 2021. This dataset includes reported economic losses, event characteristics (such as intensity, duration, and geographic information), socioeconomic indicators of affected regions, resilience attributes, and metrics related to interventions implemented by governments at different levels. The dataset was preprocessed and used to train ML models, each evaluated based on predictive accuracy, robustness, and interpretability. The optimal model was selected for further analysis.

Using the optimal model, the impact of interventions was analysed by categorising loss predictions into three intensity levels: moderate, severe, and catastrophic. Feature importance analysis indicated that meteorological factors are strongly associated with predicted losses. While machine learning models are powerful tools for predicting events and assessing risks, they are often viewed by policymakers as "black boxes" due to their lack of transparency, which can undermine trust and limit their practical use (Ghaffarian et al., 2023).

To address this, we further employed XAI techniques to quantify the contributions of socioeconomic and intervention features. Based on the XAI application, including SHAP values, it is possible to enhance the transparency of machine learning models. By enhancing model transparency, XAI fosters greater trust and supports informed decision-making, allowing users to better understand the drivers of losses and how interventions influence resilience (Ghaffarian et al., 2023).

Results

Based on the outcomes, it was seen that in SHAP analysis, as economic losses increase, the relative importance shifts from meteorological factors toward socioeconomic and intervention features. The main interventions that influenced the model prediction were related to infrastructure, flood awareness, alert systems, and response plans. These findings inform not

only retrospective evaluation of the intervention but also guide the enhancement of essential measures.

Another advantage of this approach is the ability to simulate intervention scenarios and assess their impact on flood outcomes across regions. We applied the catastrophic 2024 Valencia flood scenario to Lugo and Getafe provinces, which differ in their socioeconomic characteristics and levels of intervention implementation. Lugo exhibits higher levels of intervention compared to Getafe. Utilising meteorological data from the meteorological agency corresponding to the Valencia event, our model forecasts that Lugo would experience severe economic losses, whereas Getafe would likely face catastrophic economic losses under similar conditions. These results are consistent with existing data and literature, which indicate that Lugo demonstrates greater resilience to water-related disasters than Getafe. This analysis identifies the combinations of interventions that most effectively reduce risk, while also highlighting regions that require additional investment or policy innovation.

Discussion and Conclusion

Based on the development work, it is possible to assess flood management interventions. The framework quantifies the effectiveness of these interventions and enhances the interpretability of model predictions. It serves as a robust decision-support tool for authorities to improve disaster preparedness, minimise economic losses, and strengthen community resilience. Beyond introducing a methodological approach to disaster risk science, this work provides actionable insights for policy development and informed decision-making. The framework allows users to predict future economic impacts based on specific interventions, locations, and hazard magnitudes. It also helps determine the necessary interventions to achieve targeted loss outcomes under given flood scenarios.

Future research will expand this framework by incorporating additional historical data to refine the models and contextualise the influence of social and environmental factors. Furthermore, ongoing enhancements to XAI techniques will aim to deliver even more granular and actionable insights, supporting the development of strategies. Ultimately, this research contributes to building a more adaptive and resilient future for Spain and serves as a replicable model for other countries facing similar flood-related challenges.

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Integrating Sociocultural Characteristics into Flood Mobility Models: Insights from Sudan and Mozambique

Eleonora Panizza[1]
1 The CIMA Research Foundation, Italy, eleonora.panizza@cimafoundation.org

Abstract

Floods and storms are major drivers of disaster- induced human displacement, posing growing global concerns and political challenges. While the causal link between housing damage and displacement is well known, the influence of sociocultural, economic, and psychological factors in shaping household responses remains underexplored. In the context of intensifying climate-induced disasters, understanding mobility dynamics through local specificities becomes critical for advancing resilience strategies and optimizing Early Warning Systems (EWS). This research draws on comparative fieldwork in rural villages in Sudan and Mozambique, using structured questionnaires to collect data on sociocultural, economic and experiential dimensions, including risk perception, trust in the EWS, and coping capacities, assessing how they influence mobility decisions across diverse population clusters. The insights provided by individual and comparative analysis inform an agent-based model simulating mobility dynamics under flood scenarios. This modeling enables policy analysis, supporting the optimization of EWS, the design of risk communication, the adoption of risk reduction strategies suitable to the context, supporting decision-makers in prioritizing actions. The comparative approach aims to identify behavioral patterns that may be generalizable across regions, with the goal of establishing thresholds and parameters for probabilistic modeling. This supports scalable applications, enhances effectiveness, and reduces the costs of displacement modeling. By integrating disaster risk reduction, social sciences, and computational modeling, this work proposes a comprehensive framework for adaptive, context-sensitive mobility management and disaster resilience, contributing to more effective, inclusive and locally-grounded EWS design.

Keywords: Disaster displacement; immobility; risk perception; Early Warning Systems; policy analysis.

Systemic Climate Risk Mapping in Rural Municipalities: A Semantic-GIS Framework for Vulnerability Assessment and Resilience Planning

Ines Hofmann, ines.hofmann@kit.edu
Sonja Rosenberg, sonja.rosenberg@kit.edu
Frank Schultmann, frank.schultmann@kit.edu

Abstract

Rural municipalities face increasing climate risks, yet lack systemic, resilience-oriented tools to assess multi-dimensional vulnerabilities and support evidence-based adaptation planning. This study presents a transferable climate risk assessment model integrating causal network analysis, stakeholder input, and spatial data. Using Freudenstadt (southwestern Germany) as a case study, the approach maps interdependencies across municipal systems, translates climate, socioeconomic, and spatial indicators into measurable nodes within a systemic network, and applies graph metrics to identify critical pathways shaping vulnerability. Embedding the model into a Geographic Information System (GIS) enables spatially explicit risk mapping and resilience planning by revealing hazard-prone zones and cross-sectoral dependencies. Its modular structure supports evidence-based decisions, context-sensitive strategy transfer, and comparative resilience planning.

Keywords: climate adaptation, rural municipalities, systemic risk assessment, resilience planning, spatial analysis

Introduction

Climate change disrupts infrastructure, strains public services, and exacerbates health risks in municipalities. While climate mitigation remains essential, many impacts are unavoidable due to lock-in effects and time delays – even under ambitious climate targets (IPCC, 2023). Adaptation is therefore required across stakeholder groups. As municipalities face context-specific impacts shaped by geography, infrastructure, and social dynamics, place-based approaches are essential.

However, municipalities – especially in rural areas, home to over half of Germany's population (Küpper, 2016) – lack tools to assess climate risks and translate them into strategies. Barriers include limited resources, fragmented responsibilities, and insufficient urgency (Friedrich et al., 2024).

Despite the growing relevance of climate adaptation, rural municipalities remain underrepresented in systemic risk research combining spatial analysis, semantic modeling, and multi-risk dynamics. Existing approaches to municipal climate risk assessment often focus on individual sectors (Egerer et al., 2021), emphasize screening over systemic analysis (Hübner & Finkbeiner, 2025), or rely on descriptive indicator frameworks (Porst et al., 2022). Their

applicability to local, interconnected systems is therefore limited, constraining strategic adaptation planning.

This study addresses these gaps by developing a locally operational and transferable model for climate risk assessment in rural municipalities. Using Freudenstadt as a case study, it integrates systemic causal analysis, stakeholder input, and spatial data. The model supports evidence-based adaptation by identifying vulnerabilities, simulating climate-related stressors, and visualizing risk patterns across municipal systems.

Methodology

To develop the model, this study employs an exploratory, multi-step methodology (see Figure 1). It is conceptually grounded in the Intergovernmental Panel on Climate Change (IPCC) framework, where climate risk emerges from the interaction of hazard, exposure, and vulnerability (IPCC, 2023). Accordingly, these components are integrated to enable spatial climate risk mapping.

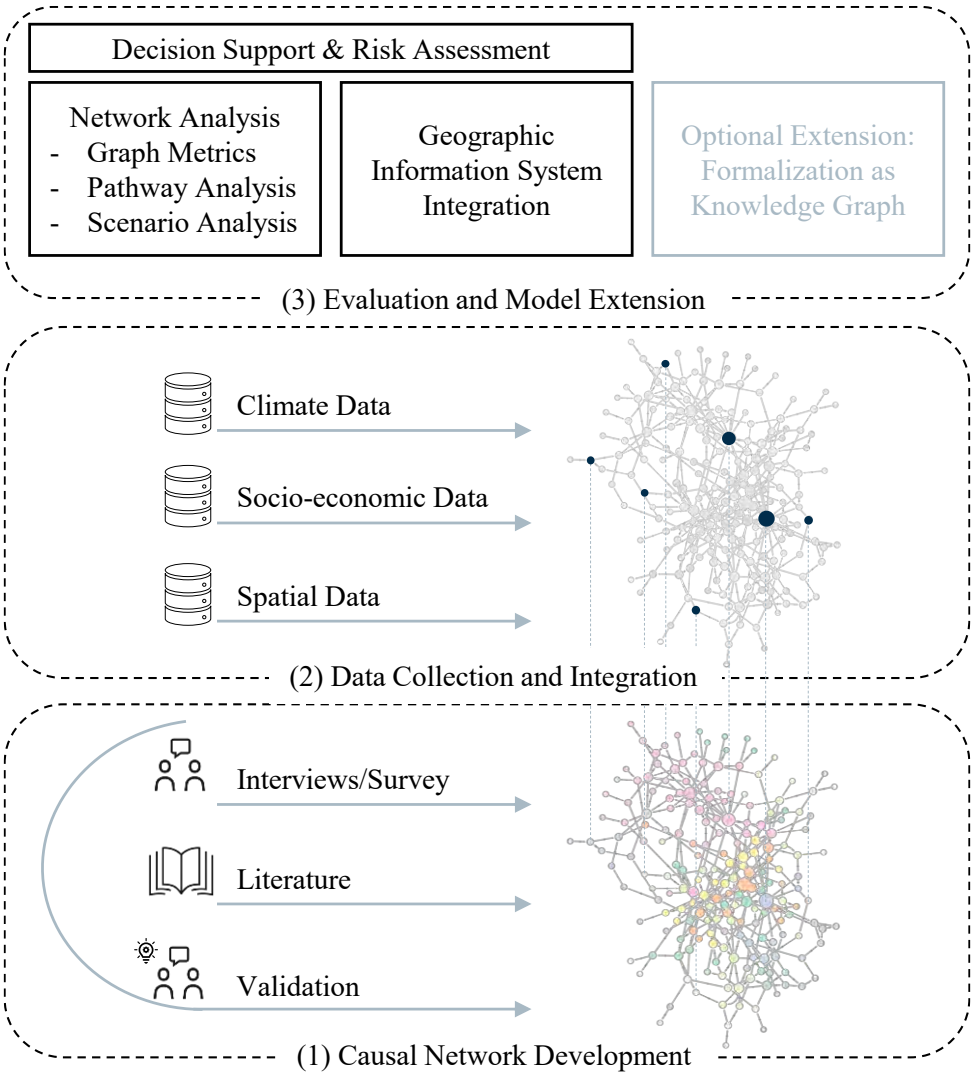


Figure 1: Multi-step methodology for climate risk assessment.

Causal Network Development

Initially, a causal network is developed to address two key questions:

- How does climate impact the municipal system under climate change?
- What additional constraints must be considered for a comprehensive understanding of climate impact and assessing the need for action?

Insights were collected through semi-structured interviews and surveys with local stakeholders from tourism, urban planning, utilities, and climate protection, allowing for targeted input and open reflections. Additionally, policy documents and scientific literature complemented these findings. The resulting interdependencies were reviewed and validated for local relevance, considering systemic links and adaptive limits.

The resulting causal network divides the municipality into five systems with associated subsystems, while climatic influences (climate stressors) act externally (see Figure 2).

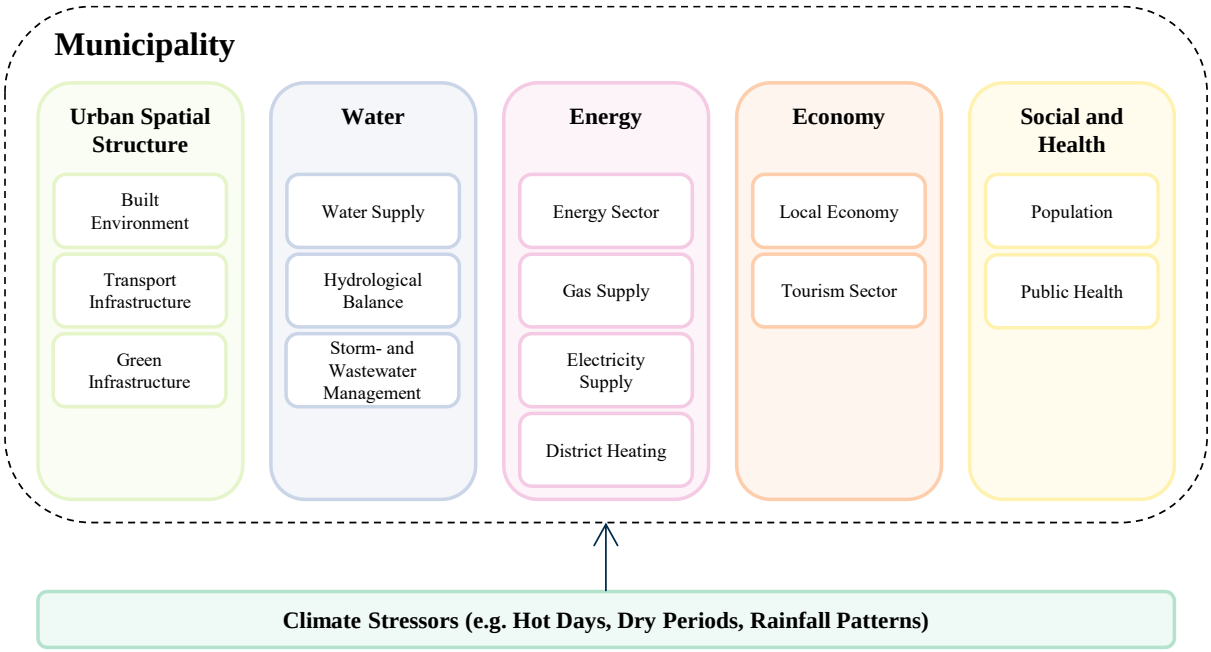


Figure 2: Municipal systems under climate influence.

Following graph-theoretical principles, the causal network consists of nodes and directed edges: Each node represents a function or process within the municipality, while edges indicate directional relationships between these elements, coded as reinforcing or counteracting (Barbrook-Johnson & Penn, 2022).

Data Collection and Integration

In the subsequent process, climate, socioeconomic, and spatial data are integrated into the causal network. Variables from public databases and municipal records were normalized for cross-node comparison. To incorporate relevant climate data for current conditions and future scenarios, thresholds for climate stressors were identified. Table 1 illustrates examples of indicators for node operationalization.

Table 1: Exemplary data allocation.

System	Urban Spatial Structure	Economy	Social and Health
Subsystem	Transport Infrastructure	Local Economy	Population
Node	Alternative Mobility Options	Tax Revenue	Elderly People
Indicator	Percentage of the population with access to public transportation[1]	Tax revenue per capita	Percentage of the population aged 65 and older
Geographic Level	Association of municipalities	Municipality	Municipality
Minimum	0.00%	-5,628 €	7.60%
Maximum	100.00%	103,476 €	52.90%
Average	80.27%	1,326 €	23.89%
Median	88.20%	1,117 €	23.30%
Freudenstadt	82.30%	1,403 €	23.20%
Normalized[2]	0.73	0.44	0.39
Source	BMWSB et al., 2020	BMWSB et al., 2023	Statistische Ämter des Bundes und der Länder, 2023

Evaluation and Model Extension

The network will be analyzed using graph metrics such as Local Reaching Centrality (Mones et al., 2012), Closeness Centrality (Freeman, 1978), and Eigenvector Centrality (Bonacich, 1972; Zhang et al., 2023) to identify key nodes, critical pathways, and structural dependencies. Pathway and scenario analysis will be applied to simulate climate-related stressors, system responses, and possible adaptation measures.

The previously acquired spatial data are utilized to embed the network within a Geographic Information System (GIS), enabling spatial queries and external dataset overlays. Exposure is integrated by linking nodes to climate hazard zones as part of the vulnerability analysis.

As a potential extension, the causal network may be formalized into a semantic knowledge graph to enhance transparency and interoperability in disaster resilience planning. Using ontologies and standardized relations, nodes can be enriched with attributes, enabling comparative analysis and integration with external datasets across municipalities.

Expected Results

The approach builds on the network analysis described in the methodology. It provides metrics of climate susceptibility for individual nodes within a network, highlighting critical nodes and sectoral connections. The categorization of municipal systems facilitates the identification of system-specific vulnerabilities and cross-sectoral dependencies, supporting integrated

[1] Access to public transportation: Living within a maximum straight-line distance of 600 m (or 1,200 m for railway stations) of a stop with at least 20 public transport departures per day (BMWSB et al., 2025)
[2] Percentile normalization (p5–p95): Data scaled to [0,1] using the 5th and 95th percentiles as anchors

adaptation planning. Building on the IPCC framework, node-specific indicators will be derived to quantify vulnerability and support spatial risk assessment.

Integrating the network into GIS allows spatially explicit vulnerability mapping, identification of hazard-prone zones, support for comparative assessments, and prioritization of adaptation needs across municipalities. By linking nodes to climate hazard zones, the approach is likely to reveal exposure patterns and infrastructure risks. The resulting visualizations aim to facilitate interdisciplinary interpretation, stakeholder communication, and evidence-based decision-making.

The semantic structure of the network is modular and transferable. Its architecture enables future semantic expansion to improve interoperability, transparency, and integration with external data and decision-support tools.

Conclusion

This study presents a structured and scalable approach to assessing climate vulnerability in rural municipalities. By integrating systemic modeling and spatial visualization, it fosters interdisciplinary collaboration and supports evidence-based decision-making. The model serves as an instrument to strengthen climate resilience by enabling targeted, cross-sectoral adaptation planning and improved risk anticipation.

Acknowledgements

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Advancements in Flood Vulnerability Models and Risk Assessments: Quantitative Analysis of Adaptation Strategies for Buildings

Jonathan Ciurlanti[1], Danny Bond[1]
1 Arup, The Netherlands

Abstract

Flood disasters remain one of the most damaging natural hazards in Europe, generating both direct losses to buildings and indirect impacts that significantly delay recovery. Current approaches often overlook how specific adaptation strategies can effectively reduce vulnerability and downtime in residential buildings. This study applies a refined component-based modelling approach to a typical Dutch terrace house, comparing as-built and adapted configurations. Results show that structural measures such as relocating service equipment reduce expected losses, while their combination with service agreements can cut downtime by nearly 50%, highlighting the importance of integrated adaptation strategies.

Keywords: Flood Resilience; Vulnerability Assessment; Adaptation Strategies; Economic Loss; Downtime

Introduction

Disaster risk is defined as the combination of three key factors: hazard, vulnerability, and exposure. The interplay of these factors determines both the extent of potential damage and the level of societal disruption. Floods alone accounted for 81% of climate-related economic losses in Europe in 2023, affecting an estimated 1.6 million people (WMO, 2023).

Beyond direct impacts such as casualties and property damage, floods generate also substantial indirect losses. These losses are not only influenced by the extent of damage but are also dependent on external factors including the effectiveness of response and recovery efforts. To address these challenges, recent research has increasingly focused on resilience-based frameworks and probabilistic approaches to assess flood-related impacts and support investment decisions. For example, the REDi guidelines (Arup, 2023) establish resilience objectives that extend beyond life safety, emphasizing aspects such as downtime reduction. Similarly, probabilistic based models (Cluster and Nishijima 2015; Nofal et al., 2020) provide a means to quantify expected damage and economic loss under uncertainty.

However, once estimated decision variables such as repair costs and downtime, the quantification of building specific adaptation strategies impacting the vulnerability of buildings is typically missed or their benefits are estimated only qualitatively.

This study advances the integration of adaptation into vulnerability assessments by explicitly evaluating multiple adaptation scenarios. A typical Dutch terrace house is implemented as a case study, first analyzed in its as-built configuration through a component-based loss

assessment. A range of adaptation measures are incorporated into the vulnerability analysis. Their effectiveness is evaluated in terms of vulnerability reduction of both repair costs and downtime. Structural and non-structural adaptation strategies are modelled, including the effect of impeding factors.

Component-level probabilistic framework

A component-based approach, similar to FEMA P-58 methodology for seismic risk assessment, is employed to estimate key decision variables in the case of flood events. By improving the existing framework proposed by Nofal et al. 2020 a fully probabilistic flood risk assessment methodology is implemented to estimate both direct and indirect losses, as described in Figure 1, enabling the estimation of building specific flood vulnerability following REDi Flood guidelines (Arup, 2023).

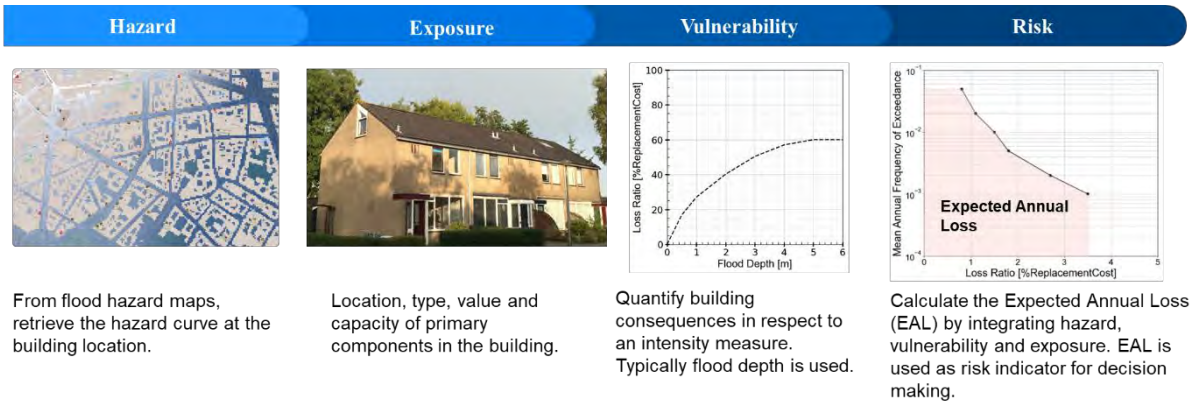


Figure 1. Framework to perform flood risk assessments including hazard, exposure and vulnerability (Ciurlanti et al. 2025).

Based on the framework presented in Figure 1, a detailed analysis of hazard, exposure, and vulnerability is typically carried out to derive loss curves and calculate Expected Annual Losses (EAL). In this study, however, the focus is limited to exposure and vulnerability components. Particularly, an exposure assessment is carried out, including all components present in the building such as structural, non-structural and building equipment. For every component its location and failure modes are identified to define damage fragility curves. To develop building-level vulnerability curves, multiple frameworks have been recently proposed in literature based on Monte Carlo analysis and uncertainty propagation (Cluster and Nishijima 2015; Nofal et al., 2020). These frameworks enable deriving the relationship between an intensity measure and its impact in terms of consequences. However, they typically quantify direct losses, and when indirect losses are integrated, only the repair time is considered, neglecting repair sequence and impeding factors. REDi for Floods, published by Arup in 2023, takes a step forward in estimating delays that affect the start of building repairs and the real sequence of repairs, including the number of workers allowable per floor. The proposed framework therefore enables the definition of a vulnerability curve for the building, considering loss ratio and the days to full recovery.

Adaptation Strategies & Vulnerability Reduction

Flood adaptation strategies for buildings are critical to reducing vulnerability and mitigating long-term impacts in flood-prone areas. FEMA guidelines (FEMA P-259; FEMA P-312) provide a framework for implementing both structural and non-structural measures, including elevation, relocation, floodproofing, and the use of flood-resistant materials. These strategies not only minimize direct physical damage but also enhance community resilience by reducing recovery time and associated economic losses. Integrating such measures into residential design and retrofitting practices is therefore essential for developing effective, risk-informed adaptation pathways. In addition to physical interventions, the implementation of service agreements is fundamental to enhancing preparedness after a major flood event. Such agreements can reduce impeding factors that often delay the initiation of building restoration, thereby facilitating faster recovery.

Within this study, both structural and non-structural measures are modeled using the methodology described in the previous section, with results presented in Figure 2. In particular, the relocation of service equipment to the attic is simulated alongside institutional measures, including pre-arranged agreements with contractors and building insurance.

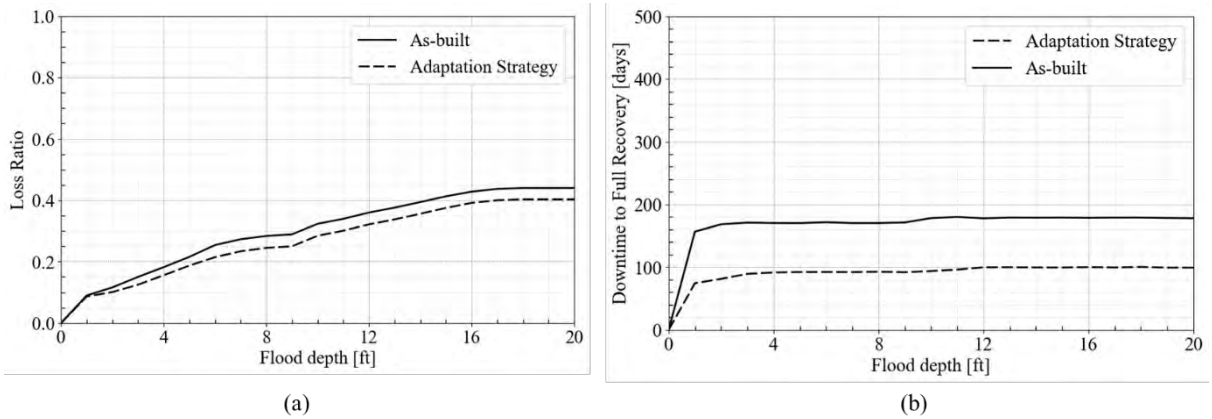


Figure 2. Vulnerability curves for (a) loss ratio (as the ratio between repair costs and total replacement costs), and (b) downtime to full recovery.

Conclusions

This study demonstrates the potential of refined component-based modelling for the vulnerability assessment of residential buildings, shown through the case of a typical Dutch terrace house. Starting from the as-built configuration, structural and non-structural components are assessed, and multiple adaptation scenarios are integrated into the analysis. The results show that while structural measures such as relocating service equipment yield a modest reduction in expected losses, they avoid the need for extensive engineering design. More importantly, when combined with non-structural strategies, particularly service agreements with contractors and insurance providers - the benefits become substantial, leading to nearly 50% reduction in downtime.

These findings underscore that adaptation should not be viewed solely through the lens of structural interventions but rather as a combination of technical and organizational strategies. By explicitly quantifying both physical and non-physical measures, the approach presented

here provides valuable insights for decision makers, enabling risk-informed planning at both the building and regional scales.

Acknowledgements

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From Review to Practice: Digital Integration of BIM and GIS for Multi-Hazard Vulnerability Analysis and Climate Resilience of Buildings

Steffen Neuner [1], Christopher Munschauer [1], Christian Braun [2], Alexander Fekete [1], Ulrich Leopold [2], Philippe Pinheiro [2], Stefania Stellacci [3], Derya Yilmaz [2], Catarina Ferreira da Silva [3]

1 TH Köln - University of Applied Sciences Cologne, Institute of Rescue Engineering and Civil Protection, Betzdorferstr. 2, 50679 Köln, Germany; steffen.neuner@th-koeln.de, christopher.munschauer@th-koeln.de, alexander.fekete@th-koeln.de

2 Sustainable Urban and Built Environment Research Group, Luxembourg Institute of Science and Technology (LIST), 5 avenue des Hauts-Fourneaux, L-4362 Esch-sur-Alzette, Luxembourg; christian.braun@list.lu, ulrich.leopold@list.lu, philippe.pinheiro@list.lu, derya.yilmaz@list.lu

3 Instituto Universitário de Lisboa (ISCTE-IUL), ISTAR, Lisboa, Portugal; stefania_stellacci@iscte-iul.pt, catarina.ferreira.silva@iscte-iul.pt

Abstract

The contribution outlines a workflow that includes a scientific review and the development of an exposure and vulnerability database, integrating Building Information Models (BIM) and Geographic Information Systems (GIS). The database is aligned with the emerging concerns in the European Union regarding the future-proofing of buildings in the context of climate change and increasing natural hazard frequency and intensity. The results of a scientific review provide the baseline for vulnerability assessments of buildings, leveraging a three-dimensional geodatabase that incorporates BIM. The objective is to facilitate the ability of homeowners to make informed decisions regarding retrofitting strategies and resilience measures.

Keywords: multi-hazard, BIM, GIS, vulnerability assessment, building resilience

Introduction

Climate change is increasing the frequency and intensity of natural hazards, leading to loss of life and high costs (DG Echo, 2021; Forzieri et al., 2016; Navarro et al., 2023). The necessity for climate adaptation of buildings and the ageing built environment in Europe is emphasized by the New European Bauhaus initiative.[1] To support these efforts, the Horizon Europe co-funded project RETIME[2] is developing advanced, digital, and user-centered applications to shape decision-making in retrofitting processes.

[1] https://new-european-bauhaus.europa.eu/about/about-initiative_en
[2] https://cordis.europa.eu/project/id/101147113

In line with the Sendai Framework for Disaster Risk Reduction (UNDRR, 2015), we aim to contribute to the reduction in disaster risk and losses in lives, livelihoods, and health by empowering homeowners to identify risks, vulnerabilities, and appropriate risk-reduction measures. *Unlike common disaster risk analyses that typically consider large areas, we evaluate single buildings, assessing their exposure and vulnerabilities towards natural hazards.* Based on this building vulnerability assessment, retrofitting solutions can be proposed to homeowners. This strategy enables a knowledge transfer to civil society to better understand mitigation potential and effectively increase risk awareness.
In an innovative approach, we combine geospatial hazard and exposure data with physical vulnerability data extracted from open-access geodatasets and BIM. The scientific foundation is an extensive review of 26 physical vulnerability studies. The usage and integration of BIM into vulnerability assessments is still limited, as discussed in literature (Amirebrahimi et al., 2016; Liu et al., 2017; Mayouf et al., 2022), but its potential to add fine-grained indicators such as interior elements is increasingly recognized.

We present findings from this review and share insights into the current development of the database developed to assess the exposure and vulnerability of buildings. By examining real-world case studies, this study aims to advance the integration of BIM into vulnerability assessments.

Methodological framework

We systematically searched WoS and Scopus and identified 26 scientific publications focusing on physical vulnerability assessments on building level. We then analyzed how many of these consider interior vulnerability indicators, such as the location of fuse boxes or stairways. These indicators are crucial for evacuation and for the function of building systems, like power supply (Khanmohammadi et al. 2020; Papathoma-Köhle 2016). Many vulnerability assessments lack interior vulnerability indicators. The integration of BIM with GIS offers a way forward for extracting such detailed information (Donkers et al., 2016; Noardo et al., 2020). The presented framework builds on these findings.

The database harmonizes multi-scale geospatial and building-level data to enable accurate analysis of multiple hazards. Buildings are the center of our database. The foundation is a 3D geodatabase with CityGML datasets, sourced from open-access datasets. Whenever possible, it is enriched with BIM-based models, providing highly detailed building data. This is combined with 2D multi-layer single hazard maps to assess the exposure of buildings to various natural hazards. Together with digital elevation models, a 3D exposure map can be produced.

Based on findings from the review, we select vulnerability indicators and demonstrate the extraction of these indicators from both open-access datasets and BIM models. The result is an integrated framework of the buildings' vulnerabilities, which can be summarized in a Building Vulnerability Report. This framework is visualized in figure 1.

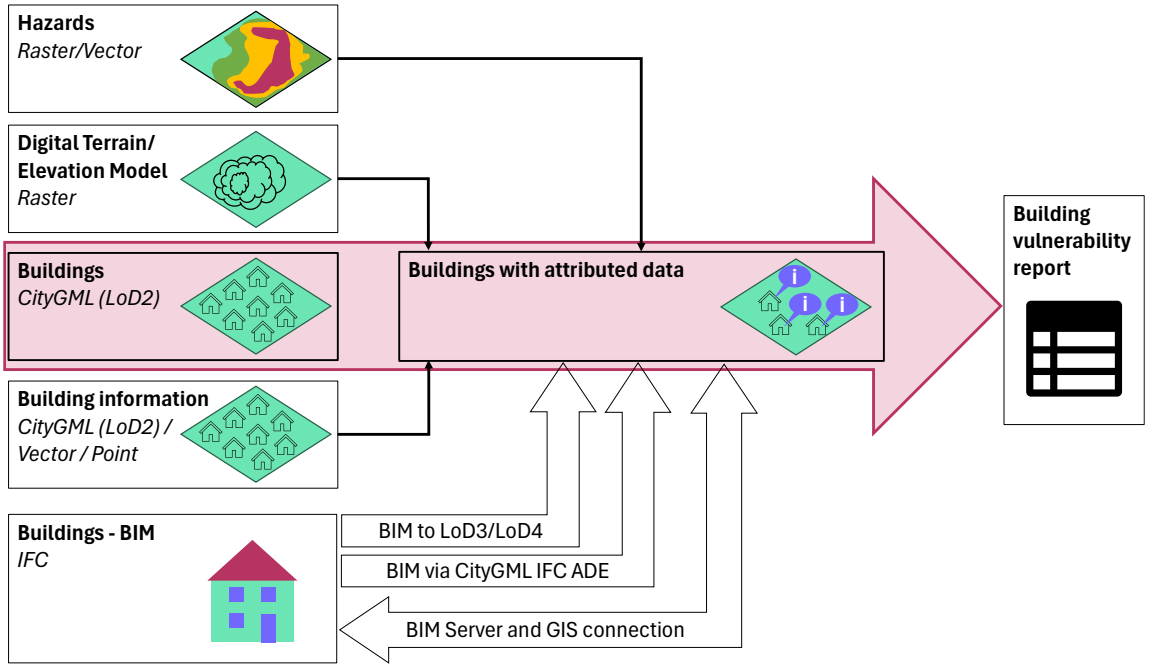


Figure 1. Framework of exposure and vulnerability database.

Technical realization

A 3D database based on Postgres/PostGIS with a 3DCityGML schema and relevant Application Domain Extensions (ADEs; e.g., IFC, Utility, Energy) offers a structured and flexible solution for managing 3D city models. This architecture enables the integration of both 2D and 3D data and ensures greater flexibility for future extensions. The use of CityGML with ADEs ensures that the data remains interoperable and can be easily exchanged with other systems, especially in the field of BIM and infrastructure management (Donkers et al., 2016; Noardo et al., 2020).

All data can be exposed through OGC Web Services (WMS, WFS, WCS for 2D data), while a 3D visualization is possible on a Cesium platform.[3]

Use cases

This Building Vulnerability Report can be used to establish data-driven retrofitting strategies relevant for homeowners, architects, engineers, and urban planners, among others. The database can provide data for tailored resilience advice for a range of key stakeholders, covering both structural and organizational measures. It can inform emergency planning by taking into account each specific features of the buildings and their physical vulnerabilities. When combined with early warning systems, the database also enables the generation of more specific automated alerts. Importantly, this approach can also be transferred to socially vulnerable housing contexts, where equity and stakeholder engagement are critical (Obonyo & Ouma, 2022).

[3] https://cesium.com/

Data and implementation challenges

The presented approach requires high-resolution and reliable data, as CityGML models are essential to perform vulnerability assessments. Higher vulnerability resolution can be obtained through available BIM data. This limits the applicability but enables tailored advice for retrofitting strategies. More broadly, challenges remain around data interoperability and adoption of BIM at scale (Succar & Kassem, 2015), requiring coordinated technical and organizational frameworks.

Acknowledgements

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Integrated Resilience and Circularity Assessment of Building Facade Retrofit Scenarios

Authors: Kyujin Kim, Natchai Suwannapruk, Puttakhun Vongsingha, Jens Böke, Abhinay Kumar, Jochen Hölscher, Anna Carolina Peres Suzano e Silva, Simona Bianchi, Alessandra Luna-Navarro

E-mails: k.j.kim@tudelft.nl, natchai.suwannapruk@priedemann.net, puttakhun.vongsingha@priedemann.net, jens.boeke@priedemann.net, akumar@hoelscher.gmbh, jhoelscher@hoelscher.gmbh, anna.silva@ams institute.org, S.Bianchi@tudelft.nl, A.LunaNavarro@tudelft.nl

Abstract

Selecting building facade retrofit solutions that meet decarbonization goals and are future-proof against natural hazards requires a multidisciplinary decision making process. However, assessment methods at the facade scale that integrates resilience and circularity remain limited. This paper proposes a method to evaluate and compare retrofit scenarios considering seismic resilience, heat resilience and circularity, by using multi-domain performance indicators such as seismic repair cost, discomfort degree hours and end of life carbon emissions. The proposed approach is demonstrated through a case study of a reinforced concrete frame building retrofitted with a timber rocking-dissipative external exoskeleton to enhance seismic capacity. Three facade retrofit scenarios are considered: a conventional rainscreen system; a rainscreen using low embodied-carbon materials; and a rainscreen supplemented with exterior solar louvers. Results highlight performance tradeoffs among retrofit scenarios, providing a rational basis for early stage design.

Keywords: building facade retrofit; seismic resilience; heat resilience; circularity; multi-criteria decision-making

Introduction

Multidisciplinary and integrated approaches to retrofitting existing buildings that address resilience to natural hazards and circularity are gaining importance (Menna et al., 2022). At the building facade scale, these approaches present distinct challenges. While insulative and airtight interventions enhance energy performance, they can increase the risk of overheating during heatwaves (Hao et al., 2022; Porritt et al., 2012). As nonstructural components, facades are designed with acceptance of high earthquake damage, which overlooks the economic and environmental cost of repairing the damage (Ahmad et al., 2024; Bianchi et al., 2020). Circularity informed material and detailing choices influence reuse potential, yet such considerations are rarely addressed at the early design stage (Hartwell et al., 2021).

As part of the Horizon Europe MULTICARE project (MULTICARE, 2024), a facade-specific resilience and circularity assessment method was developed. A database of market ready facade systems, including cost and material information, was also compiled. This work supports systematic assessment of facade resilience against multiple hazards for any given building. The proposed method was demonstrated on a real-world case study building in Acerra, Italy, considering alternative retrofit scenarios.

Methods

The baseline ("as-built") building is a reinforced concrete frame with masonry infill walls, located in Acerra, Italy, and constructed in the 1980s for residential use. A 3 m² room on the south-facing facade was selected as the representative context for evaluating retrofit scenarios. All calculations refer to a facade module comprising 10.74 m² of opaque wall and 2.73 m² of glazing (window-to-wall ratio = 0.25).

For the baseline building, three retrofit scenarios were defined (Table 1). In all cases, a timber rocking-dissipative external exoskeleton (D'Amore et al., 2025) was incorporated, aligned with the plane of the existing frame to resist in-plane lateral loads, thereby enhancing seismic capacity while limiting damage to both the structural frame and the facade components. Scenario R1 reflects conventional facade practice: a rainscreen system, in which the insulation layer is separated from cladding to form a ventilated cavity. Scenario R2 retains the rainscreen configuration but replaces the materials with lower embodied carbon. Scenario R3 adds exterior solar louvers to the rainscreen system.

Retrofit performance was quantified using the following indicators. Seismic repair cost was estimated with a consequence model linking damage extent to repair cost. Damage was characterized with fragility curves – i.e., masonry infill from Cardone and Perrone (2015) and timber stud wall from the FEMA P-58 fragility database (FEMA, 2018) – and considering a life-safety design response spectrum (475-year return period) for the seismic hazard input. Heat resilience was expressed as cumulative discomfort degree hours using Standard Effective Temperature (SET), applying the passive survivability threshold (USGBC, 2019). The evaluation focused on 8-15 August 2021 heatwave, which recorded the highest daily maximum temperature in 1951-2023. Circularity was assessed through end of life carbon emissions estimated using the Bombyx plug-in (Basic et al., 2019). Indicators were then min–max normalized and plotted on a radar chart to enable comparison of the baseline and retrofit scenarios.

Table 1. Systems and construction details of selected retrofit scenarios

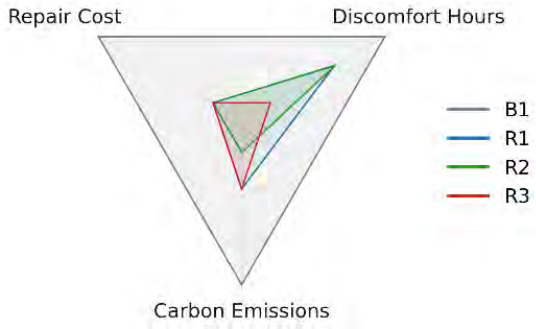
ID	Scenario	Structural System	Facade System	Facade Construction Layers
B1	Baseline	RC Frame	Masonry Infill	Plaster + Brick + Air gap + Glass wool + Cement + Plaster
R1	Retrofit	RC Frame + Timber Exoskeleton	Timber Stud Wall	Polyisocyanurate + Rock wool + Aluminum Cladding
R2	Retrofit	RC Frame + Timber Exoskeleton	Timber Stud Wall	Cellulose + Cellulose + Wooden Based Board
R3	Retrofit	RC Frame + Timber Exoskeleton	Timber Stud Wall	Polyisocyanurate + Rock wool + Aluminum Cladding + Solar Louver

Results

Table 2 presents the calculation results for seismic resilience, heat resilience and circularity across the four retrofit cases. Structural strengthening through the implementation of an exoskeleton (R1, R2, R3) reduced severe damage, thereby lowering the overall cost of repairing damaged components. Reducing solar radiation transmittance through the implementation of

external louver (R3) resulted in the lowest discomfort degree hours, performing better than adding insulative layers (R1, R2). Retrofit scenario with low carbon materials (R3) resulted in lowest end of life carbon emissions.

Table 2. Comparison of resilience and circularity across facade retrofit scenarios (values per facade module)

ID	Scenario	Seismic Resilience	Heat Resilience	Circularity	Comparison of Retrofit Scenarios
		Seismic Repair Cost (EUR)	Discomfort Degree Hours (SETh)	End of Life Carbon Emissions (kg CO2eq)	
B1	Baseline	9326.9	311.8	69.8	
R1	Retrofit	6848.3	288.6	21.7	
R2	Retrofit	6848.3	289.3	3.4	
R3	Retrofit	6848.3	259.4	21.7	

Discussion and Conclusions

This paper presented a method to guide future-proof building facade retrofit design decisions, demonstrated on a six-story residential building from the 1980s in Acerra, Italy. The as-built structure, a reinforced concrete frame with masonry infill, was seismically strengthened with a timber exoskeleton in all retrofit scenarios. Three alternative scenarios were configured: a rain screen cladding measure suited to the local context, a low carbon solution, and a heatwave mitigation measure. Three scenarios were evaluated across seismic resilience, heat resilience and circularity, using performance indicators including seismic repair cost, discomfort degree hours, and end of life carbon emissions. Results showed that adding external solar louver reduced the discomfort degree hours during heatwave but raised carbon emissions. This highlights tradeoffs between domains and the need for multi domain evaluation to guide resource allocation in retrofit decisions. The study was limited to scenarios with deterministic attributes based on typical, market-ready components. Future work could examine variability in material properties and facade configurations to develop balanced, effective solutions that optimize resilience and circularity.

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Strategic Green Roof Implementation for Pluvial Flood Risk Reduction

Ahmed Owais Durrani[1], Marcello Arosio[1], Maria Pregnolato[2]
1 IUSS Pavia, Italy
2 TU Delft, Netherlands

Abstract

The increasing intensity and frequency of extreme rainfall events, coupled with rapid urbanization, are amplifying the pluvial flood risk. Urbanization reduces the natural infiltration process and increases surface runoff. To improve the surface infiltration in urban areas, Nature-Based Solutions (NBS) are gaining importance. Among these NBS, Green Roofs (GR) are considered a suitable solution for urban regions as they enhance infiltration, offer co-benefits, and require limited space. The study presents a risk-based framework to evaluate the capacity of GR in reducing pluvial floods, using Milan as a case study. A novel hybrid Curve Number-Cellular Automata (CN-CA) approach is presented in the study to assess the hazard. The exposure is focused on physical buildings and the road transport network. To evaluate vulnerability, the study incorporates various vulnerability functions. The framework compares alternative GR implementation strategies for optimizing the design. The results reveal that GR can substantially reduce exposure and the overall risk.

Keywords: Pluvial flood risk; Risk-based framework; Nature-based solutions; Urban Resilience

Introduction

Climate change is exacerbating the intensity and frequency of extreme rainfall events, impacting urban areas adversely. Pluvial floods occur when these intense rainfall events overwhelm the capacity of the natural or artificial drainage network. Urbanization intensifies the impacts of these floods by reducing surface infiltration. Conventional flood risk mitigation measures are constrained in urban areas due to limited space. To tackle this problem, NBS are increasingly promoted for urban flood risk management as they can restore the infiltration capacity of the surface. GR, a form of NBS, is well-suited for urban areas where horizontal space for NBS is limited. GR can intercept rainfall, enhance the retention, and delay the surface runoff.

Despite the evidence on the benefits of GR in the literature, there is limited evidence about how different implementation strategies can influence their effectiveness. Moreover, most studies focus on the hazard reduction capabilities. Comprehensive frameworks that evaluate risk reduction remain scarce in the literature. Therefore, the study aims to determine how different implementation strategies can influence pluvial flood risk in Milan by assessing their impact on the exposure of residential buildings and road transport networks. Milan serves as the case study, given the availability of potential GR in Milan from (Comune di Milano, 2024).

Data and Methods

The hazard is modeled using a hybrid CN method combined with the CA approach. The CN method was selected for its simplicity in integrating the GR changes within the framework.

The CN method was modeled using (InVEST, 2025), which requires Land Use Land Cover, Soil Hydraulic groups, biophysical table, and rainfall inputs. The rainfall inputs, representing a six-hour extreme event, were formulated through a Generalized Extreme Value analysis of ERA5 rainfall data (Hersbach et al., 2023). A limitation of the CN method is that it formulates the flood volume but does not spatially propagate it. To overcome this limitation, the generated flood volume was converted into a hydrograph. The outputs of this hydrograph, combined with a digital elevation model, were used as an input for the CA approach proposed by (Ghimire et al., 2013). The CA approach alone was insufficient for the analysis, as it does not directly account for the integration of GR. The exposure datasets were sourced from OpenStreetMap and datasets available from the Milan Municipality. The InSYDE model developed by Dottori et al. (2016) was used to assess the impact on physical buildings. Similarly, the impact on the road network will be assessed using the JRC depth damage function form (Huizinga et al., 2017).

Three different GR implementation strategies were incorporated within the framework. The Water Depth (WD) strategy prioritized areas with the highest water depths, followed by the Area (AR) strategy, which prioritized roofs with the largest area. Finally, the Random Iteration (ITE) strategy allocated GR randomly. The GR integration was carried out in increments of 5% ranging from a baseline scenario with no GR integration to complete coverage of the potential GR dataset.

Results

The results indicated a reduction in exposure across different GR implementations. Figure 1 illustrates the reduction in exposure under baseline and 10% GR integration for the WD strategy. Even a limited implementation of 10% in the WD strategy significantly reduces the buildings exposed to pluvial floods.

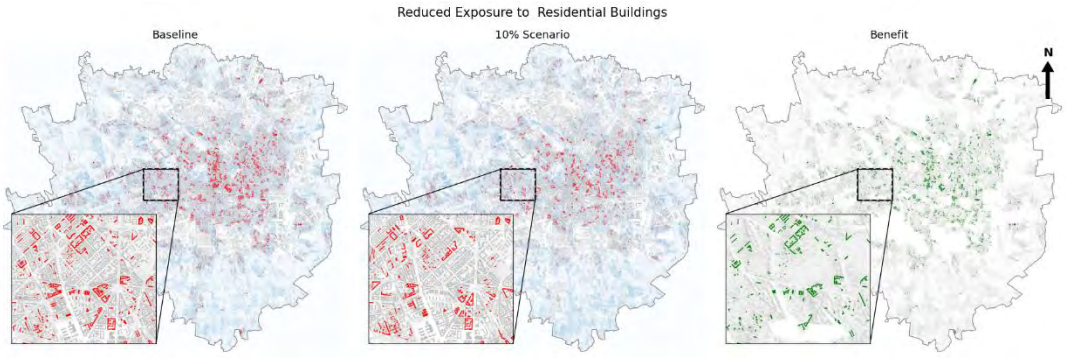


Figure 1: Reduction in the exposure of buildings to pluvial floods

Similar patterns of reduced exposure were observed for impact on transport networks as well. These findings indicate that the conceptual framework of GR integration can enhance surface infiltration and deliver co-benefits across different exposure domains.

The Average Annual Loss (AAL) shown in Figure 2 highlights the capacity of GR to reduce flood risk under different strategies. Even with limited GR integration of 10%, the losses decreased by 23-26% with WD and AR performing better than the ITE approach. At 50% integration, a significant drop in AAL can be observed. Notably, the losses do not differ significantly between 50% and 100% implementation for AR and WD scenarios.

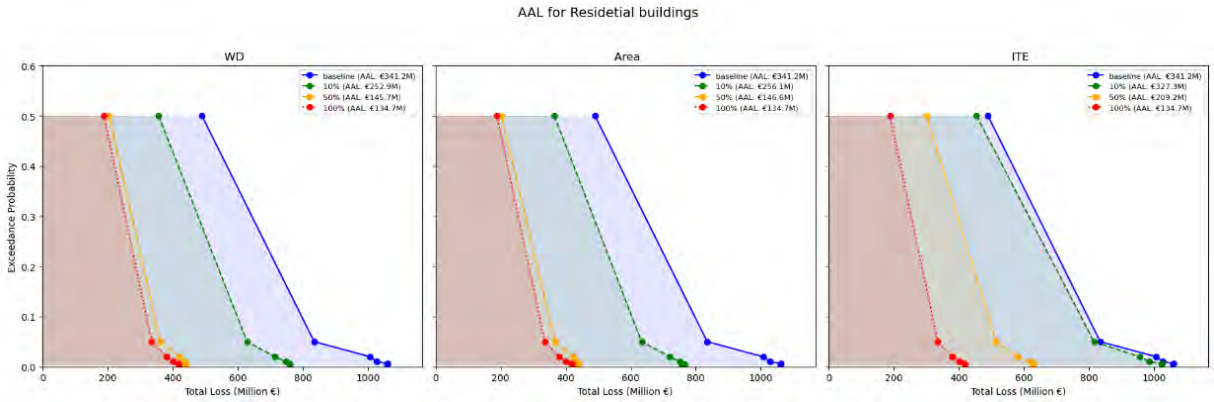


Figure 2: Average Annual Loss for residential buildings under different GR implementation strategies

Across strategies, prioritization based on WD and AR yielded better results at lower GR integration, with WD yielding slightly better results. This underlines the importance of strategic implementation. At higher integration levels, the benefits for WD and ITE converged. From a planning perspective, these results highlight the importance of targeted GR implementation, while further optimization of the design will require a comprehensive cost-benefit analysis.

Conclusion

The study demonstrates the effectiveness of GR in reducing pluvial floods in Milan by proposing a risk-based framework. However, the study has certain limitations, such as reliance on the ERA5 rainfall data, which can be unreliable for higher return periods. Future work will extend the framework to fully incorporate the impacts on the transport network and conduct a comprehensive cost-benefit analysis, including co-benefits, to support evidence-based decision-making for resilience planning.

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From Challenges to Solutions: A Framework for Nature-Based Solutions Selection in Deltas

Hao Su LMU Munich, Germany, hao.su@lmu.de

Abstract

River deltas face compound risks such as flooding, salinity intrusion, land subsidence, and sediment deficits, which increasingly undermine their resilience to climate change and natural hazards. Nature-based Solutions (NBS) are promising strategies to address these challenges, yet their adoption often lacks a systematic framework for targeted selection and model-based evaluation. This study introduces a target-issue-based NBS selection framework that explicitly links identified deltaic stressors to suitable NBS measures. The framework follows two key steps: (i) issue diagnosis, which characterizes dominant hazards and environmental pressures, and (ii) NBS mapping and selection, where each issue is matched with candidate measures such as mangrove restoration, floodplain reconnection, sediment-trapping structures, or wetland rehabilitation.

To quantify effectiveness, selected measures are parametrized in hydrodynamic models. Parametrization translates ecological interventions into measurable variables, including modified roughness coefficients for vegetated floodplains, infiltration and storage terms for wetlands, or adjusted sediment transport parameters for trapping structures. This enables the simulation of NBS scenarios under varying boundary conditions and the comparative assessment of their performance in mitigating deltaic hazards.

By systematically connecting issues, measures, and model parameters, the framework provides a transferable approach to designing, implementing, and evaluating NBS strategies. It contributes to advancing decision-support for resilient delta management and offers practical insights for integrating ecosystem-based measures into climate and disaster resilience planning.

Keywords: Nature-Based Solutions; Delta Resilience; Issue-Based Framework

Advancing Engineering Assessment, Planning, and Design to Achieve Natural Infrastructure Resilience

Margaret Kurth[1], Matthew Smith[2], Todd Steissberg[1], Caleb Sytsma[3]
1US Army Corps of Engineers, Engineer Research and Development
2US Army Corps of Engineers, Institute of Water Resources
3 ORISE Research Fellowship

Abstract

Natural landscapes and features are increasingly being framed as infrastructure assets and discussions ensue about whether and how concepts from traditional infrastructure sectors can be applied to them, despite their dynamism. The natural or otherwise cost-effective resilience (self-recovering and adaptiveness) of natural infrastructure is often cited as a strength over alternative hard solutions. Although they are nascent, many researchers and practitioners of risk management and ecosystem restoration are beginning to envision standards for natural infrastructure design and methods to understand what human interventions are necessary through time to support resilient outcomes. Realizing the framing of nature as infrastructure requires new interpretations of existing engineering methods and a strategic, virtuous cycle of monitoring and modeling. This presentation will report on a variety of related work in the realm of engineering concepts for natural infrastructure, spanning from conceptual to quantitative. First, a lifecycle management framework is proposed as well as lifecycle cost as a resilience metric. Next, ongoing research that aims to guide the selection of performance-based natural infrastructure design parameters is presented. This research uses a salt marsh model that dynamically couples hydrodynamic, waves, morphology, and vegetation growth/death to support a better understanding of the relationships between specific marsh characteristics and performance objectives such as wave attenuation. Ultimately, these are part of a research agenda to development a design framework that links modeling, field and lab research, and monitoring to inform salt marsh design for specific performance objectives and informs lifecycle interventions to support resilience.

Keywords: natural infrastructure, performance-based engineering, lifecycle cost analysis, resilience

Climate-resilient water management in low-range mountain areas

Sophie Charlotte Kuhlmann[1], Prof. Dr. Sascha Henninger[2], Prof. Dr.-Ing. Dörte Ziegler[1]
1 University of Applied Sciences Koblenz, Germany
2 RPTU Kaiserslautern, Germany

Abstract

Climate change poses an increasing number of challenges to communities. Especially in low range mountain areas, water management is sometimes confronted with conflicting challenges, such as an increasing possibility of heavy rainfall and dry periods (IPCC 2022). In addition to climate adaptation and the sponge city and water-sensitive city concepts, climate resilience emerges as a way of addressing these challenges.
This PhD study examines the relationship between these concepts as well as the potential benefits of climate resilience and how it can be achieved. As there is no common definition of resilience (Fekete et al. 2014; Camacho et al. 2024; DWA T2/2024), the study first considers how to operationalize the concept and identify indicators for measurement.
Two case studies then analyze current blue-green infrastructure measures that are or are intended to be implemented in low-range mountain areas and how they can contribute making communities more resilient.

Keywords: low-range mountain areas; communal decision-making; water management; effectiveness; blue-green infrastructure

Introduction

Climate change poses an increasing number of challenges to communities. In low-range mountain areas in particular, water management is sometimes confronted with conflicting challenges, such as an increased possibility of heavy rainfall and dry periods (IPCC 2022). Alongside climate adaptation and the concepts of sponge cities and water-sensitive cities, climate resilience emerges as a concept to provide solutions to these challenges.
However, there is no common definition of resilience in the literature (Fekete et al. 2014; Camacho et al. 2024; DWA T2/2024). At the same time, communities are facing an increasing number of obligations to achieve it. This creates a dilemma for communal decision-making processes regarding how to measure and increase climate resilience. Furthermore, the relationship to other concepts, such as climate adaptation, sponge cities and water-sensitive cities and vulnerability, is not always clear. This calls for an operationalization of climate resilience in relation to existing water management concepts. This paper will therefore propose practical indicators.
In addition to the existing concepts mentioned above, communities are implementing blue-green infrastructure measures. The effectiveness of these measures in terms of climate

resilience will be analyzed using the above-mentioned indicators by modelling of heavy rainfall and dry periods.

Methodology

In a first step, the concept of climate resilience is analyzed alongside existing concepts through a literature review. Furthermore, the suitability of existing evaluation frameworks for blue-green infrastructure in urban areas in relation to heavy rainfall and dry periods is assessed.

Two case studies in low-range mountainous areas in Germany will analyze the effectiveness of existing measures. In a first step, the current understanding and status of climate resilience within the communities will be investigated through semi-structured interviews with relevant stakeholders. The intended blue-green infrastructure will then be modelled using hydrological and hydraulic modelling as well as calculations to evaluate its effectiveness. Regarding decision-making, the impact of past experiences with extreme climatic events on progress towards climate resilience will be analyzed.

Operationalization of climate-resilience in water management

Although definitions of resilience vary in literature, there is a common understanding that it describes the management of disruptive, unpredictable and/ or unimaginable events (Mentges et al. 2023). This makes it relevant to the challenges posed by climate change. While flood protection and water management currently focus largely on the probability of events (based on historical statistics), decisions regarding climate change are determined by uncertainty (Birkmann et al. 2023). Furthermore, the existing concepts mainly focus either on too much or on too little water. This paper adopts the approach of Cutter and Derakhshan (2019) defining the system boundaries by asking the following questions "*Resilience to what? And resilience for whom"* (ibid, 13).

The concept of climate resilience considers the possibility of events occurring closely together in both time and place. Along these lines, the following indicators were defined to evaluate climate resilience in relation to water management:

Table 1 Indicators chosen for climate resilience.

Climate-resilience				
Water balance with distribution of infiltration, run off and evapotranspiration	Storage capacity with retention volume	Flooding area with water level, Velocity	Need for watering with division of supply and demand	Capability for further development; e.g., expandability
Interconnection with vulnerability				
Age distribution		Economic situation (income)		
Further evaluation factor				
Former experience with disruptive events				

The indicators are not weighted because the objective of the study is not to provide a generic evaluation of climate resilience, but rather to take a differentiated view of which measures can contribute to which aspects. Furthermore, weighting is often considered to be either subjective (Aroca-Jiménes et al. 2023) or normative (Held 2023). While the study analyses decision-making processes, it does not intend to provide normative recommendations, as these depend on the specific context of each community.

Case studies

In order to apply the indicators and evaluate measures of blue-green infrastructure, two areas were selected for study. Due to the particular challenges posed by low-range mountainous terrain, the topography played a significant role in the selection of these areas. The following criteria were also considered, with the exclusion criteria highlighted in gray:

Table 2 Criteria for the selection of study areas (exclusion criteria in gray)

#	Criteria	Elaboration	Characteristic	Impor-tance
1	Exposure to flash floods / heavy rains	Exposure	Dismay of population at heavy rain	High
2	State	State of Rhineland-Palatinate, Germany	Yes / no	High
3	Topography	Low range mountain area	Absolute altitude of 500-1.500 m and difference in altitude of 200-1.000 m | yes / no	High
4	Data of water management | gauge	Availability of data	Available / not available	High
5	Data of water management | weather station	Availability of data	Allocable weather station available / not available	Low
6	Data of water management | ground water gauge	Availability of data	Allocable gauge available / not available	Low
7	Size of catchment area	Catchment area in km²	Small, middle, large	Mediate
8	Administrative units in catchment area	Responsibilities within catchment area	Number of administrative units	Mediate
9	Experience of disruptive events related to climate change	Previous events such as flash floods	Vulnerability high, middle, low	High

10	Vulnerability to climate change (temperature increase)		Temperature increase since pre-industrial times of > 1,5 °C	High
11	Type of landscape		Comparable landscape type	Mediate
12	Land use	Type of land use	Comparable distribution of land use types (agro / forest etc.)	Mediate
13	Scenery	Characterized by water	Body of water	High
14	Soil characteristic		Water retention	Mediate
15		Quality for agrological use	Field capacity	Low
16	Settlement structure	type and distribution of building development	Share of settlement area (low, middle, high)	High
17		Share of traffic area	Share of traffic area (low, middle, high)	High
18		Population density	Population per km²	Mediate
19	Economy	Comparable distribution beyond economic sectors	Distribution in %	High
20	Concept for flash flood / climate adaptation management	Availability of concepts	Available / not available	high

Both, the *Bad Neuenahr-Ahrweiler* and the *Kirner Land* communities have experienced heavy rainfall in the past. In particular, the 2021 flood in the Ahr valley captured international attention. Both areas have policy documents and implementation plans in place addressing questions regarding water management in the context of climate change. These plans mainly focus on protecting against flooding caused by heavy rainfall. These include measures such as renaturation and trough-and-trench systems.

Currently (08/2025), the semi-structured interviews are ongoing looking at how climate resilience is approached and the role of previous experiences play in decision-making. Interview partners include the civil engineering department, the urban planning department and the climate adaptation management, among others.

Preparations are also ongoing to model the measures using the *NASIM* and *Scenarify* systems. The latter is the stat of Rhineland-Palatinate´s semi-public model.

As the focus is not solely on heavy rainfall and flood protection, the modelling will use input data from not only the 2021 Ahr flooding, but also from lower-scale rainfall coupled with a period of no rain. The long-term effects, possible synergies and weaknesses will therefore be analyzed.

Conclusions and way forward

The study made a proposal for operationalizing climate resilience of water management. During this process, links were established with existing concepts such as climate adaptation, vulnerability, and water-sensitive urban planning. The next step is to analyze whether and how measures of blue-green infrastructure measures can increase the climate resilience of communities in low-range mountain areas. To this end, hydrological and hydraulic modelling, as well as water balance calculations, will be employed.

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Accelerated Delhi Heat Action with Artificial Intelligence (AI) and Machine Learning (ML)

Haripriya Kesavan[1], Meghna[1], Samhita R[1], Mrinalini Srivastava[2]
1 Resilience AI, India, haripriya@resilience360.ai, meghna@resilience360.ai, samhita@resilience360.ai
2 IPS Director National Disaster Management Authority, Ministry of Home Affairs, Government of India, mridus007@gmail.com

Abstract

Rising global temperatures are driving an increase in extreme heat events, which threaten public health, strain infrastructure, and disrupt daily life in cities worldwide, including India, where rapid urbanization, dense built environments, and socio-economic disparities amplify vulnerability. Among India's urban centers, the national capital, Delhi stands out as a critical heat hotspot, shaped by pronounced urban heat island effects and uneven socio-spatial exposure. The Delhi Heat Action Plan (DHAP) 2025, envisioned by the National Disaster Management Authority (NDMA) is anchored on the state disaster database guideline of Disaster Management Act 2005, serves as a city-wide, multi-scalar framework to combat extreme heat by integrating scientific assessments, local context, and targeted interventions. To support DHAP's data-driven planning, this study presents Resilience360™, a disaster decision system using Artificial Intelligence (AI) and Machine Learning (ML) to conduct heat assessments through a scientific evidence-based approach. The platform incorporates locations with diverse urban morphologies and socio-economic profiles, selecting four representative areas for hyperlocal heat risk assessment. These represent a mix of transit nodes, administrative hubs, and residential areas with distinct risk profiles. The analysis utilizes built-environment datasets and building structural typologies across all four heat-vulnerable regions. Integrating multi-stack technology with on-ground action, Resilience360™ serves as a tool to inform DHAP's strategy by identifying micro-hotspots of heat exposure. The system classified buildings into five risk categories based on exposure, structure, and building materials, revealing most mapped structures as high to moderate risk. The resulting risk maps guided ground-level surveys, helping field teams visually identify high-risk areas and prioritize buildings for on-ground validation and accelerate structural intervention implementation. Its modularity and use of scalable datasets make it replicable across other heat-vulnerable Indian cities. This study highlights the potential of AI and ML-driven granularized intelligence to strengthen inclusive and climate-resilient urban governance, offering a scalable playbook for addressing heat risks through science and technology integration.

Keywords: Artificial Intelligence, Machine Learning, Hyperlocal Heat Risk Assessment, Climate Resilience, Urban Heat Island Effect

Introduction

The escalating heat crisis in Delhi presents a significant challenge to urban infrastructure resilience. Urban areas globally are increasingly vulnerable to intensifying climate challenges, particularly extreme heat events (Calvin, 2023). This paper presents an innovative, Artificial Intelligence (AI) and Machine Learning (ML)-based decision support system designed to enhance urban resilience by minimizing the "cost of inaction" and expediting “speed of mitigation intervention” throughout the year as heat preparedness initiative. Delhi experiences extreme summer conditions, marked by intense heat and exceptionally high temperatures, often approaching 45°C during peak months. Delhi is highly susceptible to the impacts of heatwaves, primarily due to its dense population and significant proportion of low-income communities (Delhi Heat Action Plan, 2025). Remote sensing plays a critical role in heat risk assessment and enables monitoring of land surface temperature, vegetation, and built-up areas (Diem et al., 2024). Machine learning algorithms have emerged as powerful tools for heat risk assessment of each building and land parcel, with detection and classification of buildings, processing satellite imageries, indices, and complex geospatial datasets (Castro et al., 2025) (Ghorbany et al., 2023). This study demonstrates the transformative potential of science and technology integrated hazard, vulnerability and risk (HVRA) intelligence, using RISE™ design principles viz., reliable (accuracy), integrated (multi-variate datasets and technology stack), simple (accessible) and effective (decisions) towards addressing urban heat vulnerability for various locations in Delhi.

AI and ML Powered Disaster Risk Assessment for Heat

The research focuses on the detailed climate risk assessment for primarily four identified locations in Delhi. A proprietary enterprise software, Resilience360™, was utilized to deploy hyperlocal heat risk assessment for the Delhi Heat Action Plan. The assessment was conducted using high-resolution satellite imageries, geo climatic and geo-spatial datasets, and thereby assigns scores to indicate hyperlocal level of heat risk. The assessment analyses severity of risk for each building in the identified area of interest. The generated structure-level risk scores across four diverse urban zones helped with informed field visits for the surveyors. The multi-variate parameters integrated into the heat risk algorithm influencing the risk scores can be classified as follows:

Building footprint detection and structure characteristics

Using satellite imagery (512 × 512-pixel tiles) was processed using a U-Net segmentation model with an Efficient Net-based encoder to extract precise building and neighbourhood footprints. The output is used as base spatial layer for localized heat risk assessment. This method allows the assessment of building-level sensitivity to excessive heat.

Building material typology

To classify building material typologies across urban structures, a convolutional neural network (CNN) was used, which has been shown to be effective at extracting spatial data. The machine was trained using a curated dataset of structural components of building, to meet input dimensionality requirements. The model had an overall classification accuracy of 84.64%, indicating strong detection performance across diverse building clusters. Accurate structural identification was critical for assessing surface heat absorption characteristics, determining risk differentials in heat exposure, and developing targeted mitigation solutions such as cool roof installations and albedo enhancement interventions.

Climate and environmental datasets

The spatial and climatic datasets used for the heat assessment include LST (Land surface temperature), water lines, water bodies and Normalized Difference Vegetation Index (NDVI).

The parameters are integrated using Analytical Hierarchy Process (AHP) with the input geo-climatic datasets. The risk profile with a composite heat risk score is generated at a building level. The risk scoring is on a scale of 1 (very low) to 5 (very high), showing the exposure of all detected buildings in the target region, along with corresponding percentage of buildings at risk for the neighboring area.

Locational Characterization: Study Area

Through a series of hyperlocal heat risk assessments conducted in four critical areas of Delhi, each selected for its unique urban built form and critical relevance to heat risk (See Figure 1). Firstly, a densely populated low-income settlement Sultanpuri, in northwest of Delhi, is characterized by compact housing, minimal green cover, and high social vulnerability. Second, a notified slum Kalakunj within the otherwise planned Shalimar Bagh sub-zone, reflects intra-ward disparities, with unplanned housing, poor ventilation, and limited access to cooling infrastructure. Followed by two high-footfall transit hubs Anand Vihar ISBT in eastern and Maharana Pratap ISBT northern Delhi are dominated by impervious surfaces and intense anthropogenic heat.

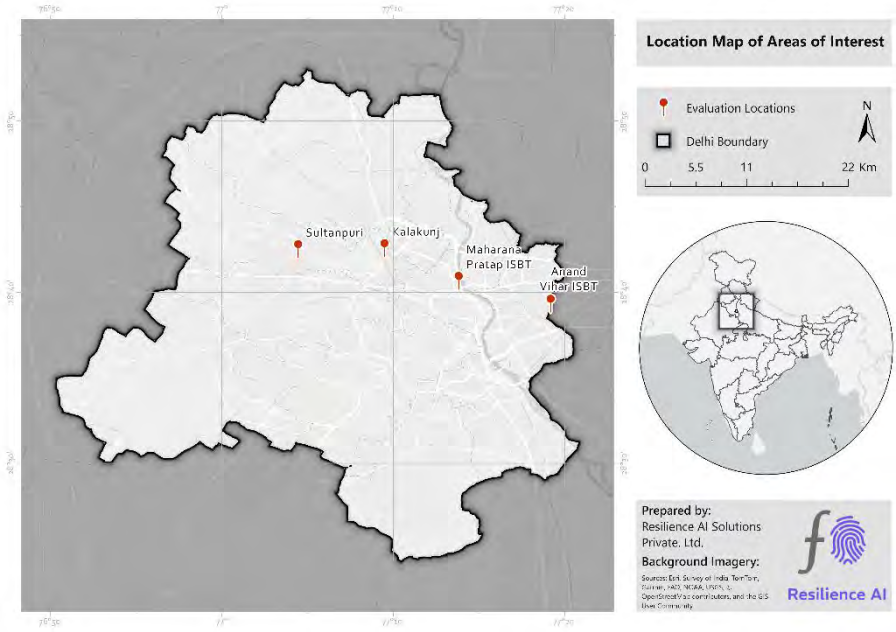


Figure 1 Location Map of Area of Interests in Delhi

Spatial Analysis and Model Output

Heat risk profiling using Resilience360™, nearly 8,346 buildings across four areas in Delhi were classified into five risk categories, whereby majority of buildings were concentrated in higher-risk zones, 65% identified as Very High Risk, 32% as High Risk, and 3% as Moderate Risk. Shalimar Bagh (including Kalakunj) is distributed between very high and high risk classes at 51% and 43% of identified built structures respectively (See Figure 2). The ISBT transit hubs, Maharana Pratap at 85% at high risk (See Figure 4) followed by Anand Vihar ISBT exhibiting the highest concentration at 96% with high risk (See Figure 3). The heat risk assessment for Sultanpuri reveals a high susceptibility to heatwaves, with 90% are at very high risk from heatwaves as emissions scenarios intensify, heatwave risks escalate sharply (See Figure 5).

The results were instrumental in planning and resource allocation for targeted on-ground field surveys in the Delhi Heat Action Plan.



Figure 2 Heat risk assessment map for Kalakunj, Shalimar Bagh



Figure 3 Heat risk assessment map for Anand Vihar ISBT



Figure 4 Heat risk assessment map for Maharana Pratap ISBT

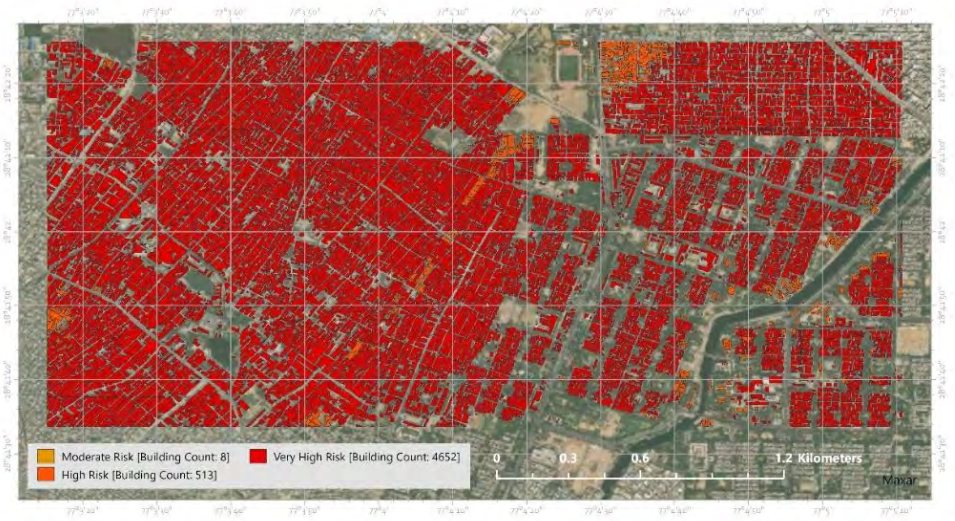


Figure 5 Heat risk assessment map for Sultanpuri

Conclusion

Resilience360™ successfully assessed 8,346 buildings across four diverse locations in Delhi for Heat Action. Hyperlocal climate (heat) risk assessment is integral to quantifying surface heat absorption characteristics, informing risk differentials in heat exposure, and enabling accelerated and targeted mitigation interventions such as cool roof installations and cooling infrastructure. The scalable methodology offers practical applications for enhancing urban resilience planning and informing evidence-based policy recommendations.

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Designing a Serious Collaborative Learning Game for Flood-Resistant Housing Reconstruction in Nepal

Garbhit Naik[1], Johannes Flacke[1], Eefje Hendriks[1],
1 Faculty of Geo-Information Science and Earth Observation, University of Twente (The Netherlands) (E-mail: garbhitnaik@gmail.com, e.hendriks@utwente.nl, j.flacke@utwente.nl)

Abstract

Disasters caused by natural hazards increasingly disrupt communities, with reconstruction often leaving households exposed to future risks. Post-disaster reconstructed houses often remain vulnerable to future hazards despite technical assistance from humanitarian or government actors. Conventional communication approaches, such as top-down training manuals or demonstration houses, often fail to respond to the diverse realities of affected households. Personalized communication is necessary to overcome barriers and support decisions toward hazard-resistant housing. However, humanitarian funding gaps limit resource-intensive assistance like door-to-door outreach. These challenges call for new ways of assessing and engaging community capacities that connect evidence, learning, and practice. This study proposes an alternative: designing audience-specific serious games to promote collaborative learning for disaster-resilient housing.

The approach builds on the Motivation–Ability–Opportunity (MAO) behavioral framework, which conceptualizes household decision-making in terms of willingness, technical capacity, and external support. Household survey data from 2,993 respondents in two flood-affected districts of Nepal were analyzed using cluster analysis and spatial autocorrelation techniques. The results segmented communities into 27 behavioral groups and revealed spatial patterns in their distribution. While motivation to rebuild safely was widespread, ability and opportunity were highly uneven, creating pockets of readiness alongside clusters of constraint. Importantly, spatial clustering showed that diverse groups often coexist across or beyond administrative boundaries, suggesting the potential for peer-to-peer learning as a pathway to resilience.

Through an iterative co-design process with local stakeholders, a localized serious game prototype was developed to stimulate social learning. Gameplay simulates incremental decision-making in reconstruction. Participants are divided into small groups and assigned roles such as homeowner, builder, or material vendor. Each round introduces a new flood scenario with higher water levels, forcing participants to make trade-offs between cost, resilience, and feasibility under budget constraints. Resilience is measured using a simple heart-based scoring system, enabling even low-literacy participants to grasp outcomes. After each round, groups reflect on their decisions and compare results, creating opportunities for peer-to-peer exchange. Prototype testing was conducted in four rounds with different stakeholder groups, including local humanitarian actors, disaster risk reduction experts, game design specialists, and university students.

Reflections showed the game's ability to influence behavior by encouraging dialogue, trust, and context-specific knowledge sharing. In conclusion, this research argues that resilience assessment in post-disaster contexts should not be separated from communication and learning. By tailoring tools to diverse community profiles and embedding them in collaborative formats, assessment itself becomes a participatory intervention. This research demonstrates that serious games, when grounded in behavioral frameworks and co-designed, can strengthen and innovate post-disaster communication. By tailoring content to community profiles and fostering peer interaction, the method provides a scalable process to develop low-cost tools to enable hazard-resistant reconstruction. The approach offers a replicable model for integrating gamification and social learning into disaster reconstruction programs.

Keywords: *Disaster Communication, Hazard-Resilient Housing, Behavioral Segmentation, Co-design, social learning*

Percolation-Based Road Network Robustness under Sea-Level Rise: Comparing Dynamic, Static, and Base-Case Criticality Strategies

Mohammad Zaher Serdar[1], Abdel Rahman Marian [2] and Eyad Masad [1]
1 College of Science and Engineering, Hamad Bin Khalifa University, Doha, Qatar. (MZS: moserdar@hbku.edu.qa , EM: emasad@hbku.edu.qa)
2 Zachry Department of Civil and Environmental Engineering, Texas A&M University, College Station, TX, USA. (AM: armarian18@tamu.edu)

Abstract

Road networks are critical infrastructure increasingly exposed to climate-driven disruptions. Ensuring their robustness is essential to maintain connectivity and mobility during and after hazards, informing where limited resources should be prioritized to reduce cascading disruption. This study presents a transferable framework for evaluating road network robustness under Sea-Level Rise (SLR) using graph-based percolation, demonstrated on Qatar's national road network across eight inundation scenarios derived from Intergovernmental Panel on Climate Change-Sixth Assessment Report (IPCC-AR6) and National Oceanic and Atmospheric Administration (NOAA) projections. Random percolation established baseline benchmarks, followed by targeted percolation guided by Node Strength (NS), previously identified as an effective graph metric, evaluated under three strategies: Dynamic Weighting (DW), Static Weighting (SW), and Base-Case Order (BCO). All targeted strategies required approximately half the removals of random percolation to reach the 50% GWCC threshold, confirming NS efficiency across all scenarios. The findings also reveal a clear trade-off evaluation among the three strategies, suggesting that full traffic model re-runs per scenario may not always be necessary to support effective emergency response planning and long-term resilience enhancement. However, such conclusions require further verification across different scales, disruption types, and network contexts. The generalizable framework supports comparative robustness assessment across networks and hazard types, providing planners with a systematic basis for resource allocation and resilience planning.

Keywords: Sea-Level Rise (SLR); Road Network Robustness; Graph-Based Percolation; Climate Change Impacts; Critical Infrastructure Resilience

Main contributions and novelty:

The principal contribution of this work is a targeted robustness-assessment approach that applies Node Strength (NS), identified as an effective metric in prior studies [1,2], across three removal strategies, Dynamic Weighting (DW), Static Weighting (SW), and Base-Case Order (BCO), to quantify strategy performance in terms of targeting efficiency (i.e., removals required to reach a connectivity-loss threshold) and computational demand, thereby clarifying practical trade-offs for resilience planning and disaster management. The approach is demonstrated using sea-level rise (SLR) as an exemplar hazard across eight high-resolution inundation scenarios plus the intact base case, with random percolation providing a consistent

baseline benchmark. The study is embedded within a transferable framework integrating hazard simulation, traffic modeling, graph analysis, and percolation-based robustness assessment, supporting comparability across networks and hazard types.

Methodology

This paper follows a stepwise framework combining hazard modeling, traffic simulation, and graph theory to analyze the robustness of road networks under the impact of SLR as illustrated in Figure 1.

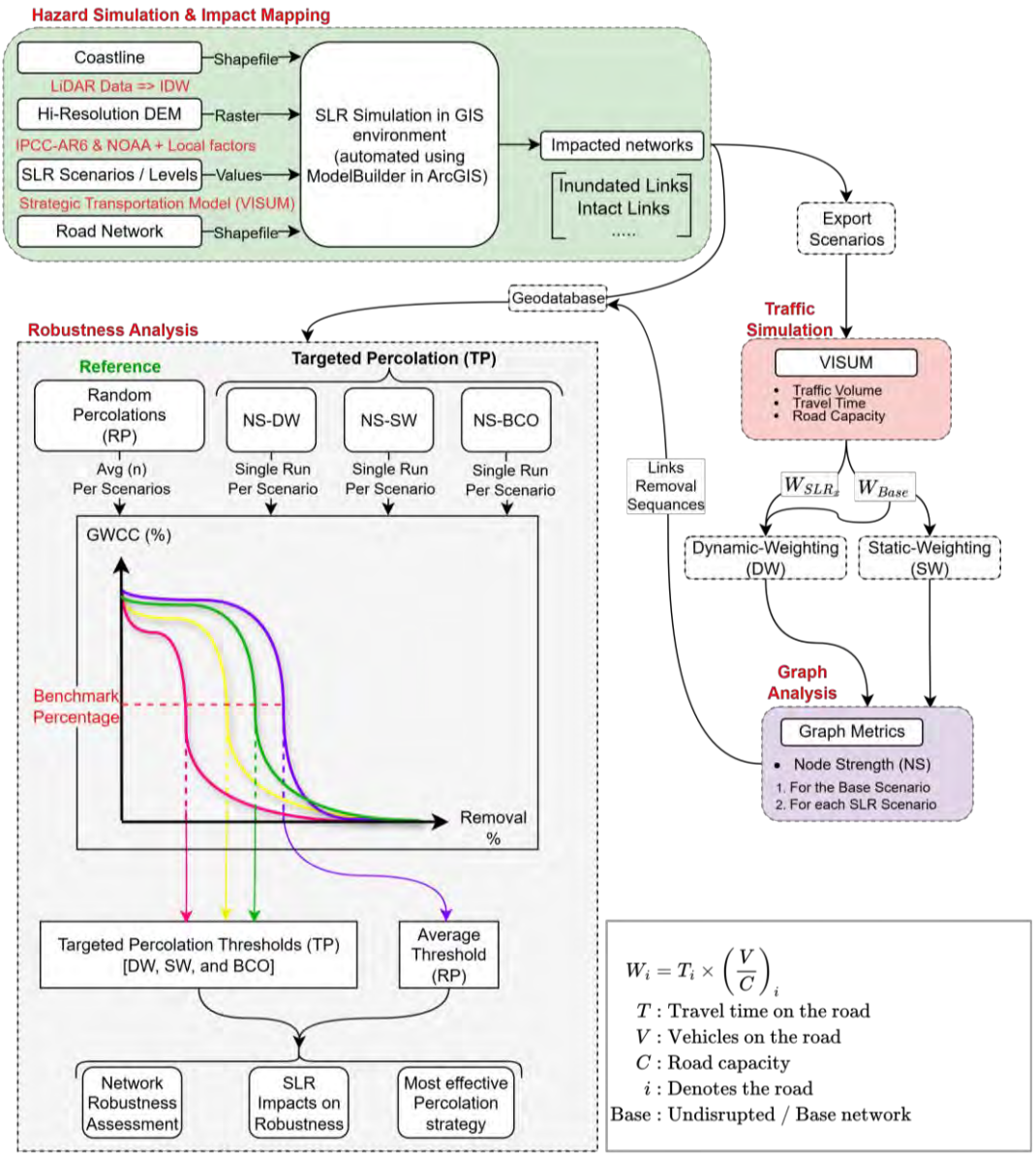


Figure 1: Methodological framework integrating hazard modeling, traffic simulation, and graph-based percolation to assess road network robustness under SLR. Random and targeted percolation sequences guided by Node Strength (NS) are applied under three strategies: Dynamic Weighting (DW), Static Weighting (SW), and Base-Case Order (BCO).

The framework proceeds across three stages. First, SLR hazard modeling was conducted using Qatar's national road network as the case study. Qatar provides a data-rich yet computationally

manageable national-scale network with diverse urban forms and road hierarchies, enabling a rigorous demonstration of traffic redistribution and robustness effects with strong potential transferability to other networks. Eight SLR scenarios were developed by combining global SLR projections, Mean Higher High Water (MHHW), and storm surges, as recommended in [3], and delineated using the bathtub approach in Geographic Information System (GIS) automated with ModelBuilder, with the inundation levels ranging from 1.61 m to 3.31 m by 2100, as summarized in **Table 1**, further details are provided in [4]. Inundated road links were identified by intersecting the network with flood polygons derived from the SLR scenario and incorporated into the traffic simulation model (VISUM).

Table 1: *SLR scenarios considered in the study and associated levels, adapted from* [4] .

Severity Level (Ascending)	Source	Emissions scenario (associated with feedback)	By 2100			
			SLR	Storm surge	MHHW	Total (m)
1	NOAA	Low (SSP1-2.6)	0.3	0.5	0.81	1.61
2	NOAA	Intermediate-Low	0.5	0.5	0.81	1.81
3	IPCC AR6	SSP1-2.6	0.62	0.5	0.81	1.93
4	IPCC AR6	SSP2-4.5	0.76	0.5	0.81	2.07
5	NOAA	Intermediate (SSP2-4.5)	1	0.5	0.81	2.31
6	IPCC AR6	SSP5-8.5	1.01	0.5	0.81	2.32
7	NOAA	Intermediate-High	1.5	0.5	0.81	2.81
8	NOAA	High (SSP5-8.5)	2	0.5	0.81	3.31

Second, VISUM was used to extract traffic volume, travel time, and road capacity for each scenario, informing two edge-weighting schemes: Dynamic Weighting (W_{SLR}), computed from scenario-specific outputs, and Static Weighting (W_{Base}), using frozen base-case parameters, both defined as [Travel Time × (Volume/Capacity)]. These weights underpinned three targeted removal strategies: NS-DW, in which Node Strength is recomputed on the degraded network using scenario-specific weights; NS-SW, where Node Strength is recomputed on the degraded network using base-case weights; and NS-BCO, where the removal order derived from the intact base network is reapplied across all scenarios without recalculation. A concise comparison of these three strategies is presented in **Table 2**.

Table 2: *Comparison of the three NS-guided targeted percolation strategies, Dynamic Weighting (DW), Static Weighting (SW), and Base-Case Order (BCO), across key methodological dimensions.*

Aspect	Dynamic Weighting (DW)	Static Weighting (SW)	Base-Case Order (BCO)
VISUM	To be re-run in each scenario	Base (intact) network only	Base (intact) network only
Graph NS metric	To be re-run in each scenario	To be re-run in each scenario	Base (intact) network only
Network used for NS computation	Degraded (flooded links removed)	Degraded (flooded links removed)	Intact base network
Edge weights used	Updated scenario-specific weights	Frozen base-case weights	Frozen base-case weights
Adapts to traffic redistribution?	Fully	No	No
Removal order updated per scenario?	Yes	Yes	No
Computational demand	High	Medium	Low
Real-world Analogies	A traffic engineer who, after every flood event, re-runs the	A traffic engineer who checks which roads are still standing	A city planner who computed a road importance ranking before

Aspect	Dynamic Weighting (DW)	Static Weighting (SW)	Base-Case Order (BCO)
	full traffic model to find out which remaining roads are now most congested and critical, then updates the priority list accordingly. Accurate but resource-intensive	after each flood, recalculates their structural importance using last year's traffic data (without re-running the model), and updates the priority list. Faster, but assumes traffic hasn't redistributed since the base scenario	any flooding occurred and continues to use that same list for all planning decisions regardless of how much flooding has happened. Simple and instant, but potentially outdated as damage accumulates.

Third, all networks were exported to a geodatabase and processed using custom Python scripts. Random percolation was applied across all scenarios to establish baseline benchmarks, with 200 iterations confirmed as sufficient for stable averages as demonstrated in **Figure 2**. The three targeted strategies (NS-DW, NS-SW, NS-BCO) were each run as a single deterministic pass per scenario, with the percolation threshold defined as the point at which the Giant Weakly Connected Component (GWCC) reaches 50% of its original size.

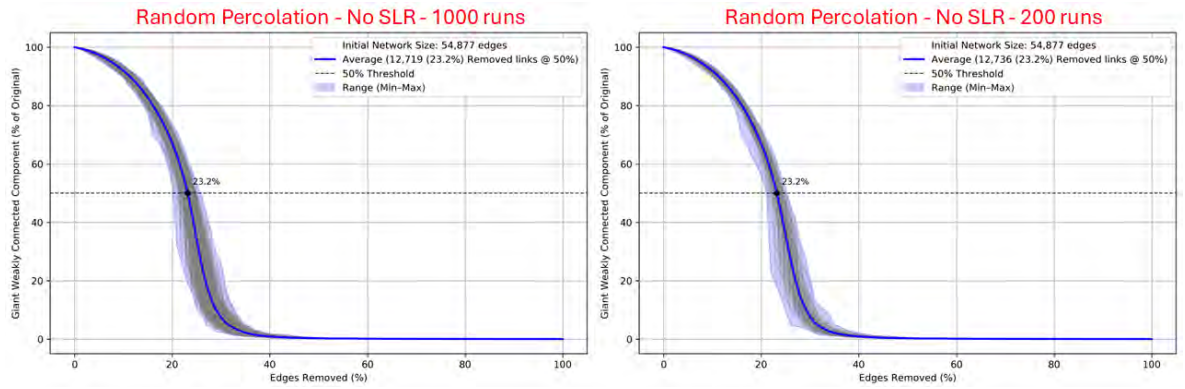


Figure 2: *Random percolation averages stability. Comparison between 1000 and 200 runs shows negligible differences, confirming that 200 runs are sufficient for stable benchmarks.*

Results

Results from all three targeted strategies and random percolation across the eight SLR scenarios are presented in **Figure 3** and **Figure 4**. Across all scenarios, all targeted NS-based strategies reach the 50% GWCC threshold at roughly half the removal percentage of random percolation, confirming the efficiency of NS in identifying critical links. In the base-case scenario, all three strategies achieve the threshold at 11.2% of removed links compared to 23.2% under random removal.

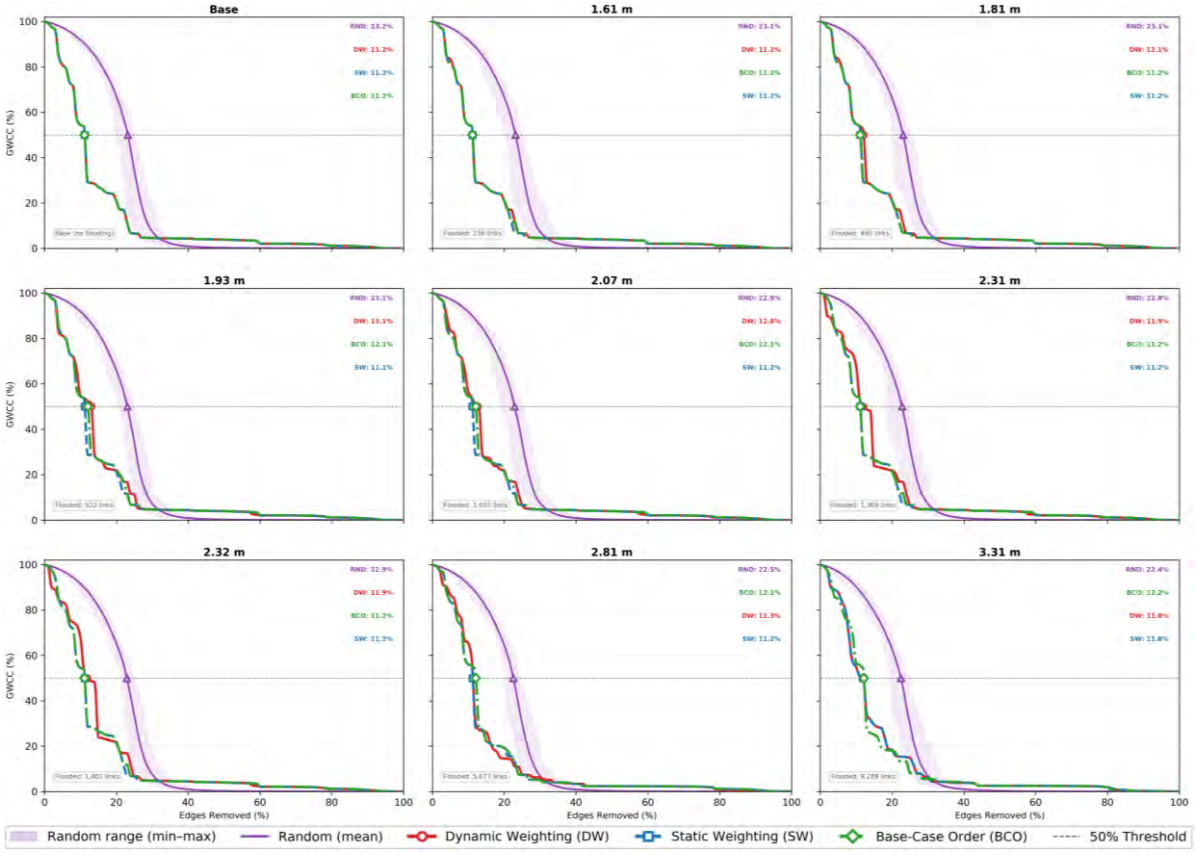


Figure 3: *Percolation curves across all scenarios comparing random removal and three NS-based targeted strategies, Dynamic Weighting (DW), Static Weighting (SW), and Base-Case Order (BCO). The shaded band represents the min-max range of random percolation runs; dashed line marks the 50% GWCC threshold.*

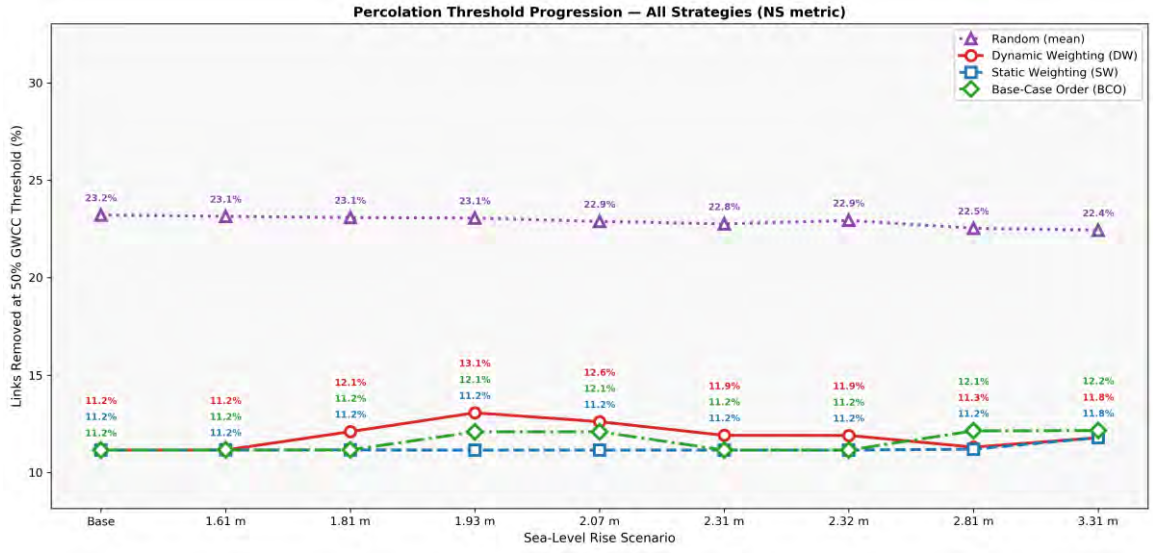


Figure 4: *Percolation threshold progression across SLR scenarios for all strategies. All targeted strategies consistently outperform random removal, with SW showing the greatest stability.*

Under moderate SLR (1.93 m), DW reaches its peak threshold of 13.1%, indicating that traffic redistribution on the degraded network generates new critical hubs not captured by base-network rankings, making targeted removal temporarily less efficient. BCO follows a similar

trend, also peaking at 12.1% under the same scenario, while SW remains the most stable strategy throughout, consistently requiring the fewest removals to reach the threshold. This stability reflects the fact that SW recomputes NS on the degraded topology without updating edge weights, avoiding the sensitivity to traffic redistribution that affects DW.

In the low-probability extreme inundation scenarios at 2.81 m and 3.31 m, BCO becomes the least efficient targeted strategy, requiring the highest number of removals among the three to reach the threshold. This suggests that at high flood extents, the pre-computed base-network removal order diverges most from actual degraded-network criticality, making it a less reliable guide for targeting. Meanwhile, the random percolation threshold decreases slightly with increasing SLR severity, consistent with the network already being weakened by pre-removed inundated links prior to the percolation sequence.

Conclusions

This study demonstrates that Node Strength-based targeted percolation consistently identifies critical links far more efficiently than random removal, requiring approximately half the removals to reach the 50% GWCC threshold across all SLR scenarios. The findings reveal clear trade-offs among the three strategies: DW offers the most adaptive targeting but at the highest computational cost, SW balances efficiency and stability at moderate cost, and BCO provides a computationally inexpensive yet surprisingly effective alternative. For practitioners, this suggests that full traffic model re-runs per scenario may not always be necessary to support effective emergency response planning and long-term resilience enhancement. These conclusions, however, warrant further investigation across different scales, hazard types, and networks beyond the presented case study.

Beyond the case study, the transferable framework integrating hazard simulation, traffic modeling, and percolation-based robustness assessment provides a systematic basis for evaluating infrastructure resilience under a wide range of climate hazards, supporting evidence-based resource allocation and adaptive planning.

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8. Shocks Shifts And Solutions

Two Sides of the Same Precarious Coin: Addressing Conflict & Climate Crises through Mindanao's Lens

Patience Saungweme [(1)], Vincenzo Bollettino [(2)], Stefan Spinler [(3)]
1. WHU - Otto Beisheim School of Management, Germany ; patience.saungweme@whu.edu
2. Harvard University - T. H. Chan School of Public Health, USA ; vbollett@hsph.harvard.edu
3. WHU - Otto Beisheim School of Management, Germany ; stefan.spinler@whu.edu

Abstract

Forced displacement is increasingly driven by integrated shocks, yet there exist limitations in how migration policies and humanitarian response mechanisms account for their combined effects. This case study explores the interplay between conflict and climate-induced displacement in Mindanao, a case uniquely illustrating complex crises. We examine how these shocks shape displacement dynamics and decision-making processes of both affected populations and intervening humanitarian actors. Using a mixed-methods approach, we integrate quantitative simulations of operational response dynamics and their outcomes, with qualitative socio-political and disaster readiness perceptions data. Findings shed light on misalignments existing between humanitarian operations responses and socio-political realities of displaced communities, along with their implications on long-term food security and sustainable livelihoods outcomes while offering a decision support framework supporting realignment. By bridging the gap between displaced populations' needs and institutional responses, this research provides insights into humanitarian operations and policy adaptations necessary for more effective humanitarian responses and enhanced community resilience. We provide initial directions for how integrated strategies can be operationalized through conflict- and climate-sensitive humanitarian response design and strategy, enabling the shift from short-term aid to long-term support that ensures sustainable food security and livelihoods recovery when complex crises become protracted.

Keywords: Humanitarian Risk Management, Strategy Formulation, Complex Crises

Introduction

In a world where armed international conflict ranks as the highest global risk, followed by climate-related weather events, there has been an increase in the number of people affected by both human-caused and natural disasters. This, in turn, has led to an escalation of global humanitarian needs as more people are forcibly displaced from their homes and centers of livelihood into states of crisis. These situations require external intervention for both care and protection, with many individuals remaining in this condition of helplessness for decades. The prevalence of protracted and complex crises has created a growing need across multiple levels of government and international organizations to develop and adopt intervention strategies that not only save lives and alleviate suffering but also strengthen community resilience in the face of ongoing shocks. This is often seen through rising levels of food insecurity and the erosion of livelihoods among forcibly displaced populations.

While studies in the field of humanitarian operations and humanitarian logistics have predominantly focused on improving how aid and support are delivered and administered, often resulting in cost-effective practices and increased efficiency, there has been relatively little attention paid to the nature of response policies required for protracted and complex crises. These crises demand approaches that go beyond meeting material needs and instead, prioritize increasing the capacity of affected communities to become self-reliant despite ongoing conflict and climate-related disasters. Disciplines such as public administration, public policy, political science, and sociology must be considered to develop a grounded approach that aims to enhance both survival and resilience outcomes for affected communities over the long term. However, the socio-political dimensions addressed by these fields are rarely incorporated into operational decision-making in resource-constrained crisis environments.

Many regions around the world are affected by both conflict and climate-related disasters, offering multiple candidate locations for analysis. The Asia-Pacific region stands out as particularly relevant due to its ongoing exposure to both protracted conflict and climate-related disasters. The study adopts a mixed methods approach to investigate these dynamics, centered on an in-depth case study in Mindanao. Findings will be triangulated to support the identification and formulation of integrated strategies that address both climate adaptation, aimed at reducing vulnerability to environmental hazards, and conflict-sensitive approaches that acknowledge the complexity of overlapping drivers, relevant in regions where the convergence of climate and conflict risks shapes both immediate humanitarian needs and long-term resilience trajectories.

We aim to support the development of more effective and integrated response policies that improve food security, health, and livelihood outcomes with the goal of contributing to saving lives, alleviating suffering, and enhancing the resilience of communities most affected by these overlapping crises.

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Would I Help You If I Needed to Save Myself? Local Initiatives in Disaster Responses, Adding Social Cohesion, Urgency and Motivation to Help Others to the Protection Motivation Theory

Julien Magana, Technical University of Delft, j.m.magana@tudelft.nl
Tina Comes, Technical University of Delft, t.comes@tudelft.nl
Saba Hinrichs-Krapels, Technical University of Delft, s.hinrichs@tudelft.nl

As disasters around the world increase in frequency and severity, governmental systems and emergency services are increasingly under strain. In response, social and community resilience emphasize engaging and empowering local communities to act during a disaster. To understand how these local mechanisms function, it is essential to know what motivates people to help *others* even if this means taking personal risks. This study expands Protection Motivation Theory (PMT) by integrating social cohesion, urgency, and the motivation to help others as key drivers of informal, locally led first disaster responses. Focusing on patient logistics during recent European floods in Western and Southern Europe, we analyze survey data to explore how people navigate self-protection and help others while facing a threat. By highlighting the role of communities in disaster response, this research offers new insights into behavioural dynamics and decision-making during crisis.

Keywords: community resilience; disasters; health; survey; protection-motivation theory

Introduction

Recent disasters from the 2021 European Floods (Hagenlocher, 2023; Fekete, 2021) and the 2023 Turkey/Syria Earthquakes (Aksoy, 2024; Akkaya, 2024) to the June 2025 Pakistan flood and the August 2025 Afghanistan Earthquake have highlighted the wide range of problems they can cause. These include disruptions to critical infrastructure (Hallgren, 2017), access and supply chain breakdowns (Hernantes, 2013; Jin, 2015), overwhelmed emergency and healthcare services (Jiang, 2019; Labrague, 2023; Aiken, 2002), displacement (Matias, 2020), secondary hazards (Van Dorst, 2024), economic disruption (UNDRR, 2020), as well as psychological (Cianconi, 2021) and social impacts (Bonanno, 2010).

Different actors contribute to the disaster response: emergency services (Bolling, 2007; Gamberini, 2022; Pokorny, 1999), healthcare providers (Ausset, 2016; Li, 2021; Kondo, 2012), military (Djalali, 2011; Walk, 2012; Kang, 2015), NGOs (Khaledi, 2022), volunteers and communities (Ganoe, 2023). They share the goal of saving lives but differ in priorities and motivations (Comes et al., 2020).

Informal responders (locals/communities) are often the first on site. The community and disaster resilience literature highlights that often communities come to the rescue, provide first aid, distribute food and shelter, clear debris, and share information (Nia, 2008; Mirhashemi, 2007; Djalali, 2011; Gingerich, 2015; Farahani, 2020; Caunhye, 2012; Tang, 2024). Their presence, local knowledge, and speed make them crucial, yet they are often excluded from

official emergency response plans. Understanding the behaviour of these communities, and what motivates them, is therefore essential for an effective disaster response and planning.

There is ample literature that studies the different motivations, yet many studies focus on organised volunteers, for instance those that are active in the Red Cross societies (Prytz et al., 2023, Smith & Grove). These studies show that a sense of belonging is a key factor in their motivation, while disaster and alarm fatigue are demotivating. Directly affected people may prioritize themselves or act under emotions (Breen, 2024), but there is a lack of research focusing on motivations to help others. Additionally, prior experiences with disasters can increase fear or urgency (Gul, 2015). Furthermore, education, social cohesion (Babcicky, 2020; Kim, 2017; Uslaner, 2015), trust, solidarity, demographics, and risk perception all shape responses (Kondo, 2012).

The Protection Motivation Theory (PMT), proposed by Rogers (1975), explains protective behavior through *threat appraisal* (severity, vulnerability) and *coping appraisal* (response efficacy, self-efficacy, costs). Our study is grounded in Protection Motivation Theory as it has been applied to a variety of disasters such as floods (Babcicky, 2019; Bubeck, 2018; Kakimoto, 2022; Tasantab, 2022; Kurata, 2022; Liu, 2024; Botzen, 2019; Gumasing, 2022; Flores, 2024), tsunamis (McCaughey, 2017), fires (Westcott, 2017; Kurata, 2023), earthquakes (Hu, 2022; Tang, 2018; Li, 2023), and COVID-19 (Hinssen, 2023; Kim, 2022). PMT also allows us to focus disaster response behaviors with the contrast between individual motivations to help others and to help yourself, based on threat and coping apraisals of respondents (Bubeck, 2012; Grothmann, 2006). It is also a well-established behavioral theory, representing a solid ground for us to build on.

Yet PMT has limits. It underplays emotional responses such as fear and stress (Li, 2023; Eze, 2024), struggles with socio-cultural contexts such as community cohesion (Balla, 2024; Makwana, 2019; Dhar, 2023; Erokhin, 2024), and focuses mainly on short-term, individual actions (Westcott, 2017; Balla, 2024; Shavarani, 2018). It also neglects altruistic motivations, despite their important role in disaster response (Tanyag, 2018; Neal, 2011; Matthewman, 2021; Li, 2024; Kotani, 2016; Igwe, 2020; Gunessee, 2018; Daimon, 2018; Carbonnier, 2015; Bailey, 2022; Arianti, 2023; Rosenbloom, 2022; Shadiqi, 2022; Appleby-Arnold, 2021) where individuals might be motivated by the idea of helping others. Finally, it relies heavily on correlational studies with limited empirical validation (Balla, 2024).

Research Gap and Questions

Firstly, there is limited research on the motivations of affected communities during disaster responses, the current research focuses more on formal actors (health workers, army, firefighters or organized volunteers from NGOs for example), despite the critical role of communities especially in the first hours of a disaster response, which is why we decided to use the PMT in the context of community-led disaster response.

Secondly, despite its wide application, the current scope of the Protection Motivation Theory (PMT) remains limited, which is why we decided to expand it. At the moment, it primarily

explains individual protective actions while underestimating the role of social cohesion, motivations to help others, and the evolving urgency of disasters.

This creates a broader gap: the lack of a comprehensive framework that captures the communities' informal responses and motivations to help others and not just to help themselves.

Therefore, what we aim to achieve is to understand the factors (threat appraisal and coping appraisal, with the addition of urgency perception, social cohesion) influencing the competing priorities that affected communities may face in a disaster, between prioritizing their own safety (protecting myself) or assisting others , even when this may put them at risk.

Addressing this gap is important and could strengthen PMT’s relevance as communities are often the first responders, and their actions significantly shape survival outcomes. Unfortunately, they remain understudied and excluded from formal planning. Furthermore, it is critical to understand communities' responses and motivations in disasters, as they influence how they would act in such cases (Patterson, 2010; Breen, 2024; Gingerich, 2015; Der Heide, 2003; Quarantelli, 1985; Provitolo, 2011; Aerts, 2018).

Methodology

Methodologically, this requires extending PMT beyond its traditional scope by empirically integrating community motivations and their social cohesion, urgency perception, and the motivation to help others. These factors better reflect the realities of disaster behavior and allow for more effective, inclusive, and context-sensitive disaster response strategies.

This study aims to extend PMT with three new elements: social cohesion (embedding), urgency (protection motivation), and helping others (behavioral intention). Hypotheses link these with traditional PMT factors such as vulnerability, severity, coping, self-efficacy, and response efficacy (Rogers, 1975). A total of 21 hypotheses were developed (Table in Appendix A). All our hypotheses are testing new elements, whether it is from a traditional PMT element (white boxes) to a new one (colored boxes) or vice versa in Figure 1.

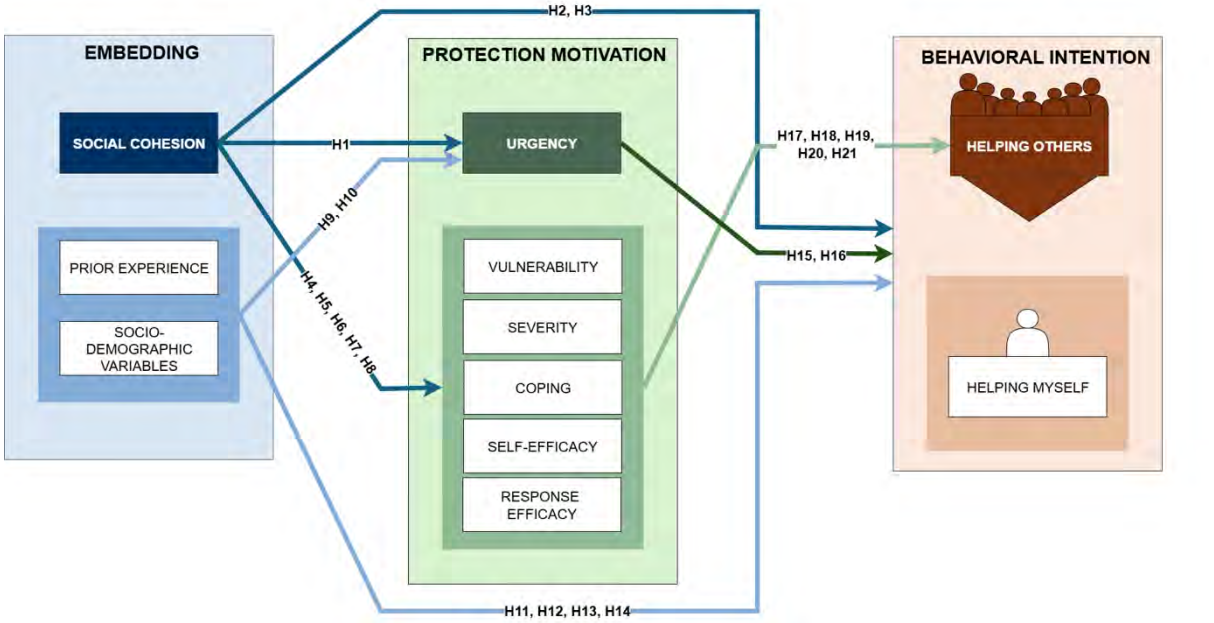


Figure 1. Our PMT Conceptual Framework – Original and New Elements from Embedding to Behavioral Intentions, passing by Protection and Motivation

To test these elements, we are currently piloting a survey which will be be distributed in September/October 2025 in European regions recently affected by floods: the Netherlands, Belgium, and Germany (2021 floods) (Fekete, 2021; Hagenlocher, 2023), Spain (Valencia, 2024) (Martin-Moreno, 2025), Italy (Emilia-Romagna, 2023) (Cremonini, 2024; Valente, 2023), and Greece (Thessaly, 2023) (Mavroulis, 2024). By comparing Northern-Western with Southern-Eastern Europe, cultural differences can also be analyzed (Lykes, 2014). We are currently piloting the survey, and we are aiming to present the results at the conference.

After distributing the survey and analyzing the results, we will conduct both descriptive and inferential analyses (regression, correlation, group analysis...) to examine relationships. This will allow us to identify patterns of self- versus other-oriented responses and test our 21

proposed hypotheses. Depending on the data structure, we will use correlation and regression analyses to explore associations, and group comparisons to assess potential cultural or demographic differences. This systematic analysis will provide a robust basis for interpreting community motivations in disaster response.

Following the data analysis, we will do follow-up interviews with respondents to validate our findings.

Expected Results and Implications

Expected results include identifying elements most likely to foster helping others in floods, and how this relates to the motivations of responders to protect themselves. This can improve understanding of disaster response mechanisms and highlight the role of communities, often overlooked despite their importance.

By knowing what leads motivations to help yourself or others, we can potentially target which groups would be interesting to give more training to and on what. For example, training could be for basic healthcare knowledge in case of a flood, or on developing the elements fostering motivations to help others.

By doing so, these groups of actors can act faster, better and with more equity among their community, and this would foster overall better responses to the impacts of floods.

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APPENDIX A : TABLE OF HYPOTHESIS TO TEST

Hyps / Description		What it Means
H1	SC ➔ U (social cohesion increases urgency perception)	"When my neighbors started warning each other, I realized it was serious."
H2	SC ➔ HO (social cohesion increases intention to help others)	"We're a close-knit block—of course I checked in on the elderly couple next door."
H3	SC ➔ HM (social cohesion increases intention to help myself)	"If others care about me, I feel more driven to protect myself too."
H4	SC ➔ V (social cohesion increases perceived vulnerability)	"Exchanging with others made me realize we're all exposed, not just me."
H5	SC ➔ S (social cohesion increases perceived severity)	"Hearing everyone's stories made the danger feel way more real."
H6	SC ➔ C (social cohesion increases coping ability)	"We made a group plan—suddenly I didn't feel so helpless."
H7	SC ➔ SE (social cohesion increases self-efficacy)	"Seeing others organize and share tips made me feel I could handle it too."
H8	SC ➔ RE (social cohesion increases response efficacy)	"They showed me what worked last time—I knew it could work again."
H9	PE ➔ U (prior experience increases urgency perception)	"I've seen how fast this escalates—no time to waste."
H10	SDV ➔ U (other variables increase urgency perception)	"Being a parent, I always sense danger faster—it's instinct."
H11	PE ➔ HO (prior experience increases intention to help others)	"Last time, someone helped me—this time, it's my turn."

H12	PE ➔ HM (prior experience increases intention to help myself)	"I've lived through this before—I know I need to act fast."
H13	SDV ➔ HO (other variables increase intention to help others)	"As a nurse, I just can't sit back when people need help."
H14	SDV ➔ HM (other variables increase intention to help myself)	"Being older, I know I have to move early before it's too late."
H15	U ➔ HO (urgency perception increases intention to help others)	"Once I saw the water rising fast, I ran to warn my neighbors."
H16	U ➔ HM (urgency perception increases intention to help myself)	"When I heard the flood sirens, I instantly started gathering my essentials."
H17	V ➔ HO (perceived vulnerability increases intention to help others)	"I saw how scared the kids were, and it pushed me to act fast for them."
H18	S ➔ HO (perceived severity increases intention to help others)	"Knowing this could be deadly made me jump into action for others."
H19	C ➔ HO (coping ability increases intention to help others)	"I felt prepared, so I used that calm to support others too."
H20	SE ➔ HO (self-efficacy increases intention to help others)	"I knew I could make a difference, so I did."
H21	RE ➔ HO (response efficacy increases intention to help others)	"Knowing that we will receive help made me more willing to check on people in need."

Who Stays, Who Goes? Uncovering Climate Displacement Dynamics with Mobile Phone Data

Laszlo Vreedenburgh[1], Jasper Verschuur[1], Femke Vossepoel[1], Tina Comes[1]
1 Department of Engineering Systems and Services, , TU Delft, The Netherlands, l.vreedenburgh@tudelft.nl, J.Verschuur@tudelft.nl, T.Comes@tudelft.nl
2 Department of Geoscience & Engineering, TU Delft, The Netherlands, F.C.Vossepoel@tudelft.nl

Abstract

Eastern and South Africa has seen an increase in climate hazards such floods, cyclones, and storms, which has led to frequent large-scale displacements. However, little is known about how displacement responses differ by region, hazard type, and sociodemographic group. This study measures and characterizes displacement dynamics prior to, during, and following extreme events using mobile phone data (MPD), which covers eight nations and 23 disasters. We categorize populations into exposed, peripheral, and non-exposed groups by combining MPD with hazard impact maps. We then use a Difference-in-Differences design to identify the specific disaster effects on mobility. To capture heterogeneity in preemptive, responsive, and return behaviors, we examine socioeconomic clustering, displacement shares, return timing, and distances traveled. While acknowledging the representativeness limitations of MPD, this approach provides unique high-resolution insights into displacement dynamics in data-sparse contexts. Findings advance both research and policy by informing models of climate mobility, identifying displacement hotspots, and improving the evidence base for equitable adaptation and humanitarian strategies.

Keywords: Displacement; Climate Hazards; Mobile Phone Data; Sub-Saharan Africa; Difference in Differences

Introduction

Climate hazards such as floods, droughts, and cyclones have intensified across Eastern and South Africa in recent years, leading to frequent and large-scale displacements, like the more than 3 million people displaced due to floods in Kenya and Tanzania in October 2023. Since 2020, the region has experienced overlapping crises, including the severe flooding in Mozambique and Cyclone Freddy making landfall twice, each triggering distinct patterns of population movement (IDMC, 2024; Wang et al., 2025). Displacement responses vary widely, some people will flee and leave everything behind, while others do not have the capabilities or the aspirations to do so (Zickgraf, 2018, Thalheimer et al., 2025).

Understanding how these responses differ across regions and socio-demographic groups, and how they are evolving over time is crucial for tailoring humanitarian aid and designing equitable adaptation policies. This study investigates regional and socio-demographic groups' differences in displacement

responses to climate hazards in Southeastern Africa since 2022, with the aim of informing both research and policy on climate mobility. Traditional data sources used in displacement research are too expensive and labor intensive for timely and granular analysis (Fussell et al. 2014, Hoffmann et al. 2021, Beyer et al. 2023). To overcome these limitations, mobile phone data (MPD) is becoming increasingly acknowledged as a useful tool for examining displacement (Hoffmann Pham & Luengo-Oroz, 2023). Since the scale, spatial and temporal granularity, and rich features of MPD allow for the creation of relevant and inexpensive indicators, it presents a great opportunity to address long-standing issues in the collecting of displacement data. MPD has been used in previous studies to investigate mobility patterns of displaced people (Lu et al., 2016; Wilson et al., 2016; Bozcaga and Cansunar, 2022). In Nepal, MPD revealed large-scale, short-term outmigration after the 2015 earthquake and detailed dynamics of population return and relocation (Wilson et al., 2016). Combining MPD with remote sensing, Bozcaga and Cansunar (2022) showed that Syrian refugees in Turkey were less likely to relocate to areas with low labor demand. Lu et al. (2016) examined Cyclone Mahasen in Bangladesh and found little evidence of long-term displacement, though unusual short-term mobility patterns occurred around warnings and landfall. While these studies demonstrate the potential of MPD for analyzing displacement, they have not systematically compared how displacement dynamics differ across population groups, hazard types, and regional contexts using MPD.

Approach

In this research, we will be using the proprietary mobile phone location data from Quadrant. We utilize granular data of mobility in eight East and Southern African countries, namely Madagascar, Mozambique, Malawi, Zambia, Kenya, Tanzania, Burundi, and Uganda. The dataset includes observations from 2022 to 2024, covering periods before, during, and after disasters. The extreme events consist of tropical storms, cyclones, and flooding. Overall, these entail 23 climate-related disasters affecting 11.2 million people in total, with a minimum of 75,000 people affected per disaster, and a total of 3,000 deaths, see *Appendix Table 1*. for specific event information.

The central aim is to measure and characterize displacement dynamics following extreme climate shocks. Specifically, we ask whether there are systematic commonalities or heterogeneities across regions, hazard types, and socio-economic contexts in the ways people move before, during, and after disasters. To do so, we integrate mobile phone mobility traces with hazard impact maps, derived from remote sensing data, like those from GDACS, Copernicus, UNOSAT, or IOM. This integration allows us to identify mobile phone users likely affected by the hazards. To do this we categorize the users into three exposure groups:

1. Exposed: users located inside the hazard footprint;
2. Peripheral: users located just outside the footprint, where exposure is uncertain;
3. Non-exposed: users completely outside the hazard area.

By constructing these exposure categories, we can apply a Difference-in-Differences (DiD) design to measure behavioral changes. DiD compares pre- and post-disaster mobility patterns between exposed and non-exposed populations, isolating the disaster's causal impact on displacement (Callaway and Sant'Anna, 2021; Shakya et al., 2022). This method will be applied within each event and then pooled across multiple disasters to assess broader patterns.

To deepen the analysis, disasters will be categorized by type, including floods and storms, and magnitude, measured by affected population and severity indices. On the displacement side, we will quantify:

- Population share displaced,
- Socio-demographic clustering (using neighborhood-level socio-economic indicators),
- Return patterns (timing, rate, permanence),
- Displacement distances (short-distance vs. long-distance migration),

We will also investigate whether individuals tend to return to previously visited safe locations or explore entirely new destinations in subsequent events, providing insight into adaptive versus habitual displacement strategies.

The methodological framework combines statistical and computational approaches. Alongside DiD, we will apply clustering techniques to classify neighborhood-level socio-economic groups and compare their displacement responses



Figure 1. Workflow of the approach

Limitations

There is a caveat to using MPD in developing countries. Important questions concerning the representation of the general population have been brought when using mobile phone data. According to earlier studies, the most vulnerable populations are frequently underrepresented in mobile phone usage. (Blumenstock and Eagle, 2012; Wesolowski et al., 2013). However, MPD gives us the opportunity to gain granular insight into the behavior of populations in a normally data sparse area.

Outcomes

This research contributes to scientific literature in several ways. First, it advances the development of analytical frameworks by integrating MPD with hazard impact maps, thereby enabling more robust analyses of displacement. Second, it generates short-term spatial and temporal evidence of displacement dynamics in data-sparse environments, while also providing insights into the longer-term duration, scale, and return dynamics of population movements. These findings can be used to improve the parameterization of displacement processes in climate mobility models and allow for the identification of displacement hotspots and high-risk routes. Finally, by grounding the analysis in fine-grained empirical evidence from African countries during extreme events, the study enhances our understanding of disaster

displacement dynamics and provides a solid basis for their use in modeling efforts and scenario building in subsequent research questions.

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Appendix

Table 1. Overview of hazard events and severity in mobile phone dataset

No.	Event Name	Event Start Date	Country	Total Deaths	Affected people
1	Tropical Storm Ana	22-1-2022	Madagascar	55	131,555
2	Tropical Storm Ana	24-1-2022	Mozambique	38	185,636
3	Tropical Storm Ana	22-1-2022	Malawi	64	945,934
4	Cyclone Batsirai	5-2-2022	Madagascar	92	112,115
5	Cyclone Emnati	23-2-2022	Madagascar	15	169,000
6	Cyclone Gombe	11-3-2022	Mozambique	63	736,123
7	Cyclone Freddy	21-2-2023	Madagascar	17	299,000
8	Cyclone Freddy	24-2-2023	Mozambique	183	1,231,389
9	Cyclone Freddy	11-3-2023	Malawi	1,209	2,269,644
10	Flood	7-2-2023	Zambia	NA	154,608
11	Flood	25-3-2023	Kenya	36	139,164
12	Flood	15-10-2023	Kenya	406	695,497
13	Flood	15-10-2023	Tanzania	38	2,896,500
14	Flood	24-3-2024	Kenya	282	205,164
15	Flood	2-4-2024	Tanzania	155	200,236
16	Flood	1-4-2024	Burundi	29	237,175
17	Flood	1-11-2022	Malawi	62	94185
18	Tropical Storm Filipo	12-3-2024	Mozambique	2	93,325
19	Tropical Storm Cheneso	19-1-2023	Madagascar	53	90,870
20	Cyclone Gamane	26-3-2024	Madagascar	22	89,469
21	Flood	7-2-2023	Mozambique	14	89,093
22	Flood	30-7-2022	Uganda	32	78,338
23	Flood	1-10-2022	Mozambique	88	78,271

Determinants of Infrastructure Access in Refugee and Internally Displaced Persons (RIDP) Settlements: Insights From a Comparative Analysis Across African Settlements

Josue Gnowa[1], Jasper Verschuur[1], Tina Comes[1]
1 Delft University of Technology, Netherlands, jgodwegnowa@tudelft.nl, j.verschuur@tudelft.nl, T.Comes@tudelft.nl

Abstract

Refugee and internally displaced persons (RIDP) living in camp settlements face challenges in accessing basic infrastructure such as healthcare, water, sanitation and hygiene (WASH), school, social facilities and energy. Inadequate access to these basic infrastructures undermines resilience and raises questions of sustainability. This research adopts a comparative approach to investigate the determinants of the difference in infrastructure access in RIDP settlements in Africa. The research evaluates accessibility of healthcare, WASH, schools, social facilities and energy in 15 refugee settlements by analyzing spatial datasets containing both infrastructure location and their functionality. The access indicators considered include facility availability and distance or travel time from habitation centroids to the basic infrastructures. We further explore the relationship between settlement characteristics such as population density in settlements, settlement age, size, type and geographic setting, and infrastructure access indicators. While our preliminary results reveal some emerging patterns in infrastructure access, we first note that all refugee settlements are located in rural geographic settings, where access to infrastructure is often limited. Secondly, small, formally planned settlements demonstrate a wide range of infrastructures with high proportions of operational facilities, comparable to those in large self-settled settlements. We further expect to advance the analysis by developing a heatmap of variation in infrastructure access across all settlements and by examining the relationships with settlement characteristics. These insights help identify which types of settlements require specific interventions, thereby improving infrastructure access and ultimately strengthening community resilience.

Keywords: Refugee settlements, spatial analysis, resilience, infrastructure access.

Introduction

Globally, RIDP numbers are increasing and projected to reach 1.2 billion by 2050 (Han et al., 2024). Low- and middle-income countries (LMICs) host 71% of forcibly displaced people, with Africa accounting for the largest share in proportion to other continents (UNHCR, 2024). This makes settlements in Africa the central focus of our research. RIDP settlements are often characterized by rapid population growth, spatial constraints, and limited long-term planning, which in turn compromise service delivery and exacerbate already high vulnerabilities (Al-Homoud & Samarah, 2025). Refugee settlements often start with chaotic, ad hoc layouts that are gradually reorganized through the incremental introduction of basic services such as healthcare, water, sanitation and hygiene (WASH), school, social facilities and energy (Moore, 2017). The provision of these essential services has been a central focus for many humanitarian organizations worldwide (Basu, 2015; Mackinnon, 2014). On the one hand, the location of such facilities in

relation to shelters is paramount as facilities should be spatially accessible and sufficient for refugees' needs. On the other hand, given the limited resources available to humanitarian organizations in RIDP settlements, these actors are compelled to maximize efficiency in service provision. Unfortunately, access to basic infrastructures in RIDP settlements such as WASH (Atuyambe et al., 2011; Behnke et al., 2024; Calderón-Villarreal et al., 2022) and health facility (Altuncu et al., 2019) continues to be a challenge (Ali & Khamees, 2025). Meanwhile, this access to essential services in RIDP settlements is critical, as inequities in service distribution or insufficient infrastructure have direct impacts on health, dignity, and well-being (Jervelund et al., 2019; McNatt et al., 2019; Nyoka et al., 2017). These challenges related to infrastructures weakens social resilience in RIDP settlements as infrastructure access shapes community resilience (Klineberg, 2018).

In RIDP settlements, infrastructures are often unavailable or insufficient in the long run, rendering services unsustainable for the displaced people. In order to improve the resilience of the RIDPs in settlements, there is need to understand how access in infrastructure services vary across different settlements and find out the underlining factors which determine the variation in access across these settlements. A study by Wardeh & Marques (2021) found that refugee settlements not only fall short of the 2030 Agenda for Sustainable Development but also fail to guarantee refugees' basic rights. The authors argue that a more inclusive and sustainable approach is needed to improve quality of life, support dignity, and foster self-reliance, benefiting both refugees and host communities. This research builds on that by adopting a multi-sectoral view to determine the pattern of infrastructure access - a basic right for RIDPs – and by finding the determinants of this difference in infrastructure access.

To guide the spatial analysis, We follow one of the most recognized standards, Sphere Project which proposes benchmarks for establishing and managing refugee settlements (SPHERE, 2011). In this paper, the analysis of accessibility to key infrastructures is carried out with reference to these standards, particularly the Sphere Project's guidance on maximum walking distances to settlement facilities (Hassan et al., 2018).

Objective

The objective of this paper is to analyze differences in infrastructure access across camps and find reasons why they differ. This can help improve existing guidelines on infrastructure planning in RIDP context.

Method

The analysis assesses accessibility to essential infrastructure within 15 RIDP settlements selected based on availability of standardized UNHCR datasets. These spatial datasets contain settlement

and infrastructure/facility information such location and functionality. The first step involved identifying the availability of infrastructure services in each settlement (categorizing them into operational and non-operational infrastructure). After the settlements are broken down into small blocks to capture spatial variation, accessibility is then assessed by calculating distance from habitation centroids to the infrastructures, including healthcare, WASH, schools and social facilities.

Infrastructure access is evaluated through indicators such as availability. The formed index (shown in table 1) provides a measure of whether existing services are adequate to sustain the settlement populations. Once access levels are established, the study examines how these indicators correlate with settlement characteristics such as settlement surface area, population size and density, settlement age, settlement type (formally planned or self-settled) and locational setting (urban or rural).

The comparative approach permits us to capture broader patterns in different settlements across African countries. This design highlights both intra-settlement disparities and inter-settlement variations, enabling the identification of structural similarities as well as context-specific challenges.

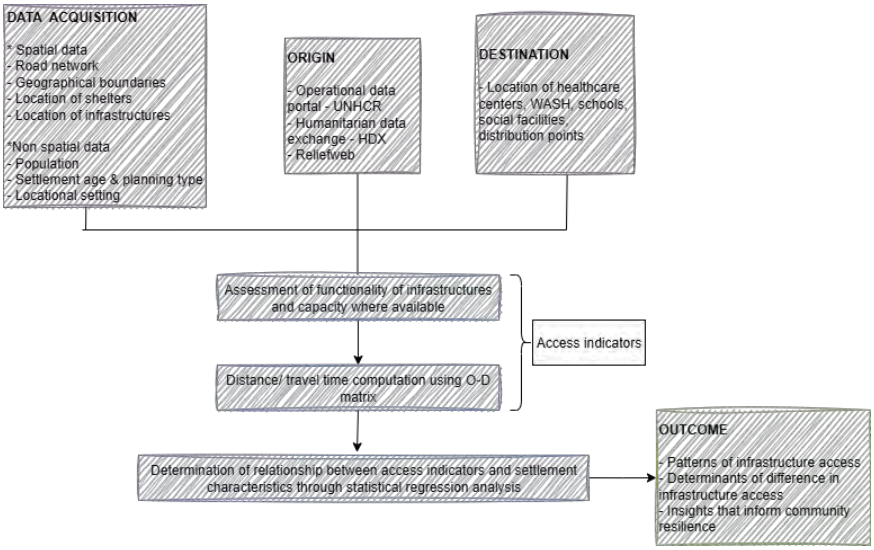


Figure 1| Methodology

We constructed an infrastructure access index by first normalizing each indicator against Sphere Standards, assigning a score between 0 and 1. Indicators within the same sector were averaged into sub-indices, and sub-indices were aggregated using equal weights across all sectors. To reduce the risk of strong performance in one sector compensating for deficits in another, the composite index was calculated using a geometric mean.

Table 1| Infrastructure access indicators and measurement criteria

Infrastructure Type	Indicator(s)	Access Measurement / Threshold	Functionality Measurement / Threshold	Normalization
Water source	Distance to nearest water point; Liters per person per day	≤200m; ≥15 L/person/day	≥90% of water points operational	Scaled 0–1
Water storage	Distance to nearest storage facility	≤200m	≥90% of storage facilities functional	Scaled 0–1
Sanitation	% of sanitation facilities per population; Distance to sanitation point	≥1 latrine per 20 people; ≤50m from household	≥90% of latrines/WASH stand usable	Scaled 0–1
Health	Distance to nearest facility	≤5 km or ≤1 hr walking	≥90% of health facilities staffed and open	Scaled 0–1
School	% of household within 1 km	≤1 km	≥90% of schools functional	Scaled 0–1
Energy	% households with electricity	≥50% connected	≥90% of installed systems functional	Scaled 0–1
Social Facilities	Distance to nearest facility (market, religious/community center, etc.)	≤1 km	≥90% of facilities open and in use	Scaled 0–1

Results

Preliminary results reveal that smaller, formally planned settlements such as Kigeme and Tsore stand out for having a range of infrastructure types with relatively high proportions of operational facilities. Similarly, large settlements, including Bidi Bidi and Nakivale, also show diversity in infrastructure, with also a high proportion of operational facility, indicating large self-settled settlements are catered for just like formally planned settlements. Equally, in this study all refugees are located in rural areas, with none in urban contexts. This contrasts with Easton-Calabria (2020) analysis, which shows that many refugees move to poor and underdeveloped cities and slums in

Africa. We further expect to extend the analysis by generating a heatmap that illustrates variations in infrastructure access across all 15 refugee settlements and by exploring how these variations relate to specific settlement characteristics.

Discussion And Conclusion

Analyzing these factors provides critical insights into systemic vulnerabilities and enables targeted, context-specific interventions, clarifying what current settlements struggle with and which settlement types require particular forms of support to strengthen sustainable infrastructure service access and eventually community resilience.

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Sunk Costs, Sunk Coastlines: The Argument for Wholesale Climate Retreat and Letting Development's Bygones Be Bygones

David Oliver KASDAN University of Southern Maine, USA, dokasdan@gmail.com

Abstract

This paper offers the rationale for strategic climate retreat policy, particularly for coastal regions and flood plain communities. Climate retreat is the withdrawal of settlements from places that were previously considered safe from environmental catastrophes but are now at risk of flooding due to natural or human-made hazards. The argument for climate retreat proceeds from the assumption that anthropogenic climate change is increasing the flood risk of previously suitable locations to the extent that long-term mitigation efforts are inevitably futile. This necessitates a disaster risk management strategy that engages with an understanding of the context and behavior of the population, as well as the policy mechanics available to encourage that population to move to higher ground. Using the recent hurricane impacts in Florida as an illustrative example, the reasonable response and forward-looking plan for at-risk communities is to retreat, rather than insist on an unsustainable course of rebuilding for a future of ever worsening flood events. The conclusion of the argument is to propose several ideas to assist in helping people to voluntarily relocate out of harm's way through buyout policies, insurance leverages, and behavioral insights.

Keywords: sunk costs; prospect theory; climate retreat; solastalgia; degrowth

https://www.icrs26.org/home

Future Costs of Climate Change for Humanitarian Aid

Juha-Pekka Jäpölä (juha-pekka.japola@ec.europa.eu) [1,2], Anna Berlin[1], Charlotte Fabri[2], Arthur Hrast Essenfelder [3], Sepehr Marzi[4], Karmen Poljansek[3], Michele Ronco[3], Steven Van Passel[2], and Sophie Van Schoubroeck[2]

1 European Commission, DG ECHO, Brussels, Belgium

2 University of Antwerp, Antwerp, Belgium

3 European Commission, DG JRC, Ispra, Italy

4 Fincons SpA external service provider of European Commission, DG JRC, Ispra, Italy

Abstract

This study introduces a novel methodology for simulating sectoral damage in humanitarian and disaster assistance up to 2100, addressing critical gaps in economic assessments of climate change impacts. Leveraging Gaussian Process Regression, a machine learning tool, and data from UN OCHA, we focus on the most fragile regions, where climate change exacerbates humanitarian needs. Our approach centres on people in need (PIN) of humanitarian aid, providing a systemic and interpretable framework for resource allocation. Preliminary simulations under the SSP2-RCP4.5 scenario highlight the growing economic magnitude of climate impacts on humanitarian crises. This work contributes to progressing climate and disaster resilience by offering actionable insights for policy and decision-making especially for a multi-risk environment.

Keywords: climate change; economics; humanitarian aid; multi-risk; Gaussian Process Regression; machine learning

Introduction

Economic assessments of climate change damage often focus on production in a neat and data-rich environment. Traditional workhorses, such as integrated assessment models (IAMs), have been criticized for their empirical calibration gaps, utilization of non-market data, and inadequate accounting for extreme events or fragile countries without sufficient institutional resources (Botzen et al., 2019; Rising et al., 2022; Stern et al., 2022). To address these gaps, we develop a new concept and methodology for sectoral damage simulations in humanitarian and disaster assistance up to 2100, calibrated with data from the United Nations Office for the Coordination of Humanitarian Affairs (UN OCHA). Our approach leverages Gaussian Process Regression (GPR), a machine learning tool well-suited for complex, asymmetric, and data-sparse environments.

Humanitarian aid, which provides material assistance from the global community to people in need, is either a short-term intervention or support during protracted crises. This aid targets victims and refugees of disasters, famines, and wars, with the primary objectives of saving lives and preventing suffering. The intensifying effects of climate change are rapidly transforming the landscape of global humanitarian needs (IPCC, 2023; UN OCHA, 2024). More frequent and severe disasters, including droughts, floods, and cyclones, combined with conflict, push the most vulnerable populations to the brink and strain the operational and financial capacity of aid systems (UN OCHA, 2024). Thus, our scope focuses on the most

fragile areas of the world, which are effectively the tip of the iceberg in indicating climate change damage and are the least resilient to withstand it.

The humanitarian sector offers an important lens on climate change, as funding provided to it does not effectively yield a net economic benefit and represents an extreme case of the broken window fallacy. While vital for alleviating human suffering and safeguarding society, all funding for humanitarian aid represents an opportunity cost for other efforts, such as disaster risk reduction or climate change adaptation. In a world with scarce resources, responding to active disasters and conflicts will, ceteris paribus, reduce the budget available for other climate change initiatives.

In 2024, approximately every 25th person in the world needed humanitarian assistance, totalling 320 million people in need. The funding requirement to cover their needs was USD 49 billion. However, only about half of that coordinated plan was funded by governments, multilateral organizations, NGOs, and private organizations. This problem is compounded by growing volatility in global aid budgeting. In early 2025, the United States implemented a freeze on USAID's (United States Agency for International Development) humanitarian disbursements (Cavalcanti et al., 2025), which accounted for 41% of the USD 35 billion of global humanitarian aid funding the previous year (UN OCHA, n.d.). This freeze will weaken critical operations in several crisis-affected regions.

Therefore, our work seeks to determine the economic magnitude of climate impact on humanitarian crises up to 2100. We use a three-phase regression to simulate possible pathways centered around the SSP2-RCP4.5 scenario, which limits warming to 3°C by 2100 over the pre-industrial average and towards which we are now heading (Bevacqua et al., 2025; Cannon, 2025; IPCC, 2023). The INFORM indices (Marzi et al., 2021) and climatic-socioeconomic projections based on CMIP6 form the foundation of the dataset's predictors. 26 countries with a humanitarian crisis in 2023 is our scope (Fig 1).

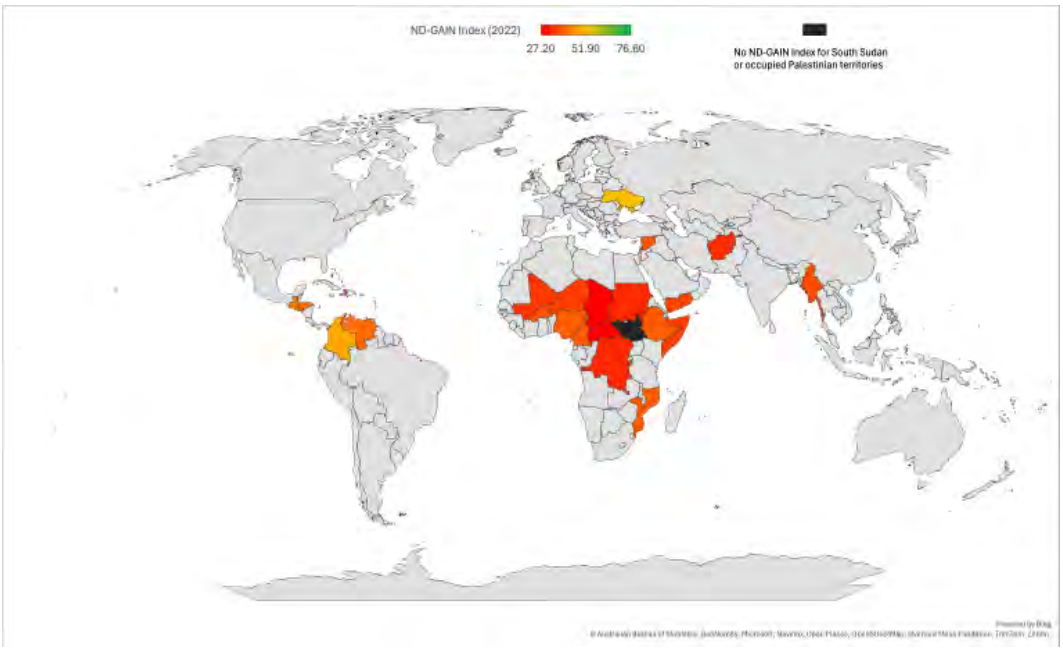


Figure 1. The 26 countries included in the analysis. The ND-GAIN Index (2022) shows country vulnerability and readiness to climate change. Its scale and colouring here resemble the original one so that Chad has the lowest score 27.2 and Norway would have the highest score 76.6 (University of Notre Dame, n.d.).

The complexity of factoring and realistically quantifying the impact chain of cascading and compounding multi-risk events, as well as considering systems instead of single entities while providing actionable outcomes, are key barriers (Higuera Roa et al., 2025; Hochrainer-Stigler et al., 2023). We propose a conceptual novelty to overcome this: basing the framework around people in need (PIN) of humanitarian aid, as assessed by UN OCHA annually.

As our previous studies show (Jäpölä et al., 2024a, 2024b; Jäpölä & Van Passel, 2025), PIN is a powerful and simple indicator of systemic climate consequences—even when collated with conflict—that consolidates micro and macro levels while remaining easy to understand. When coupled with funding data, its realistic magnitude levels transfer nearly directly to resource allocation decision-making (in comparison to, e.g., an index). Additionally, we utilize artificial intelligence (AI)—namely GPR—by following explainable AI (XAI) recommendations to reap its benefits while keeping it interpretable (Dramsch et al., 2025).

Similar past studies have underestimated the recent rise in the total number of people in need and have noted analytical limitations. For example, the number of people in need due to climate-related disasters under a pessimistic scenario based on SSP4 was expected to be 200 million by 2050 (IFRC, 2019), while the current global PIN is 320 million. Our work attempts to bridge those gaps, such as the interaction between conflict and climate change, and provide a more systemic multi-risk analysis.

Preliminary simulations

Below we show preliminary simulations from the model under various beneficial or negative scenarios of both temporary shocks and a long-term structural break (Fig 2). The break assumes either increase or decrease in investment to disaster risk reduction and climate change

adaptation, technological progress, coordination effectiveness, as well as over or under estimation of the impact and speed of climate change.

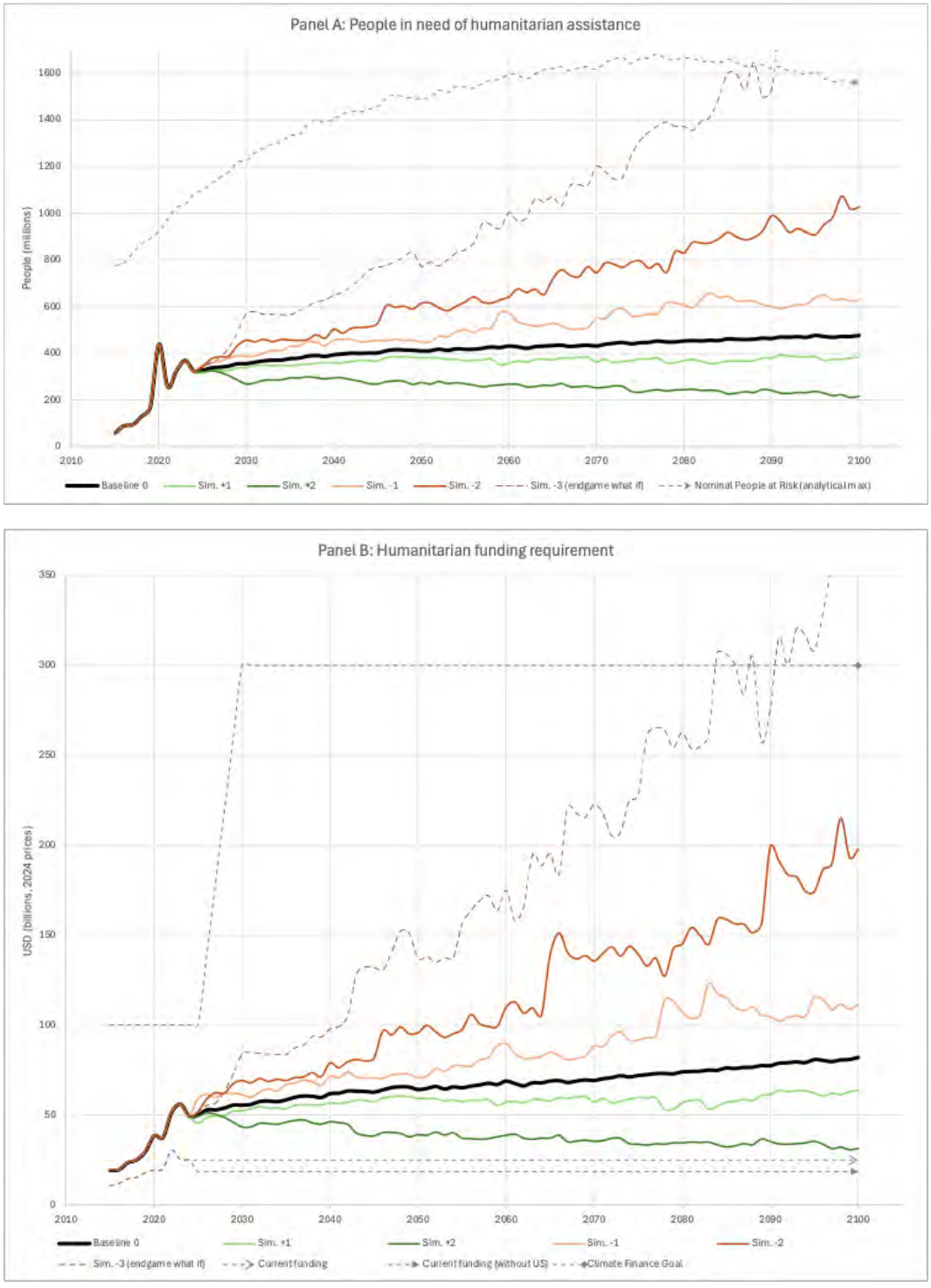


Figure 2. Preliminary simulations of people in need of humanitarian assistance (Panel A) and humanitarian funding requirement (Panel B) in the future under climate change scenario RCP4.5-SSP2.

The data is an aggregate of all 26 countries in the dataset. The simulations start from 2025 while data before that is historical. Baseline is in the middle while beneficial and negative shocks in both short-term and structural break aspect are added symmetrically. The spike around 2020 is COVID-19 and was removed from the training dataset as a huge outlier but shown here for transparency.

In Panel A, the nominal people at risk are shown as an analytical upper boundary. In Panel B, no inflation or discount factor is displayed. The current humanitarian funding level with and without United States (US) funding (excluding food security sector) are shown as a reference in addition to the climate finance goal including the New Collective Quantified Goal (NCQG) by 2030.

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Invited Speaker: Mizuki Aosaki

Mizuki Aosaki, Siemens Financial Services, mizuki.aosaki@siemens.com

Abstract

This talk explores how physical climate risks and adaptation strategies are becoming increasingly relevant within financial decision-making, with a focus on the evolving work at Siemens Financial Services (SFS). Based in Munich and part of the central sustainability team, the speaker brings a perspective shaped by a transition from traditional banking and finance into corporate sustainability. Her work spans both carbon emissions reporting and the growing challenge of integrating physical climate risks into organizational and investment frameworks.

Framed within the conference's "Shock, Shift, and Solution" theme, this session will reflect on how financial institutions like Siemens are navigating climate-related shocks such as floods and hurricanes, addressing systemic shifts like climate-induced migration, and exploring emerging solutions that combine risk mitigation with long-term opportunity. The talk will also touch on current questions around the role of data, risk prioritization, and the business case for adaptation, drawing attention to the practical tensions and possibilities that arise at the intersection of finance, infrastructure, and sustainability. The session offers a contribution to an ongoing dialogue, between industry and academia, on how best to advance resilient investment strategies in a rapidly changing risk landscape.

Keywords: Climate Adaptation, Sustainable Finance, Infrastructure Resilience

9. Complex Adaptive Social Systems

Walking towards a cliff edge: *Can a combination of participatory futures and agent-based modelling approaches help make SES tipping-points feel real?*

Bruce Edmonds[1,2], Melania Borit[1]
1 CRAFT research group, UiT Norway University of the Arctic, Tromsø, NO.
melania.borit@uit.no
2 Centre for Policy Modelling, UK. bruce@edmonds.name

Abstract

Many Socio-Ecological Systems (SES) have the property that they deal with environmental stress up to a certain point and then suddenly collapse – i.e. a tipping point. The problem we address here is how to make such possibilities seem real to stakeholders before the point of no return. Here we suggest an iterative combination of agent-based modelling (ABM) and participatory futures (PF) techniques where stakeholders develop narratives about the future. The ABM can be used to project otherwise unconsidered future possibilities into the PF which, in turn, can be used to inform the values and mechanisms that the ABM represents. This approach is discussed with its opportunities and issues.

Keywords: agent-based modelling; futures; participation; narrative; tipping-point

Complex systems (such as SES) can react non-linearly to environmental (or internal) changes. They are typically composed of many overlapping processes and can change "phase" to a completely different behavioral pattern. As a result of this complexity, they can exhibit "tipping point" behavior, where there is marginal change as a result of increasing stress before the point ("walking towards a cliff edge"), but followed by a run-away catastrophe after (Brovkin & al. 2021). This pattern of behavior causes a collective policy problem, since it is hard to mobilize the necessary political support for inconvenient measures to address the causes of the tipping points until they happen (and then it is very hard to get back to a pre-tipping-point conditions).

There are many examples of this kind of situation. Two well-known examples are the following.

> After years of overfishing, the Northwest Atlantic Cod stocks suddenly collapsed to 1% of historical levels in 1992. The overfishing had continued despite an earlier partial collapse in the 1970s after which Canada started managing the waters and gradually excluding other country's fishing boats. Contributing to this collapse was the lack of good data, that the managers did not listen to the local fishers as well as simplistic and over-optimistic modelling.
>
> It is well known that there are a number of tipping-point processes that will kick in somewhere above 1.5C global warming (compared to pre-industrial levels). Once a

number of these processes start, it will be very much harder to limit further temperature increases. However, despite this, there is not enough political will to convince enough people that difficult/costly changes need to be made now, to prevent a vastly more costly future disaster. Once the issue had some level of cross-party support but now the issue has become politicized. This is especially true in the US, but across a broad range of other countries there has also been significant back-peddling in terms of previous plans for action, enabled by the lack of sufficiently broad public support.

There is probably no ‘silver bullet' solution to these kinds of situation, but rather a combination of methods may help. We propose using two different kinds of method together:

(a) *participatory futures methods* where groups of citizens/stakeholders envisage possible futures by collectively developing coherent stories of possible developments (Barendregt, Bendor & van Eekelen 2024),

(b) *agent-based modelling* (ABM) that can capture some of the complexities of the situation and trace out some of the possible future trajectories (Edmonds & Adoha 2019).

Each of these have shortcomings. It can be hard to get a group of stakeholders to seriously consider futures that they do not think are likely or are outside the time-frame they are concerned with - they tend to be concerned with currently manifest problems and so do not necessarily welcome an additional (and to them hypothetical) future issue. On the other hand, ABMs are often very abstract and hence unconvincing - especially if they are suggesting events considered unlikely and unpalatable by citizens.

However, we hypothesize that an iterative combination of these two approaches might address some of these shortcomings. The idea is that the ideas from the participatory foresight sessions are used to inform the specification of the simulation (the ABM) and that narratives derived from the simulation are introduced for discussion to the participatory foresight sessions (Bartelemy 2006). This is similar to “Companion Modelling” (Barreteau et al. 2003), where there is a tight loop between participant discussions, where they use simulation (either board or computer based) to help ground and structure their discussions. Their aim there is to inform and improve the discussions, whilst we have the slightly different aim of establishing an interaction between a simulation which projects future possibilities and the development of future narratives.

To make our idea work three aspects are necessary:

1. That the issues, values and facts on the ground that the stakeholders bring up are able to be implemented in a simulation in a way that is plausible to them. This kind of exercise has been done before but generally within a one-off project structure with longer gaps between simulation and participation.

2. That the possible trajectories that come out of the simulation can be translated into a plausible narrative, including crucially that the reasons why it may come about have been analyzed and elucidated in the narrative.

3. That the simulation ↔ participatory foresight iterative loop can be done a sufficient number of times that participants can better understand and trust the simulation input.

All three aspects present difficulties, but none of these are insurmountable. The greatest challenge is step 2, which is often done informally, but not so well researched. There is not yet a field of 'narratisation' in a similar way to that of 'visualization'. The elements are there, but the whole package as a coherent and well-researched methodology is not yet developed. However, the need to facilitate the public realization of cliff-edge situations in a democratic manner is clear. Combining simulation modelling and human discursive deliberation might be more effective than either on its own (Polhill & Edmonds 2023).

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Assessing Global Vulnerability to Natural Disasters: A Structural Equation Modeling (SEM) Analysis of the World Risk Index

Rosewine Joy, Associate professor, School of Business and Management, Christ University, Banaglore,India, rosewine.joy@christuniversity.in

Abstract

This study use SEM models to understand the interlinkages between exposure and vulnerabilities causing risk among different countries using WRI calculated for 193 countries. The SEM models are analysed using R programming .We employed Confirmatory Factor Analysis (CFA) to validate latent constructs (E and V).Structural Equation Modeling (SEM) for path estimation.Multi-group SEM to compare low-risk vs. high-risk countries (based on 66th percentile of WRI)

Keywords: Exposure; Vulnerability; Risk; WRI;SEM

Introduction

Natural disasters are happening more often and with greater intensity, which makes it all the more important to understand what shapes people's vulnerability, readiness, and ability to bounce back. Increasingly, researchers are turning to structural equation modeling (SEM) because it helps untangle the complex web of social, environmental, and behavioral factors behind disaster risk.

For example, Fatehpanah and colleagues (2025) used SEM to explore what drives earthquake preparedness in Iran, finding that people's attitudes, social pressure, and their sense of control really matter. In Indonesia, Oktari et al. (2025) showed that education and experience make coastal communities better prepared for storms. SEM is also helping assess risks tied to specific hazards, like how Sun et al. (2025) studied landslide risks or how Kim et al. (2024) looked at heatwaves in South Korea under climate change.

Beyond physical threats, researchers like Cheng and Shan (2025) found that cooperation and flexible supply chains help communities stay resilient, while Heshmati et al. (2025) spotlighted the importance of social connections during COVID-19. Others have focused on health—Özşahin (2024) showed that poor housing and food insecurity worsened women's health after earthquakes in Türkiye—and governance—Sambuaga et al. (2024) emphasized how quality leadership boosts environmental awareness and prevention.

This study investigates the structural foundations of disaster risk by addressing the following three research questions using the World Risk Index (WRI) dataset (2020), covering 193 countries:

- RQ1: Can disaster risk, as reflected in the World Risk Index (WRI), be explained as a direct function of natural hazard exposure alone?
- RQ2: Which specific vulnerability indicators—across the dimensions of susceptibility, coping, and adaptive capacity—most significantly predict national-level disaster risk?

- RQ3: Does the relationship between exposure and vulnerability in predicting disaster risk differ across countries with high versus low levels of disaster risk?

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Methodology

This study utilizes the WorldRiskIndex (WRI) 2020 dataset, covering 193 countries, to assess global vulnerability to natural disasters. The WRI, developed by UNU-EHS and refined by IFHV at Ruhr University Bochum, operationalizes disaster risk as the geometric mean of two latent constructs: Exposure (E) and Vulnerability (V).

The Disaster Risk (W) is defined by the composite WRI score:

$$W = \sqrt{E} * V$$

To validate these latent constructs, Confirmatory Factor Analysis (CFA) was performed, assessing model fit using indices such as CFI, RMSEA, and SRMR to ensure measurement validity. Structural Equation Modeling (SEM) then estimated the paths between Exposure, Vulnerability, and Disaster Risk, quantifying their relationships and hierarchical structure.

A multi-group SEM approach distinguished countries with low versus high disaster risk based on the 66th percentile cutoff of the WRI distribution. This allowed testing of measurement invariance and comparison of structural path differences between risk groups, providing insights into context-specific vulnerability dynamics.The data is analysed using R programming

Results

Confirmatory Factor Analysis (CFA) and Structural Equation Modeling (SEM) were applied to examine whether natural hazard exposure alone predicts disaster risk as measured by the WorldRiskIndex (WRI) 2020. Exposure was modeled as a latent construct composed of six indicators (EI_01, EI_02, EI_03, EI_05, EI_06, EI_07), excluding EI_04. CFA results showed moderate to strong standardized loadings (β = 0.44 to 0.61), with two residual covariances included to improve model fit. The model exhibited acceptable fit indices (CFI = 0.919, TLI = 0.859, RMSEA = 0.112, SRMR = 0.065). SEM analysis revealed a statistically significant path from Exposure to disaster risk (β = 1.057, $p < .001$), with negligible residual variance, indicating near-complete explanation of risk by exposure alone. These results suggest that, within this model, disaster risk variation across countries is predominantly driven by hazard exposure, rendering societal vulnerability metrics unnecessary for explaining WRI in this context.

A second-order Structural Equation Model (SEM) was developed to assess how key vulnerability dimensions influence disaster risk, operationalized by the World Risk Index (WRI). The model included three latent constructs measured by their respective indicators: Susceptibility (S_01 to S_05), Coping Capacity (C_01_rev to C_03_rev), and Adaptive Capacity (A_01_rev to A_03_rev). Confirmatory Factor Analysis (CFA) validated the measurement models, with all constructs exhibiting strong standardized loadings (β > 0.44) and no indicators removed.

SEM results demonstrated significant paths from all vulnerability dimensions to disaster risk: Susceptibility ($\beta = 292.35$), Coping ($\beta = 115.02$), and Adaptive Capacity ($\beta = 174.53$), all $p < .001$. These findings underscore the crucial role of societal vulnerability—especially susceptibility factors such as public health, poverty, infrastructure resilience, and institutional capacity—in shaping national disaster risk. Strengthening these areas is vital for reducing disaster impacts.

This study employed multi-group Structural Equation Modeling (SEM) to explore how relationships between Exposure and Vulnerability vary across countries stratified by disaster risk severity, categorized into quartiles based on the World Risk Index (WRI). The analysis compared the lowest risk quartile (Q1) with the highest risk quartile (Q4).

Latent constructs included Exposure (indicators EI_01, EI_02, EI_03, EI_05, EI_06, EI_07) and Vulnerability, modeled as a higher-order construct composed of Susceptibility (S_01 to S_05), Coping (C_01_rev to C_03_rev), and Adaptive Capacity (A_01_rev to A_03_rev). Confirmatory Factor Analysis (CFA) indicated strong indicator loadings ($\beta > 0.44$) in the high-risk group, whereas the low-risk group showed weaker or non-significant loadings on some exposure items.

SEM path results revealed that in the high-risk quartile, both Exposure ($\beta = 1.190$, $p < .01$) and Vulnerability ($\beta = 0.790$, $p < .001$) significantly predicted disaster risk. In contrast, neither construct had a significant effect in the low-risk quartile. These findings suggest that in high-risk regions, exposure and vulnerability jointly drive disaster risk, whereas in low-risk areas, factors such as effective governance or geographic advantages may buffer disaster impacts.

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This is to acknowledge that we have used Grammarly for language correction and ChatGPT to format the R programming output

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Understanding socio-ecological urban flood risk complexity: Using causal loop diagrams and network analysis to support sustainable climate change adaptation decision-making

Franziska S. Hanf[1] and Nikita Strelkovskii[2]
1 Meteorological Institute, Center for Earth System Research and Sustainability (CEN), University of Hamburg, Hamburg, Germany
2 International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

Abstract

Cities are facing increasing challenges of flood risk due to combined effects of climate change and socioeconomic development. Despite growing awareness of the dynamics of flood risk in urban systems, flood risk management and urban adaptation planning often focus on isolated measures, overlooking the broader system complexity. This study analyses an integrated causal loop diagram (CLD) co-developed by researchers and stakeholders to explore multi-hazard urban flood risk and climate adaptation in the city of Hamburg, a coupled socio-ecological system. While CLDs offer a powerful qualitative modeling approach for revealing system connections, indirect effects and feedback mechanisms, large, interconnected diagrams can be difficult to grasp and interpret. To address this, we apply network analysis to examine the structure and complexity of the CLD and to identify key system components, including leverage points that are most likely to shift system-level behavior. By combining causal loop diagramming, network analysis, and the leverage points perspective, we identify systemic drivers of change and understand their role in initiating and reinforcing change in the system or in balancing system behavior to support sustainable climate adaptation decision-making. Using both network-level metrics (structural graph measures characterizing the entire CLD) and node-level metrics (individual graph measures quantifying the influence of individual nodes in the CLD), we provide a systematic, semi-quantitative approach to understand the myriad of interacting factors and feedback loops that shape the urban flood risk-adaptation nexus.

Keywords: urban flood risk complexity; causal loop diagrams; network analysis; leverage points perspective; sustainable flood risk adaptation

Using household motivations, abilities and opportunities to customize humanitarian assistance for hazard resistant housing

Eefje Hendriks [(1)], Mia Stokmans [(2)]
1. University of Twente, Netherlands, e.hendriks@utwente.nl
2. University of Tilburg, Netherlands, m.j.w.stokmans@tilburguniversity.edu

Abstract

Technical post-disaster reconstruction assistance insufficiently enables vulnerable households to rebuild hazard-resistant houses that can withstand future natural hazards, calling for stronger customization. Methods are needed to design evidence-based strategic targeted interactions to support reconstruction based on differences in household assets and measure the impact of interactions on individuals. We propose a novel innovative method using an adapted version of the MAO behavioral model (motivations, abilities, and opportunities). The method is developed to follow dynamic behavioral intentions throughout the reconstruction process and seek for pathways to support resilience building. The method acknowledges the influence of individual motivations as part of a social system within environmental opportunities on behavioral intentions. The method employs an open-ended interview scheme to measure assets through a random sample of affected households. Responses are deductively coded into quantitative data, allowing for a nuanced understanding of both enabling and limiting factors perceived by respondents. Scores are rescaled and used in a cluster analysis and qualitatively analysed to segment households in 27 different groups, each requiring different forms of engagement and support. Characteristics of each group are then used to co-design localized customized interventions aimed at facilitating safer reconstruction practices, preparing for future hazard events. This mixed-methods approach, demonstrated using data from households affected by the 2015 Nepal earthquake, provides a practical tool for humanitarian actors seeking to improve the effectiveness of post-disaster recovery programs. By uniquely combining qualitative depth with quantitative structure, the method practically enables agencies to tailor their outreach based on household-specific indicators, while also offering a means to assess the impact of their interventions with a strong theoretical foundation. This method gives an image of the behavior of an autonomously acting individual, identifying a set of important indicators for reconstruction decisions. Further research could explore decisions of individuals as part of a community and a specific environment.

Keywords: reconstruction; decision-making; hazard; customization method; support

Predicting Short-Length Discharge Data Using Fuzzy Logic Models

Mahshid Khazaeiathar [1], Britta Schmalz [2]
1,2 Chair of Engineering Hydrology and Water Management, TU Darmstadt, Germany
m.khazaei@ihwb.tu-darmstadt.de b.schmalz@ihwb.tu-darmstadt.de

Abstract

Flood protection and adaptive monitoring remain critical challenges for resilient socio-technical-environmental systems. In this study, we investigate the potential of a fuzzy logic-based modeling framework to enhance short-term discharge prediction, particularly peak flow modeling, for the Schwarzbach River (gauge Nauheim, Hesse, Germany), using observed hydrological datasets of four high-variability events. The motivation arises from the limitations of data-intensive models under data-scarce and volatile conditions, where nonlinearity, uncertainty, and variance fluctuations often reduce reliability. Our goal is to develop an interpretable, computationally efficient, and robust approach that can be embedded into dynamic monitoring infrastructures to strengthen continuous surveillance, early warning, and adaptive response capabilities. The central research question guiding this work is: To what extent can fuzzy logic-based models improve the accuracy, interpretability, and resilience of short-term discharge predictions, thereby supporting adaptive flood risk management under disruptive conditions? In pursuit of this objective, we developed and applied the proposed fuzzy logic-based framework, with results highlighting its practical and scientific value. Results demonstrate that this approach successfully captures gradual transitions and imprecise dynamics in streamflow, reducing computational complexity while maintaining robust performance under uncertainty. These findings not only advance the scientific basis of resilient flood forecasting but also align with integrating cyber-physical systems with adaptable monitoring, prevention, and response strategies for complex crises.

Keywords: Fuzzy logic; short-term discharge prediction; peak flow modeling; flood resilience

Introduction

Flood events represent one of the most critical natural hazards, often threatening human lives, infrastructure, and economic stability. Reliable discharge prediction is essential for flood resilience, particularly when only short-term datasets are available and hydrological variability and uncertainty complicate accurate forecasting [1]. Traditional data-intensive models such as artificial neural networks are often limited in application when confronted with data-scarce conditions or abrupt fluctuations in variance, which restricts their usability for real-time crisis management [2]. These challenges highlight the need for adaptable, interpretable, and computationally efficient approaches that can operate under uncertainty while still providing robust predictions [3]. Fuzzy logic-based modeling provides a promising framework to address these challenges by capturing gradual transitions, imprecise dynamics, and nonlinear behaviors

in hydrological time series. This method utilizes membership functions to cluster discharge data according to statistical behavior and allow predictions to be drawn from both local and neighboring patterns. This structure enables models to not only improve prediction accuracy but also enhance interpretability, which is vital for decision-making in flood risk management. In the context of resilient monitoring, prediction and response, such approaches are highly relevant as they strengthen continuous observation, early warning, and adaptive response to disruptive flood events. By focusing especially on peak flow modeling, this study contributes to advancing resilient forecasting methodologies and lays the foundation for integrating intelligent, adaptive tools into future flood protection infrastructures.

Case Study, Data Collection, and Methods

The study focuses on the Schwarzbach River catchment upstream of the Nauheim gauge (ID 23980353; 49.9508, 8.4526) in Hesse, Germany, part of the Rhine River Basin. The 135 km² catchment features a flat, mostly rural landscape, with settlements like Mörfelden-Walldorf, Langen, and Frankfurt Airport in the north. The Nauheim gauge records mean, low, and high discharges of 0.60, 0.02, and 5.00 m³/s (1965–2009)[4]. Four flood events linked to heavy rainfall (>25 mm/h) in spring/summer were selected for analysis. Discharge data (1985–2023) [5] at hourly intervals were used to develop and test a statistical and fuzzy logic-based model for flood prediction methods. Methodologically, we employ statistical testing for nonstationarity and long memory, followed by a fuzzification and clustering process (Singh method) that groups discharge data according to similar statistical behavior, enabling prediction through both local and neighboring patterns.

Results

The results of this study demonstrate that the fuzzy logic-based framework can model the actual discharge dynamics of four events which we selected of the Schwarzbach discharge with very high accuracy. Four presented graphs in Figure 1, violin plots of the prediction errors for the four events, illustrating the distribution and magnitude of deviations between observed and predicted discharges. The median lines close to zero indicate that the model predictions are generally accurate, while the limited number of outliers (red points) shows that extreme errors are rare. Notably, the model exhibits strong performance in capturing and predicting peak flows, as reflected by the median lines of the boxplots being consistently near zero and the relatively short interquartile ranges, indicating that both typical and extreme values are well reproduced. These findings not only enhance short-term prediction accuracy but also indicate that fuzzy logic models can serve as effective tools for supporting dynamic flood management. The model's robust performance under high variability further emphasizes its potential applicability within intelligent monitoring and early-warning systems.

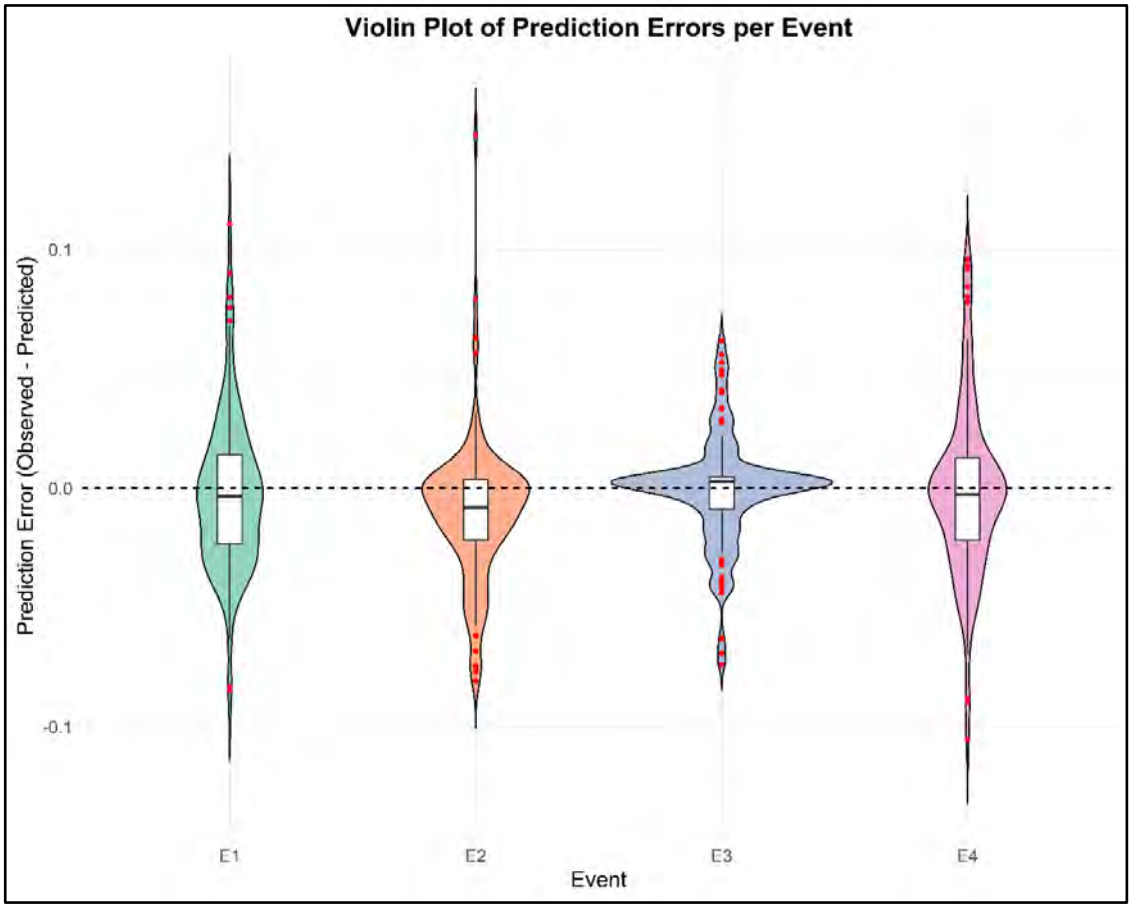


Figure 1. Distribution of prediction errors per event

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Will be added after the review process

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Moroccan Local Adaptive Systems Balancing Resilience and Development

Asmaa MAAROUFI [1], Sarah Alami [2], Edmond Seabright [3]
1 School of Collective Intelligence, University Mohammed VI Polytechnic , Morocco, asmaa.maaroufi@um6p.ma
2 School of Collective Intelligence, University Mohammed VI Polytechnic , Morocco, sarah.alami@um6p.ma
3 School of Collective Intelligence, University Mohammed VI Polytechnic , Morocco, edmond.seabright@um6p.ma

Abstract

This study investigates Moroccan rural associations as complex adaptive systems and examines their viability and adaptive legitimacy in disaster risk reduction, preparedness, resilience and rural governance.

Keywords: rural associations, complex adaptive systems, disaster risk reduction, institutionalization, resilience

Introduction

In the aftermath of natural disasters, local communities frequently mobilise grassroots responses that can later be institutionalised. While these bottom-up structures often begin as emergency relief actors, they may eventually either get absorbed into broader official frameworks for long-term development and resilience-building, or break down. Although most local disaster response formalised initiatives originate in critical times when they usually demonstrate high performance and utility, many of these institutions eventually devolve into bureaucratic or inactive structures. Despite their importance to emergency responses and resilience building, particularly in rural settings, the institutional trajectories of these community-led mechanisms - how they evolve, gain or lose legitimacy, and sustain relevance - remain poorly theorised and documented across different contexts.

From an alternate analytical perspective, Scharte (2025) concludes that “complexity is a necessary condition for resilience because only complex systems can possess of general adaptive capacity.” He also declares that the complex adaptive systems (CAS) theory shows how applying system design principles helps to increase general adaptive capacity, thus, “social capital—on the community level— and measures for individual disaster preparedness—on the individual level—provide general adaptive capacity, which increases the resilience of the affected systems.”

This study examines the institutionalisation of grassroots disaster-response mechanisms, focusing on their long-term viability and adaptive legitimacy in governance and disaster preparedness systems, drawing on Morocco as a case illustration. In it, we review the history and role of these institutions as CASs in responding to natural disasters, and discuss whether they remain viable actors in rural governance and/or disaster preparedness, or if their role requires fundamental reconsideration.

Moroccan rural associations as complex adaptive systems

Holland (1992) defines CAS as ones that "change and reorganize their component parts to adapt themselves to the problems posed by their surroundings." Moroccan rural associations, therefore, qualify as CAS as they have been adapting to their changing environment and the roles expected of them. He further elaborates that three key characteristics make them complex and adaptive: evolution, aggregate behaviour, and anticipation.

Morocco's rural associations' evolution manifests in their capacity to learn and adapt in complex dynamics regarding the diverse stakeholders they interact with: local communities, conventional local governing bodies, other national and international non-governmental organisations and government and state representatives, among others.

Their aggregate behaviour is represented on the micro-level by their internal functioning, the internal laws they elaborate on, the policies they execute, and the interactions between members and the communities. On the macro-level, it is their implication in nation-wide development schemes, disaster recovery, and resilience plans. Also, they identify as bottom-up structures since local communities create them, yet they can be perceived as "a top-down directive from public authorities to involve these populations in territorial development responsibilities." Zein Taleb et al. (2024)

As for their anticipation aspect, many are prone to develop rules and practices to help them solve potential problems, remain alert to the early warning signals of challenges, and prepare to face them, particularly concerning recurring hazards.

Complete adaptive loop: community-led disaster response, resilience-building, and territorial development

The evolution of rural associations in Morocco remains largely undocumented: while rural Morocco's communities have always had their conventional governance and problem solving mechanisms represented by Jma'a (communal council/assembly) and Zaouïas (religious institutions) among others that are responsible for local decision-making, conflict resolution, and the management of communal affairs, based on customary law and local consensus, the first formal institutions with a legal status, clearly delineated roles and established procedures emerged with the introduction of the cooperatives model by IFAD in the 1980s as a response to long years of drought, as stated by Messer (2003), which was successful in creating formal institutions eligible to receive funding, with structured teams and determined roles with accountability for achieving projects. According to Saaf's (2016) extensive report, formal institutions in rural areas only started emerging in the 1990s, then gained the government's trust and encouragement in the early 2000s as they were included in the participative approach of development, Green Morocco's Plan and the National Initiative for Human Development. Thus, a wave of jam'ias (associations) were created; some were sustainable, others soon became inactive or conflictual, which led to a debate questioning their efficiency and legitimacy as a rural development mechanism. The Haouz earthquake of 2023 reestablished a crisis scenario similar to the one that provoked the establishment of their model: a natural crisis generating a need for local coordination mechanisms to reach the communities, transfer funds and implement recovery projects, revealing both strengths and weaknesses. Many local rural

associations were closely involved in this disaster, thus completing the adaptive loop of their system: from cumulative strain to long-term development, then acute disruption.

The graphs below show potential correlations between the formation and scope of associations and natural disaster events in Morocco.

Challenges and limitations

One of the challenges in this research is the difficulty of accessing detailed data to investigate the potential patterns linking the formation and scope of associations with natural disaster events in Morocco. However, the HCP (2023) data provide longitudinal statistics on non-profit NGOs in Morocco, detailing their establishment, regional distribution, and areas of activity. Unfortunately, these data do not differentiate between rural and urban dynamics.

Future research directions

To further explore the role of local rural associations as complex adaptive systems in Disaster Risk Reduction (DRR) and resilience, we are currently conducting an assessment of these institutions' effectiveness in coordinating external relief aid, compared to independent community representatives who were fulfilling the same role across 579 villages affected by Morocco's 2023 earthquake. We aim to address the question: Are local associations dependable mechanisms for fostering resilience?

Another anticipated research project would analyse the social networks of rural associations throughout Morocco's Atlas region to determine whether and to what extent these institutions alleviate the lack of infrastructure that isolates most villages and increases their vulnerability.

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Mobility Data-Driven Assessment of Dialysis Access and Resilience

Saurabh Mohite [1], Shangjia Dong [1], Jennifer Horney [2]
1 Department of Civil, Construction, and Environmental Engineering, University of Delaware, Newark, DE, USA
2 Department of Epidemiology, University of Delaware, Newark, DE, USA

Abstract

Dialysis access is critical yet highly vulnerable to geographic, social, and infrastructural inequities. Using Delaware as a case study, we analyzed dialysis visitation data with a predictive model to identify factors shaping facility choice. Travel patterns revealed a clear North-South divide: patients in northern New Castle County accessed nearby clinics, while those in southern Sussex County traveled significantly farther, reflecting both sparse facility distribution and patient preferences. Distance emerged as the dominant statewide predictor of facility choice, consistent with the burden of thrice-weekly treatments and highlighting disproportionate challenges in rural areas with limited options. Beyond distance, demographic and vulnerability indicators, such as elderly population and proportion of minority residents, were strongly associated with facility selection, emphasizing the heightened sensitivity of these communities to disruptions. Facility quality measures, including hypercalcemia prevalence, infection rates, and transplant referral activity, also influenced patient choice, suggesting that when alternatives exist, patients gravitate toward higher-quality care. These findings reveal that dialysis access is shaped by the intersection of geography, community vulnerability, and facility quality, underscoring multidimensional inequities that must be addressed in disaster preparedness and healthcare resilience planning.

Keywords: Dialysis access; Human mobility; Acute care resilience

Introduction

Reliable dialysis access is vital for patients with End-Stage Renal Disease (ESRD) (Horney et al., 2024; Kaiser et al., 2021), yet it remains highly susceptible to inequities, geographic barriers, and infrastructure disruptions. Rural and socioeconomically disadvantaged populations are especially vulnerable, as disasters, clinic closures, or transportation failures can abruptly interrupt care. Recognizing these risks, agencies such as the Centers for Medicare & Medicaid Services (CMS) and the Federal Emergency Management Agency (FEMA) have called for a more resilient dialysis system. However, conventional healthcare access models, such as the two-step floating catchment area (2SFCA) method, gravity indices, and discrete choice frameworks, offer only static assessments of spatial coverage. They assume patients visit the nearest facility (Hoseini et al., 2018), and overlook critical factors such as insurance

restrictions, facility quality, cultural and language barriers, and personal preferences (Gao et al., 2023). For instance, patients frequently bypass the closest dialysis center in favor of one that better meets their needs (Aggarwal et al., 2017) due to higher quality of care and availability of preferred treatment schedules. Moreover, these models are not well-suited to dynamic conditions, such as facility closures or sudden shifts in patient behavior during disruptions.

To address these limitations, this study introduces a data-driven framework that integrates real-world mobility data from anonymized mobile phone records. Unlike traditional distance-based methods, this approach directly observes which populations travel to which facilities, and when, revealing patient preferences and adaptive travel behaviors. By moving beyond static assumptions, our framework provides a richer understanding of dialysis access dynamics, offering critical insights to inform proactive and equitable disaster preparedness and healthcare resilience planning.

Data

Our analysis combines six complementary datasets to capture population distribution, mobility, facilities, and infrastructure:

- *Census Block Data (2020)*: Fine-grained population counts at the block level, used to refine spatial distribution and improve accessibility estimates.
- *Census Block Group (CBG) Boundaries*: Geospatial polygons representing neighborhoods (~600–3,000 people) for mapping social vulnerability metrics and community-level analysis.
- *Road Network (OpenStreetMap)*: Road networks used to calculate realistic driving distances and paths between CBGs and dialysis centers.
- *SafeGraph Mobility Data*: Anonymized mobile device data capturing visits from CBGs to dialysis facilities, forming an origin-destination matrix of real patient flows.
- *Dialysis Facility Data*: Registry of ESRD treatment centers with attributes such as location, ownership, and quality ratings, providing verified facility information matched to SafeGraph POIs.

Results

Dialysis Facility Access Disparity

Our spatial data mining of dialysis access in Delaware, USA, identified patient visits to 26 in-state and 70 out-of-state facilities (include only those captured by SafeGraph data). A distinct North–South divide emerged: residents of New Castle County generally traveled shorter distances, while those in Sussex County faced longer trips, reflecting both facility distribution and patient preferences. Travel distances showed little variation by ethnicity or income statewide, but elderly patients in Sussex County traveled significantly farther, likely linked to the county's growing retiree population. These patterns underscore Delaware's distinctive dialysis access challenges.

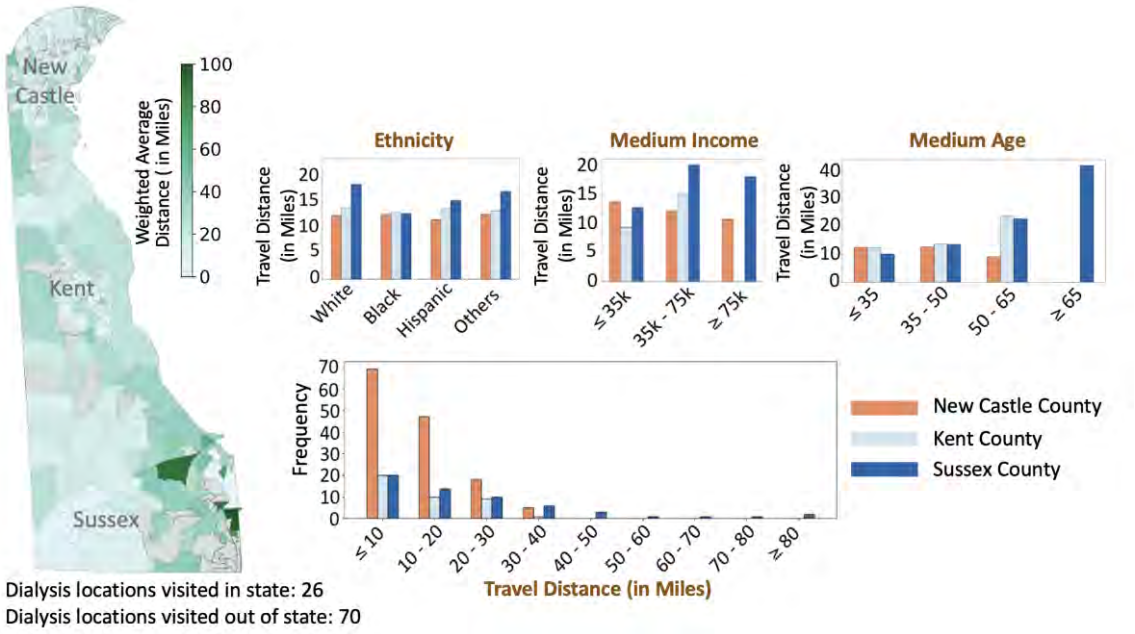


Figure 1 Dialysis facility access disparity

Flood-induced Dialysis Care Disruption

We also examined the effects of flooding, a major risk given the state's low-lying geography. Two disruption mechanisms were considered: (1) direct inundation of facilities and roadways, and (2) isolation of communities cut off from care. Our findings quantify both localized disruptions and broader cumulative impacts. Spatial analysis shows that urban "resilient zones" with shorter dialysis travel distances disproportionately serve minority populations, while suburban zones with similar travel advantages primarily serve non-minority groups. By contrast, coastal communities, already highly exposed to flooding, face some of the longest travel distances, illustrating inequities in access resilience.

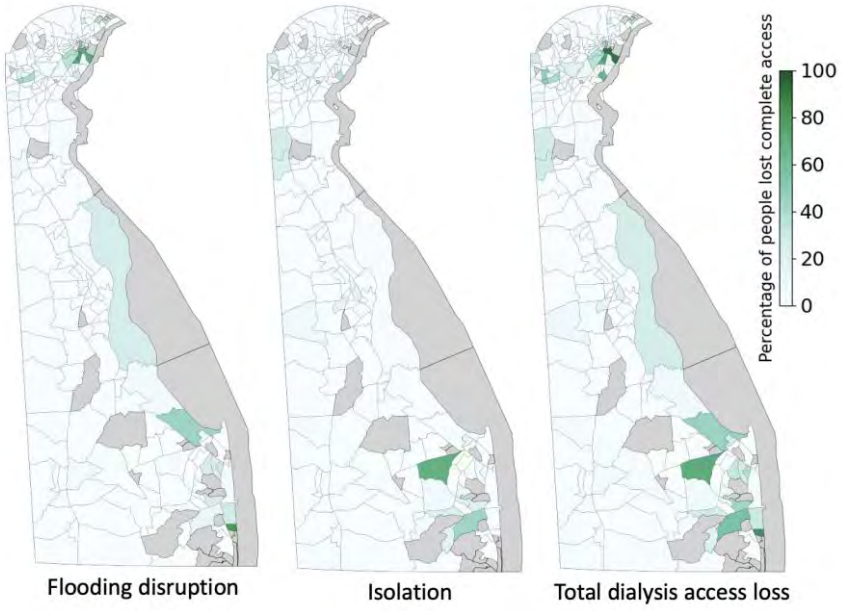


Figure 2 Flood-induced dialysis care disruption

Contributors of Dialysis Visit Preference

To investigate key factors shaping dialysis facility choice, we developed a contrastive learning-based Graph Neural Network (GNN) trained on Delaware human mobility POI data, facility attributes, and community characteristics. The model embeds Census Block Groups (CBGs) and facilities, ranks likely destinations, and uses SHAP (Shapley Additive Explanations) analysis to interpret feature importance.

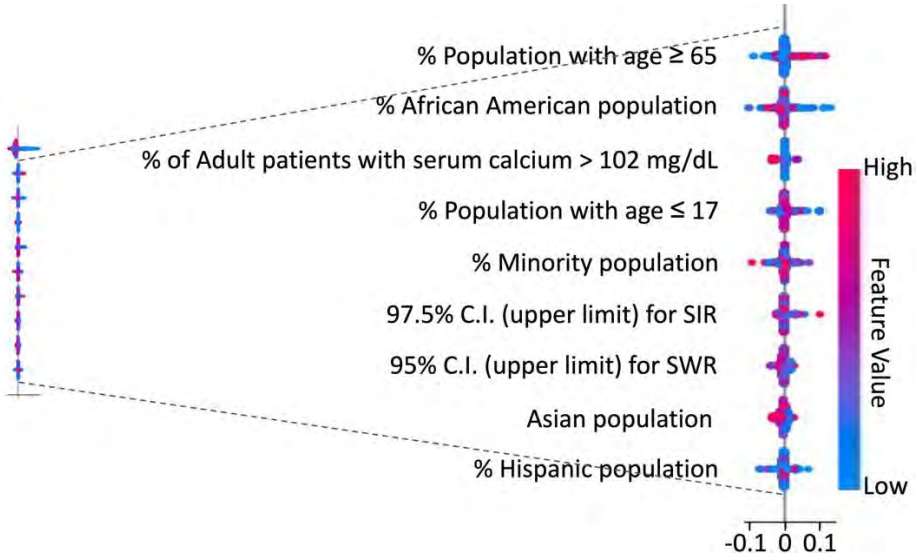


Figure 3 Feature importance through SHAP analysis

Statewide, distance was the dominant predictor, reflecting the burden of thrice-weekly travel. Communities with older populations and higher proportions of minority residents showed higher demand, as reflected by the prominence of EP_AGE65 and EP_afam in the model. These patterns suggest that both aging and racially diverse populations are particularly sensitive to access disruptions, emphasizing the need for targeted planning in these

communities. Facility quality indicators, such as hypercalcemia prevalence, infection rates, and transplant referral activity, further influenced choice, suggesting patients gravitate toward higher-quality care when alternatives exist.

Results also revealed clear urban-rural disparities. In urban areas, facility quality and transplant access mattered alongside distance, with patients preferring centers with lower transfusion and hospitalization rates and stronger transplant programs. The proportion of African American residents was influential, highlighting inequities in access to high-quality facilities. In rural areas, distance was often much greater, with patients constrained by limited options. Facility outcomes such as mortality and emergency visits, along with socioeconomic indicators like housing cost burden and prevalence of mobile homes, strongly shaped access. Transplant referral activity was far less influential, pointing to disparities in referral and awareness. Together, these findings reveal that dialysis access is shaped not only by geography but also by the intersection of community vulnerability and facility quality, highlighting the multidimensional inequities that must be addressed in resilience planning.

Acknowledgements

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Flood Robustness of Urban Road Networks Across Geographical Contexts

Ylenia Casali, LMU, Germany, ylenia.casali@gmail.com

Abstract

This study analyses the road robustness levels across different cities under flooding risk. By applying fragmentation processes on road networks, robustness is quantified and compared. However, as not all cities share the same geographical, morphological, and infrastructural characteristics, the analysis also considers how these contextual factors influence the observed robustness patterns. This research enhances our understanding of how road network robustness differs across urban geographies and shows how network theory can support resilience assessments by revealing structural limitations and initial conditions.

Keywords: networks, robustness, percolation, world cities, geography

Introduction

Urban infrastructure networks, particularly road systems, are increasingly vulnerable to natural hazards due to rapid urbanization and climate change (see 1). Flooding poses a significant threat as more than one in five people around the world live in areas directly exposed to 1-in-100 year flood risk [2]. While prior studies have assessed the impact of localized flooding on transport, fewer have analyzed network robustness across multiple cities with differing geographic and social characteristics (see 3, 4). In particular, previous studies have reported contradictory findings regarding the robustness of road networks across cities. For example, [3] concluded that geographical form is irrelevant to network robustness, based on analyses of clustering coefficient and average path length. In contrast, [4] found substantial differences in robustness across cities by examining the percolation point—defined as the fraction of edges removed when the size of the second-largest connected component reaches its maximum. These diverging conclusions highlight the importance of discussing both topological measures and context-specific factors when assessing the robustness of urban infrastructure networks.

Scope of the study

Building on previous literature that applied percolation theory framework to analyze fragmentation processes on the network structure (see 5), this study looks at the robustness level of road infrastructures across 10 global cities exposed to flooding risk. Robustness will be quantified by using the size of the largest component. However, by recognizing that topology alone cannot explain urban resilience, this study also integrates the geographical and morphological context of each city. Cities differ largely in their terrain, morphology, hydrological features, and historical development patterns—all of which influence how flood events interact with infrastructures. For example, a dense grid-like city on a floodplain may maintain redundant paths despite high exposure, while a mountainous city with limited road intersections may collapse easily despite lower overall exposure. To account for these differences, we compare road network robustness in a diverse set of cities representing different

types of environments, for example deltaic, coastal, riverine, and highland. Discussion of the results will contribute to advance our understanding about how robustness changes in different urban geographical contexts. Ultimately, this research contributes to advancing our understanding of how robustness varies across urban geographies, and how network theory can inform resilience assessments by identifying initial conditions and structural constraints. These findings offer insights for integrating topological analysis with spatial and environmental context in the pursuit of flood-resilient urban systems. This work contributes also to the growing recognition that metrics used to assess network resilience must be contextually grounded (see 6). A meaningful understanding of infrastructure robustness under climate risks requires bridging quantitative methods with qualitative, place-based insights, guiding future research toward a more nuanced and useful analysis of complex adaptive urban systems.

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A Geospatial Generative Adversarial Network Approach for Future Urban and Infrastructure Resilience

Richard Dawson[1], Richard Burke[2], Alistair Ford[3]
1 School of Engineering, Newcastle University, UK, richard.dawson@newcastle.ac.uk
2 School of Engineering, Newcastle University, UK, R.Burke1@newcastle.ac.uk
3 School of Engineering, Newcastle University, UK, Alastair.ford@newcastle.ac.uk

Abstract

Rapid urbanization, especially in data scarce regions, demands innovative tools to simulate future urban growth and understand resilience. This study introduces a geospatial framework combining agent-based modelling and Generative Adversarial Networks (GANs) to generate realistic urban form scenarios. Applied to Phnom Penh, Cambodia the model translates projected population growth to generate plausible road networks and building layouts. Validation of the trained model against observed development shows good performance. Under five different socio-economic scenarios, projections range from 39–106% increase in buildings and 22–72% for road length. The framework supports decision-makers in visualizing future urban morphologies and evaluating strategies to mitigate climate-related risks such as flooding and heatwaves. It offers a scalable, data-efficient approach to guide sustainable urban planning in fast-growing cities.

Keywords: Urban growth; Generative AI; Agent-based modelling; Urban form; Infrastructure networks

Introduction

Urbanisation is a global driver of change, with the majority of the world's population now living in urban areas. This growth is particularly pronounced in developing regions. Given the role of urban form in climate risk, it is essential to simulate the future layout, character and structure of urban areas to understand how risk and resilience might change. Urban growth modelling offers decision-makers a valuable tool to understand the complexities of urban dynamics, anticipate future transformations, and design sustainable and resilient cities. Current approaches typically use raster grids or administrative polygons to project changes in population and thus exposure to climate hazards. These do not consider different possible building layouts or infrastructure configurations that modulate resilience through changes to the vulnerability, exposure, and hazard components of risk. This paper introduces a novel geospatial framework that uses Generative AI methods to simulate, explore and characterise future urban form scenarios.

Case study site

Phnom Penh, Cambodia, was selected as a case study due to its rapid urban expansion, data-scarce environment, and the relatively small proportion of built-up area. Cambodia is one of the most rapidly developing countries within the Greater Mekong region. Between 2000-2010, Cambodia's built-up area and population increased by 4.3% and 4.4 % per year (National Institute of Statistics, 2019). The population of the capital city, Phnom Penh, grew to 2.2 million (Figure 1). The associated urbanisation of floodplains increased impervious surface area, coupled with climate change, this has increased the risks of flooding, posing a significant hazard to human life and infrastructure (Tierolf et al., 2021).

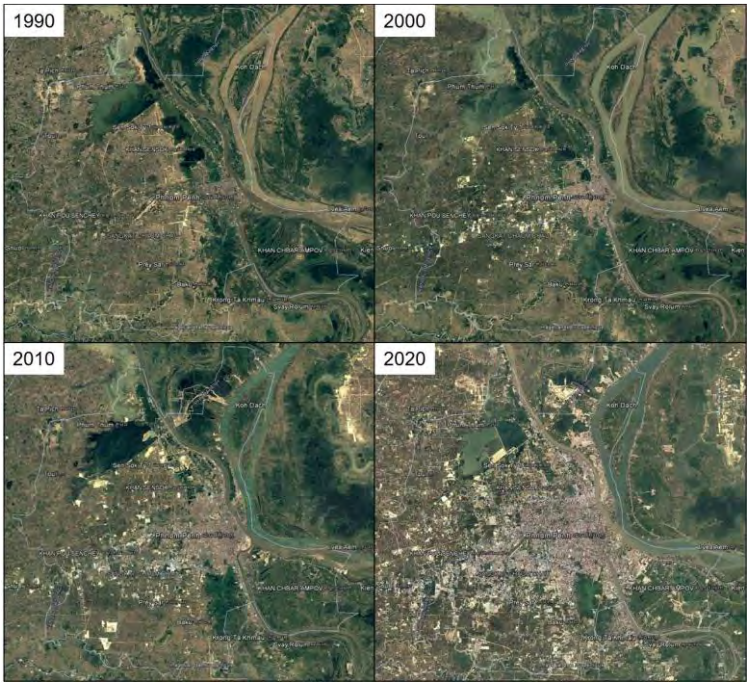


Figure 1. Phnom Penh urban land expansion between 1990-2020.

Methodology

The framework first uses agent-based modelling (ABM) to simulate future urban growth. The ABM represents interactions between key actors, such as urban planners, property developers, landowners and residents to provide projects of future development according to land parcels (Figure 2).

A Generative Adversarial Network then uses this future growth to perform image-to-image translation, converting a raster output of population growth into future road network layouts and building footprints. GANs provide a framework for data generation (Goodfellow et al., 2014). They function as a two-player game between two neural networks: a generator and a discriminator, trained simultaneously in an adversarial setup (Figure 3). The generator learns to produce plausible data from random noise sampled from a simple distribution, which serves as fake examples for the discriminator. The discriminator learns to distinguish between real data from the training set and fake data from the generator. During training the generator aims

to maximise the probability that the discriminator misclassifies its fake data as real. In contrast, the discriminator aims to minimise this probability, improving its ability to differentiate real and fake data. This adversarial process drives both models to improve iteratively, resulting in generated data that become increasingly indistinguishable from real data.

GANs can generate images conditioned on inputs, enabling context specific data generation suitable for generating urban form or infrastructure networks. The pix2pixHD GAN (Wang et al., 2018) is used here as it can use high-definition images and has been shown to be suitable for operation in the built environment. Here, we used satellite and building footprint data to train the GAN. Wayback Imagery offers a digital archive of satellite imagery since 2014 from providers such as Maxar, Microsoft, and DigitalGlobe (Esri, 2024). Building footprints were taken from Google Buildings which were more complete than other sources for Phenom Penh such as OpenStreetMap (Sirko et al., 2021). To allow for assessment of model validity, the timeseries of observed development from 2014-2023 was split into two periods. Between 2014-2019 was used for model training, whilst 2019-2023 was used for validation.

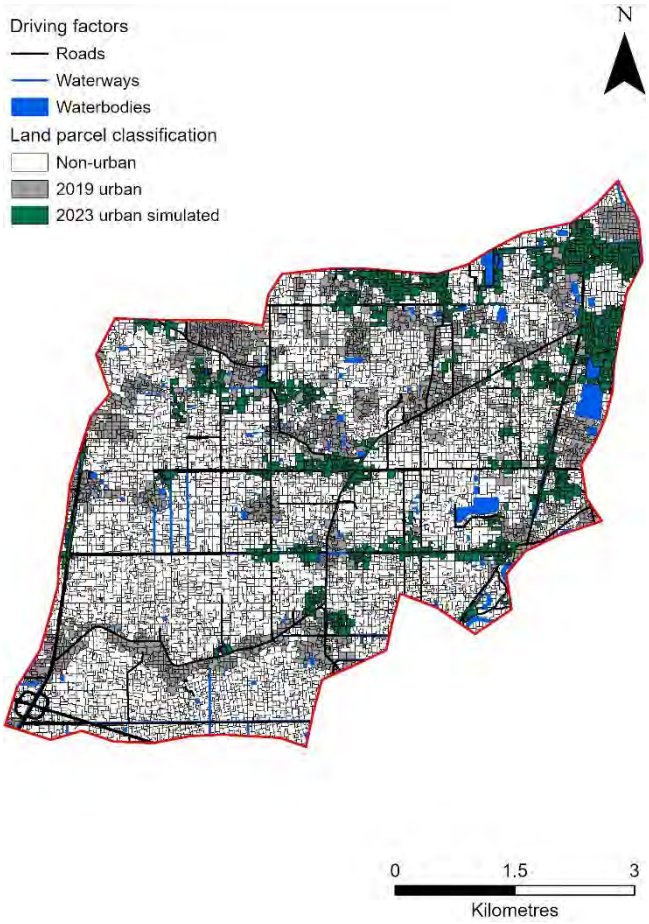


Figure 2. Simulated future urban growth for land parcels within three communes of Phnom Penh: Pong Tuek, Prey Sa, and Prey Veaeng.

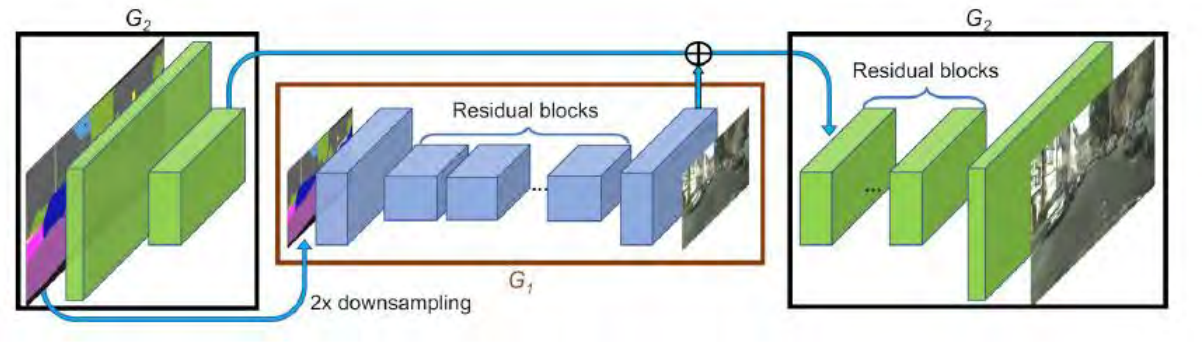


Figure 3. Pix2pixHD generator architecture (after Wang et al., 2018).

Key findings

The modelling framework is able to achieve varied, distinct and plausible patterns of growth. Notably, the GAN model is demonstrated to provide a feasible and practical technique to create realistic and convincing future urban and infrastructure form (Figure 4). Moreover, the model is able to integrate new infrastructure seamlessly with existing urban morphology.

Simulations were compared against observed development in the validation time period for a number of metrics, including the degree distribution of the road network; building footprint perimeters; and Fréchet Inception Distance (FID), which compares the distribution of the generated images to the distribution of real images by computing the distance between the feature vectors of real and generated images. Here, simulations were able to achieve an FID of close to 40, which shows solid performance especially for urban growth modelling where FIDs can often exceed 80 (Wu and Biljecki, 2023). Further analysis showed the performance was sensitive to input image resolution and the content (i.e. type of buildings and form) used for training.



Figure 4 (i) Indicative output of the GAN showing new road network and building form to meet projected population growth for the case study area, with (ii) zoom into the dotted inset box.

Exploration of five future socioeconomic scenarios shows the number of buildings could increase by between 39-106% and the length of road by 22-72%, with different spatial patterns, infrastructure topologies and urban morphologies. This demonstrates how urban development may unfold in the coming decades and supports the municipal authority to manage these developments effectively and devise strategies to mitigate potential negative impacts including flood and heatwave risks and greenhouse gas emissions. Future work will integrate a diverse range of built environment forms and infrastructure networks with models of natural hazard to understand how different patterns and topologies influence risks.

Acknowledgements

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From Households to Communities: Collective Action Pathways for Equitable Heat Adaptation

Aulia Imania Sukma, Dr.ir. Amineh Ghorbani, Prof.dr. Tatiana Filatova
1. Technische Universiteit Delft, Netherlands, a.i.sukma@tudelft.nl
2. Technische Universiteit Delft, Netherlands, A.Ghorbani@tudelft.nl
3. Technische Universiteit Delft, Netherlands, T.Filatova@tudelft.nl

Abstract

Climate change disproportionately affects socio-economically vulnerable households, raising urgent concerns about climate justice in adaptation actions. Although public protection mechanisms exist, they frequently fall short of effectively reaching and safeguarding individual households, thereby shifting the burden of responsibility onto those least equipped to bear it. Community-Based Adaptation (CBA) offers a promising bottom-up approach that strengthens adaptive capacity, redistributes responsibility, and fosters greater justice in climate responses. This study explores the development of CBA for adaptation to heatwaves. A mixed-methods design is employed, combining agent-based model simulations (ABMS) with empirical survey data to capture household and community behaviours in response to extreme heat episodes. The ABM conceptualizes households as heterogeneous agents with varying adaptive capacities, social ties, and access to resources, allowing exploration of emergent patterns of collective adaptation. The survey aims to gather data on risk perception, coping strategies, and informal support networks, which will inform model parameters and validate behavioural assumptions. Ultimately, this research seeks to identify pathways for more equitable and locally grounded heat adaptation strategies that enhance climate justice for vulnerable communities.

Keywords: CBA; ABMS; heat adaptation; climate justice

Introduction

Globally, climate change has doubled the number of extreme heat days in 195 countries, with approximately four billion people, nearly half the world's population, experiencing at least 30 days of extreme heat between May 2024 and May 2025 (Giguere et al., 2025). Although the health consequences of extreme heat, including elevated mortality and morbidity, are well documented (Hossain et al., 2024; Vargo et al., 2016), the implementation of adaptation measures remains inadequate (Lao et al., 2025). Climate adaptation strategies either rely on top-down approaches that emphasize centralized planning and technical solutions while neglecting local contexts and community needs (Woodruff & Stults, 2016), or focus on private adaptation action by individual households (Berrang-Ford et al, 2021). However, top-down adaptation strategies have shown limited effectiveness (Dupuits et al., 2024), failing to provide adequate protection at the neighborhood and household levels (Laranjeira et al., 2021). At the same time, individual household adaptation is often hindered by financial constraints, and further limited by social isolation and the absence of coordination mechanisms, which makes it difficult for households to access shared resources or learn from others, reinforcing the need for community-level strategies that promote mutual support and collective learning. Scholars

have emphasized that these local scales are among the most vulnerable and exposed, as environmental and demographic factors can amplify heat exposure (Borsky et al., 2024; Gabbe et al., 2023; Lo et al., 2022; Sharmin et al., 2023; Vargo et al., 2016). These factors are closely tied to disparities in adaptive capacity among households, which influences their ability to respond to heat stress and raises concerns about climate justice. Many studies have shown that marginalized households and neighborhoods are more susceptible to heat episodes due to limited financial resources, inadequate housing conditions, and densely built environments that lack open and green spaces (Büchs et al., 2024; Cutter et al., 2003; Johnson et al., 2010; Osberghaus & Abeling, 2022).

One promising approach to address climate injustice in adaptation efforts is community-based adaptation (CBA). The Intergovernmental Panel on Climate Change (IPCC) describes CBA as a local, community-driven approach that focuses on empowering and promoting the adaptive capacity of communities, treating context, culture, knowledge, agency, and preferences as strengths (IPCC, 2023). CBA has emerged in response to the limitations of top-down adaptation strategies, which often overlook the lived experiences and knowledge of vulnerable communities. By centering local participation and knowledge, CBA aims to equitably distribute the burdens and responsibilities of climate adaptation (Schreuder & Horlings, 2022).

Despite its growing relevance, CBA remains relatively unfamiliar to many of the citizens who are expected to carry it forward. Although widely discussed in academic domains, its practical application in everyday community settings is limited (Shammin, Wang, et al., 2022). Literature often separates CBA into bottom-up participatory efforts (Parsons et al., 2025) or top-down policy frameworks, with little attention to how household-level actions and government strategies can be effectively integrated (Shammin, Haque, et al., 2022). Furthermore, the potential of CBA to promote distributive justice at a regional scale is still unclear. While CBA has shown effectiveness at the neighborhood level, its transferability across different urban contexts, even within the same city, remains underexplored (Shammin, Wang, et al., 2022). Building on these gaps, the study explores how CBA can be integrated with existing individual and top-down government strategies to address heat stress in daily life practices, alongside household-level actions that are often constrained by financial and structural limitations.

Research design

This study adopts a mixed-methods approach, integrating a qualitative empirical survey with quantitative agent-based simulation modeling. The empirical component is designed to investigate how individual households perceive and respond to CBA initiatives. To capture the evolving nature of household engagement, the survey incorporates a temporal dimension, examining past experiences, current realities, and future expectations. These insights will inform the structure and parameters of the agent-based model, enabling a dynamic simulation of individual household behavior and institutional framework within CBA contexts. This dual-layered design enables the model to reflect both individual agency and systemic governance, offering a holistic view of adaptation processes. The conceptual framework guiding this approach is illustrated in Figure 1. This conceptual model is applied to selected neighborhoods

in Antwerp city. Further, the study evaluates the transferability and out-scaling potential of CBA across these neighborhoods to understand their potential for broader application within the same urban context.

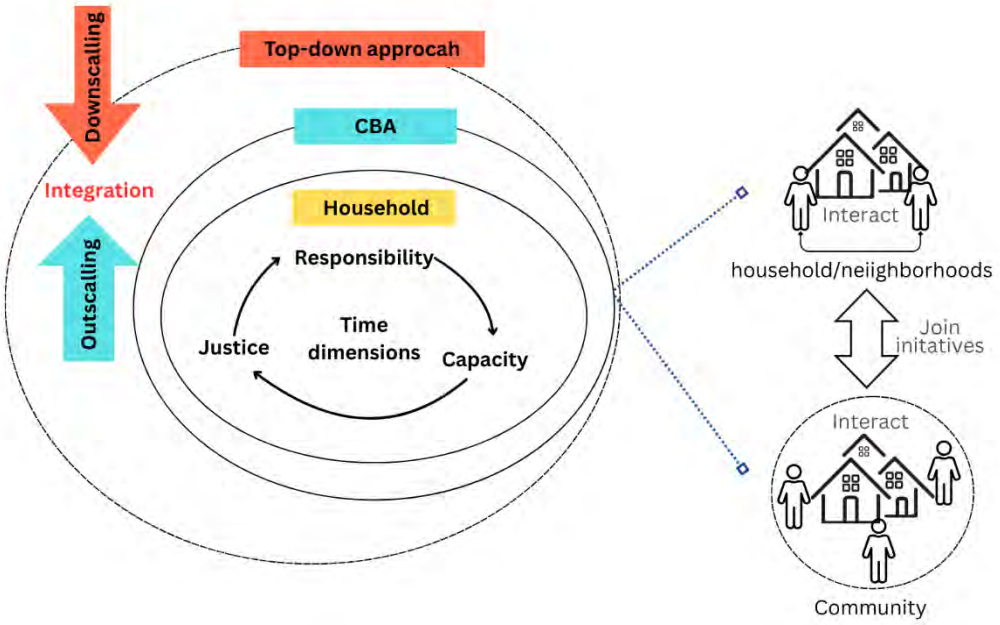


Figure 1 Conceptual framework illustrating the integration of top-down and bottom-up approaches in community-based adaptation, using responsibility, capacity, and justice as analytical lenses, with time as a dimension reflecting both long-term and historical aspects.

Conclusions

This abstract has laid the groundwork for investigating the role of CBA in addressing heat stress and promoting climate justice at the urban scale. By combining empirical insights with agent-based modeling, the study aims to capture the dynamics of household behavior and institutional support in response to extreme heat. The conceptual model and research design presented here mark the starting point of a broader inquiry into how adaptation can be made more inclusive and responsive to local realities. At the ICRS26 conference, we will present the first simulation results, offering initial reflections on how CBA mechanisms shape adaptation pathways and contribute to more equitable climate responses.

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Managing grassroots initiatives in the context of spatial change and public health.

Sylwia Widzisz-Pronobis, Silesian University of Technology, Poland
sylwia.widzisz-pronobis@polsl.pl

Abstract

Observing grassroots movements in Polish municipalities, the characteristics of a nonlinear response to crisis situations, described as the Complex Adaptive Social System, are evident. Research on the resilience of local communities involved organizing workshops with potential initiators of adaptive actions. Active residents of Gdańsk participated in the first meeting, while students from the Faculty of Architecture participated in the second. Both groups were tasked with developing ideas for spatial and social interventions based on a carefully prepared visualization of the crisis situation and knowledge of urban resilience. While the workshops yielded completely different results, common themes emerged regarding the involvement of public administration in managing grassroots initiatives in the areas of spatial change and public health. Both cases revealed the need to support the agency of local actors and to stimulate civic activity among youth using local institutional resources. The research resulted in a model for networking institutions and their resources to animate and manage grassroots initiatives.

Keywords: include three to five keywords; separated by semicolons

Introduction

In the social sciences, the Complex Adaptive System (CAS) manifests itself in a way comparable to adaptive systems found in nature. In administrative structures based on linear action, the challenge is to utilize self-organizing local communities to build urban resilience (Lansing, 2003). In the context of spatial change and public health, CAS refers to social activity in crisis situations, when local communities undertake actions to improve their quality of life. These changes are forced by various factors. In her research, Anna Domaradzka noted that the activity of urban activists increases in the context of issues related to the appropriation of common spaces by developers (Domaradzka Anna, 2021). At the same time, growing civic and climate awareness leads local communities to undertake initiatives aimed at providing rapid relief from the crisis and raising awareness among neighbors. Such grassroots activities often also have an educational dimension for public administration, which is often unable to keep up with rapidly emerging crises. The research question that emerged during analyses, among others, for the doctoral dissertation and in social activities is: How can the administration animate and manage grassroots initiatives to actively support building the resilience of local communities to social and spatial crises?

Methodology

As part of the research, two workshops on resilience in local communities were conducted. The workshops included visualization sessions, allowing participants to approach a similar crisis situation. This method allows participants to approach the issue with a similar emotional baggage, facilitating the definition of spatial and social resources and gaps, and stimulating an active search for shared solutions. The workshop agenda included an introduction to resilience, an assessment of resources and gaps, and the design of actions to address specific socio-spatial challenges.

1. Workshops with Gdańsk residents involved in the project "Common Street" implemented by the European Solidarity Centre. The aim of the meeting was to develop directions for local community action related to resilience to climate change. Seventeen people participated in the workshops, most of whom were residents of the same street.

2. Workshops with students of the "Healthy City" faculty at the Faculty of Architecture of the Silesian University of Technology. The aim of the meeting was to introduce the topic of resilience, engage students in observing their neighborhoods, and select a topic that could serve as a potential local community initiative.

Results

During the Gdańsk workshop, the following resilience analysis criteria were identified:

- access to data
- social participation
- sense of responsibility for the neighborhood
- social issues
- spatial and social issues
- spatial and infrastructural issues.

The criteria identified were not intended to serve as a comprehensive and multi-threaded analysis of community resilience, but rather to open the topic and indicate directions for further exploration. The main objective was to examine social cohesion (Jewett et al., 2021), thereby identifying those themes that appear most difficult to implement or are a key asset of local communities in Gdańsk. In developing local initiatives, residents undertook to plan actions for two challenges: the sudden closure of nurseries and preschools (inspired by restrictions during the COVID-19 pandemic); the inclusion of new people in the community and preventing sudden gentrification in the district (inspired by migration and the effects of urban revitalization). Both challenges yielded a wealth of interesting ideas based on the resources available to residents. The workshop summary raised questions about the role of public administration in adaptive measures. Local communities can organize in response to an emergency, but this is a short-term measure that allows for rapid organization and planning of long-term actions.

Following the initial public response, residents expected the administration to define its role in, among other things, activities related to:

- planning long-term processes requiring financial resources,
- changes in legislation needed to address challenges at the local level,
- access to public resources and institutions.

In the case of the workshops with students, difficulties arose due to the students' lack of social engagement. Only four of the 20 participants were active, frequently referencing the experiences of their parents and grandparents. Due to the specific nature of architectural studies, the focus was clearly on resilience. Students focused primarily on spatial issues, ignoring the social aspect. A lack of experience in administrative and social matters was evident, making it difficult for the young people to define the resources of their local community and plan spatial and social interventions to address the climate crisis.

One group had initiatives and needed to determine the scope of support they could receive from the administration. Suggestions were made regarding the scope of activities of individual city institutions in relation to specific ideas. Residents see potential in the activities undertaken by public institutions such as community centers, civic centers, and even theaters. The second group required education and encouragement of their involvement, so that it could potentially serve as local support.

The research resulted in a model for networking institutions and their resources to animate and manage grassroots initiatives.

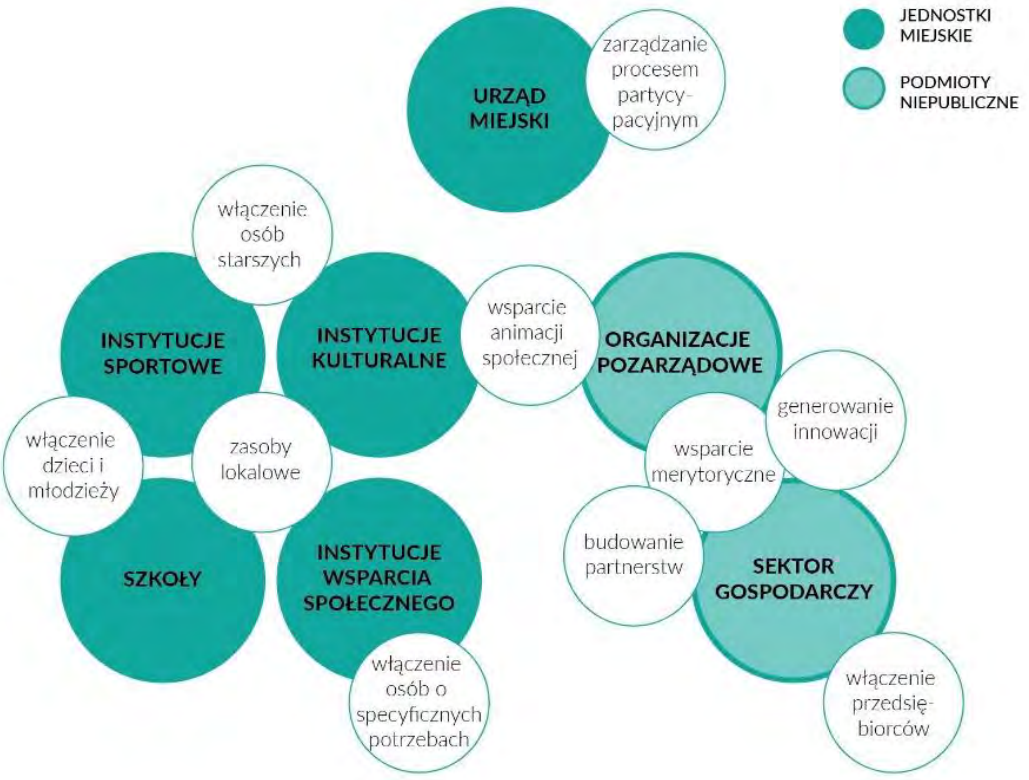


Figure 1 The potential of municipal institutions and the environment supporting the implementation of the participatory process, prepared by the author (Widzisz-Pronobis Sylwia, 2024)

Conclusions

Grassroots activity based on CAS theory can support administration, although it is often perceived as a hindrance by officials. Residents perceive particular administrative challenges in the context of implementing municipal tasks based on legal regulations, developing strategic documents that do not directly address initiatives, and financing their own tasks and grassroots activities. Institutions can manage initiatives and, through internal networking within the municipality, support administrative processes without the need to constantly engage local communities in strategic and operational discussions. Youth education and engagement are essential to provide real support and foster a sense of empowerment that strengthens their civic engagement.

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10. Resilience Assessment Methodologies

Integrated Climate Risk Assessment for the Panama Canal: Social Vulnerability Analyses

Key Authors: Mila van Druten, Margriet Hartman, Ingrid Lambert,

Contributors:
From The International Finance Corporation (IFC):
Arjun Bhalla, Edward Cameron, Gabriela Eslava Bejarano, Roop Singh, Carla Toledo, and Maria Lopez Conde.
From Haskoning:
Arend de Wilde, Danilo Amaral Cançado, Margriet Hartman, Ric Huting, Ingrid Lambert, Joost Trommelen, Mila van Druten, and Thijs Smeekes.

Abstract

This Climate Risk Assessment (CRA) for the Panama Canal Authority (ACP), conducted by Haskoning and contracted by the International Finance Corporation (IFC), evaluates how intensifying climate hazards threaten the resilience of critical infrastructure, ecosystems, and communities in the Panama Canal's watershed. Using climate modeling, exposure and vulnerability analysis, and stakeholder engagement, the CRA identifies key risks to water availability, vessel transit operations, and hydropower, with projected financial losses and cascading impacts across ACP systems – such as the ecological and social impacts around the watershed, highlighting the need for targeted adaptation. The CRA produced a portfolio of adaptation interventions and guidance on avoiding maladaptation, aimed at strengthening ACP's governance and adaptive capacity in the face of uncertain climate futures. This work presents insight into applied social vulnerability analyses within climate risk methodologies, aiming to provide insights into methodologies that can be applied while looking at real-world climate resilience planning within complex socio-technical-environmental systems from a community perspective.

Keywords: Climate change risk assessment; Social Vulnerability; Communities; Socio-economic indicators

Introduction

The Panama Canal is a globally critical infrastructure asset that facilitates maritime trade and shortens shipping routes, while contributing to Panama's GDP and national development. The Panama Canal Authority also prioritizes the provision of drinking water to surrounding communities, highlighting the Canal's dual role in supporting both global commerce and local livelihoods. However, in recent years, the Panama Canal and its surrounding watershed have faced intensifying climate-related challenges, including extreme rainfall events, and most notably the severe drought of 2023-2024 which resulted in vessel and draught restrictions.

With climate change impacts expected to intensify, the Panama Canal Authority (ACP), commissioned a comprehensive **Climate Risk Assessment (CRA).** This assessment was

contracted by the International Finance Corporation (IFC) and conducted by Haskoning, which evaluated **how shifting climate hazards** like extreme weather, rising temperatures, sea-level rise, and changing precipitation patterns, combined with the exposure and vulnerability of assets, populations and ecosystems could affect ACP's operations, finances and broader responsibilities under Panamanian law.

As an **applied research example**, this project followed the adaptation planning cycle, from identifying climate hazards and risks, through to prioritizing more than 60 adaptation measures, the identification of targets, the establishment of enabling conditions, and creating monitoring and evaluation systems, all to enhance resilience across the **complex technical and socio-environmental systems** of the Panama Canal.

Scope and Objectives

The CRA focused on the Eastern watershed of the Panama Canal, centered on the Chagres River basin. This abstract focuses on the **social assessment covering the identification and prioritization of climate risks to populations in the watershed**. By gaining insights into the exposure, vulnerability and risks specifically for different social groups within the watershed, recommended tailored adaptation interventions could be proposed to ACP to enhance resilience and avoid maladaptation. Lastly, this research was used to build institutional capacity within ACP to manage and facilitate decision-making on climate risks.

Methodology

The CRA for the APC employed a mixed-methods approach to evaluate climate risks across infrastructure, ecosystems, and communities. Key methodological components included:

- Climate Modeling: Utilized CMIP6 datasets to simulate climate hazards under SSP2-4.5 and SSP5-8.5 scenarios for near-, mid-, and long-term projections.
- Exposure Analysis: Mapped ACP's operational systems, populations, and ecosystems within the Eastern watershed.
- Participatory Engagement: Conducted site visits, focus groups, and stakeholder workshops to integrate local knowledge and validate findings.
- Impact Evaluation: Linked climate hazards to operational and financial outcomes, including historical case studies and anecdotal evidence from recent droughts and floods.

For the social analysis, the methodology of research was aligned with the CRA methodology, describing Exposure, Vulnerability and Risk from the social perspective, while incorporating the results from the Climate Hazard analysis.

- **Exposure:** The exposure of people and livelihoods in the watershed is presented through a spatial analysis, showing the current distribution of people and infrastructure within the Panama Canal watershed. This spatial analysis is supported by a literature

study to provide further context, indicating the current circumstances in the watershed, as well as future trends discussed in (academic) literature.

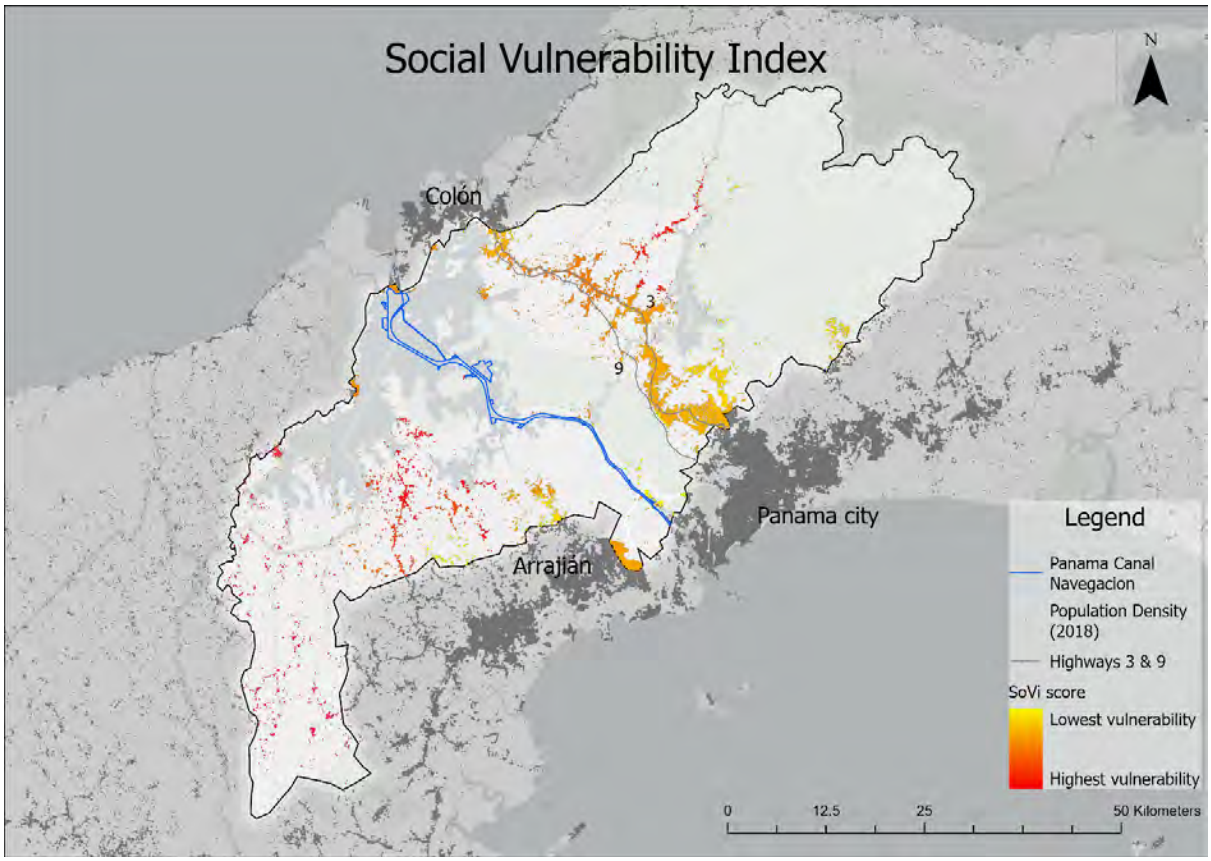
- **V**ulnerability: The vulnerability of populations to the identified climate hazards is influenced not only by their location in an area at risk of a climate hazard or by the physical nature of the hazard but also by social factors (Cutter S.L., 2000). Social vulnerability is a combination of social, cultural, economic, political, and institutional factors that shape socioeconomic differentials in the experience of, and recovery from hazards (Spielman 2020). Vulnerability varies widely among communities and among groups within communities. Inequalities in intersecting economic, environmental, social, cultural and political inequalities as well as environmental factors create different inequal vulnerabilities, resulting in differential impacts to climate hazards. By presenting social vulnerability indicators, retrieved from a 2023 Census on 'corrigimentos' level spatially, areas that score high on a multitude of vulnerability indicators can be highlighted, which makes up a non-weighted Social Vulnerability Index (SoVI).

- **Risk:** To determine the climate risks for people and their livelihoods, the changes in climate hazard over time between the baseline scenario and the business-as-usual 2050 scenario were applied. By using a 100-year return period, the spatial changes over time were determined for each hazard. The resulting maps were overlaid with the SoVI results, aggregated by the population density map to show the population distribution over the watershed. Anecdotal evidence from recent events of drought and flooding in the watershed, as mentioned by the attendees in the site visit and during the Focus Group Meetings by ACP, was integrated.

Key Findings

Direct links between social indicators and the person or communities' adaptive capacity, include (physical) access to (resources that provide) security during times of a hazard event. To assess climate-related risks to the population, the climate hazards, exposure and the social vulnerability maps were combined, providing insights into both the areas that will likely see the largest increase or changes in climate hazards occurring over time, as well as the areas that house communities which score high on different social vulnerabilities. The SoVI data shows vulnerability differences based on factors like income, education, housing, water, electricity, and access to information.

The SoVI provided insights into the locations of people with the highest vulnerability to different hazards. Identifying these areas can support ACP to focus their efforts in implementing targeted adaptation intervention measures and increase adaptive capacity of these specific groups.



Conclusion

This Panama Canal CRA, conducted by Haskoning, illustrates the value of integrated, systems-based climate risk assessments for critical infrastructure. By combining robust climate science with participatory stakeholder engagement and operational analysis, ACP is better equipped to manage climate risks while safeguarding its operations, ecosystems, and communities. This CRA demonstrates the importance of highlighting social vulnerabilities within interconnected socio-technical-environmental systems. Adopting such methodologies aims to ensure that infrastructure planning not only protects assets but also supports the well-being of the most at-risk communities.

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High-frequency survey data reveals the role of infrastructure in shaping household vulnerability and resilience to climate shocks: Evidence from Malawi and Uganda

Shreya Deep Bansod[(1)], Tina Comes[(2)], Jasper Verschuur[(3)]
(1) Delft University of Technology, Netherlands, s.d.b.bansod@tudelft.nl
(2) Delft University of Technology, Netherlands, T.Comes@tudelft.nl
(3) Delft University of Technology, Netherlands, J.Verschuur@tudelft.nl

Abstract

Moving beyond conventional income and asset measures, this study develops an infrastructure standard index to assess the vulnerability and resilience of households to climate shocks, using high-frequency survey data from Malawi and Uganda. We test how deprivation of household-level services such as water, electricity and sanitation shapes exposure to climate shocks, severity of impacts and coping responses. It is expected that infrastructure deprivation will more clearly differentiate vulnerable groups, with deprived households facing greater exposure, losses and constrained coping capacities. This information helps introduce a new approach for assessing socioeconomic resilience of households to climate shocks.

Keywords: climate shocks; infrastructure deprivation; socioeconomic resilience

Introduction

Climate shocks disproportionately impact poor and marginalized households, exacerbating existing socioeconomic inequalities. While much of the literature assesses welfare impacts through income, consumption, or asset-based indices (Becchetti et al., 2024; Gemessa, 2022; Winsemius et al., 2018), such measures may obscure structural deprivations in access to essential services. For example, a household may own livestock or a bicycle (raising its 'asset wealth') but still lack access to safe drinking water, electricity, sanitation. Households facing deprivation of such services often experience greater disruption to daily life and distress when disaster strikes (Dargin & Mostafavi, 2020). Some studies have recognized the need to move beyond monetary indicators, incorporating access to services like health and education, along with asset ownership to construct multidimensional poverty and deprivation measures (Alkire & Foster, 2011; Hallegate et al., 2019), and have highlighted the critical role of infrastructure in mediating welfare loss. However, few have quantified household-level infrastructure deprivation and examined its relationship to climate shocks. This study explores if pre-existing infrastructure deprivation at the household level influences how different socioeconomic groups experience climate shocks, offering insights into their exposure, vulnerability, and resilience.

Objective

The objective of this study is to examine how household-level infrastructure deprivation shapes exposure, impacts, and coping responses to climate shocks, using econometric methods with Malawi and Uganda as case studies. We utilise the World Bank's Living Standard Measurement Study's (LSMS) high-frequency phone survey data (2021-2024) from the two countries. This high-frequency dataset covers major climate-related events such as Cyclone Freddy (2023) and widespread flooding and drought in Malawi, and floods, landslides, and prolonged droughts in Uganda. We test whether infrastructure deprivation predicts high exposure to climate shocks, higher impacts due to climate shocks and use of coping strategies

such as cutting back on food or healthcare, or selling productive assets like livestock. Such coping strategies may help households manage in the short term but carry serious long-term consequences for welfare and human development (Ovadiya & Costella, 2013). Additionally, we explore whether these relationships differ across urban and rural setting and between countries.

Methodology

We constructed an infrastructure index (refer Table 1 to check the variables used), an asset index (Table 2) capturing material assets and combined- asset and infrastructure index (Table 3) using the same dataset. To construct the indices, we applied the Demographic and Health Surveys (DHS) Wealth Index methodology (Rutstein, 2008), which uses principal component analysis (PCA) to assign weights to household characteristics (i.e., ownership of different assets and quality of infrastructure) and generate composite scores. These indices were created using information from one of the survey rounds from both Malawi and Uganda that covered questions on household characteristics. Information from the face-to-face surveys were also utilised in creating these indices. The phone surveys were continuation of the face-to-face surveys, and hence covered the same households, making it feasible to use the information to construct the indices. The indices were constructed for urban and rural population separately for the two countries. The composite scores generated using PCA were then divided into five quintiles, where the lowest quintile reflects the most asset or infrastructure deprived households and highest quintiles reflects those with better quality of infrastructure or more assets. Following the construction of the indices, we will use the responses from LSMS survey data on climate shock exposure, reported impacts, and coping strategies to conduct descriptive statistics and examine how these outcomes vary across quintiles. In the next step, we will use logistic regression models to analyse the relationship between the indices created and exposure, impact and coping strategies.

Expected results

We expect that the infrastructure standard index willy reveal clearer patterns of vulnerability and resilience compared to asset-based measures. Households in lower infrastructure quintiles are expected to report higher exposure to climate shocks, greater likelihood of impacts like livelihood losses and more constrained coping strategies like reducing consumption or doing nothing. In contrast, households in higher infrastructure-standard index are expected to rely more on financial or resource-based coping strategies, such as use of savings and income diversification. The detailed descriptive and regression results will be presented at the conference, comparing Malawi and Uganda as well as urban and rural settings, to show how an infrastructure focused lens reveals useful patterns on socioeconomic vulnerability and resilience of households to climate shocks.

Contribution

This work moves beyond income and asset-based measures to understand the impacts of climate shocks through household-level infrastructure deprivation. By applying a comparable index across Malawi and Uganda, it provides new evidence on how access of services shapes exposure, impacts and coping capacity. Through this, the study introduces a different resilience approach that captures structural household-level deprivations faced by the most vulnerable households and provides insights into resilience pathways of different socioeconomic groups.

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Annexure

I. Constructing the indices

A. Infrastructure Standard Index

The following table lists the variables used to construct the Infrastructure Standard Index. For drinking water and sanitation, the available options in the LSMS survey were grouped into basic/improved and unimproved following the classification used by the WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene (JMP) (Girmay et al., 2022). While JMP distinguishes five service levels, in this study three categories were used due to insufficient options to cover five categories. For electricity, grid and solar connections were classified as basic/improved, while torches, firewood, and kerosene were considered unimproved. For communication, access to television was treated as high, radio as medium, and absence of both as none. For constructing the index, the ordinal values shown in the table below were first standardised so that all variables are placed on a comparable scale. Principal component analysis (PCA) was then applied to these standardised variables. PCA assigns weights to each variable based on the variation it explains across household, producing a continuous household infrastructure score. Finally, this score was divided into five equal quintiles, where the lowest quintile reflects the most deprived households and the highest quintiles the least deprived.

Table 1. Variables used for constructing Infrastructure Standard Index

Variable from the survey	Characterisation in the survey	Inclusion in index
Safe drinking water source	Piped connection, protected well, unprotected well, pond/lake, dam, rainwater, unprotected spring, river	Basic/improved- 3 Unimproved- 2 No source/facility- 1
Electricity for lighting	Grid connection, solar, torches, firewood, kerosene	Basic/improved- 3 Unimproved- 2 No source/facility- 1
Sanitation facility	Flush toilet, open pit with slab, open pit without slab, field/bushes/open	Basic/improved- 3 Unimproved- 2 No source/facility- 1
Communication means	Television, radio	High (Television)- 3 Medium (Radio)- 2 None (no means)- 1

B. Asset Index

The following table lists the variables used to construct the Asset Index, based on ownership information available in the survey data. While Uganda's survey included a more detailed set of assets than Malawi's, only those common to both countries were included to ensure comparability. The variables were expressed in binary terms, representing whether the household owns the asset or not.

These binary variables as listed in the table below were first standardized to ensure comparability across different asset types. PCA was then applied to the standardized variables to assign weights based on the variation they explain across households. The resulting asset index is a continuous score of relative asset ownership, which was then divided into quintiles, with the lowest quintile representing the least asset-rich households and the highest quintile representing the most asset-rich households.

Table 2. Variables used for constructing Asset Index

Variable from the survey	Inclusion in index
Furniture (e.g., bed, table, chair)	Yes = 1, No = 0
Bicycle	Yes = 1, No = 0
Motor vehicle	Yes = 1, No = 0
Own appliances (e.g., kettle, blender)	Yes = 1, No = 0
Refrigerator	Yes = 1, No = 0
Solar panel	Yes = 1, No = 0
Computer equipment	Yes = 1, No = 0
Agriculture land	Yes = 1, No = 0
Livestock	Yes = 1, No = 0

C. Asset + Infrastructure Index (Combined Index)

The combined Asset–Infrastructure Index was constructed using the same PCA-based approach described for the Asset Index. In this case, the variables included both asset ownership (e.g., furniture, livestock, appliances) and household-level infrastructure characteristics (e.g., water, sanitation, electricity).

Table 3. Variables used for constructing Asset + Infrastructure Index

Variable from the survey	Inclusion in index
Furniture (e.g., bed, table, chair)	Yes = 1, No = 0
Bicycle	Yes = 1, No = 0
Motor vehicle	Yes = 1, No = 0
Own appliances (e.g., kettle, blender)	Yes = 1, No = 0
Communication- Radio/Television	Yes = 1, No = 0
Refrigerator	Yes = 1, No = 0
Solar panel	Yes = 1, No = 0
Computer equipment	Yes = 1, No = 0
Agriculture land	Yes = 1, No = 0
Livestock	Yes = 1, No = 0
Safe drinking water source	Yes = 1, No = 0
Electricity	Yes = 1, No = 0
Sanitation facility	Yes = 1, No = 0

The Heat is On: A Scenario-based Resilience Framework to capture community and planning perceptions and priorities for urban heat

Su Li Heng[1], Srijith Balakrishan[1], Tina Comes[1]
1 Faculteit Techniek, Bestuur en Management, TU Delft, Delft, Netherlands,
S.L.Heng@tudelft.nl; S.Balakrishnan@tudelft.nl; T.Comes@tudelft.nl

Abstract

Resilience assessments are central to climate planning in cities, yet when they fail to capture societal perceptions, uncertainties, and contested priorities, they risk producing strategies that lack legitimacy or misalign with community needs. These challenges are amplified for extreme heat, a deadly hazard that remains abstract for many residents and planners. This study develops a framework that combines surveys and stakeholder workshops to link public concerns with institutional decision-making. The survey elicits concerns and perceptions of readiness across different urban heat scenarios. Those scenarios that are especially concerning, confusing, or underestimated are then tested in workshops, where planning objectives and their evaluation criteria are negotiated. The framework advances decision-relevant, co-produced resilience assessment for heat extremes.

Keywords: scenarios; co-production; perception elicitation; abstract climate extremes

Introduction

Cities worldwide are increasingly challenged by longer, more intense, and frequent extreme heat (Perkins, Alexander, & Nairn, 2012). Yet, the translation of such evidence into decision-relevant knowledge for urban resilience actions remains slow (Turner, et al., 2022). While resilience is often framed in terms of infrastructural and social capacities (Lorenz, 2013), it also depends on awareness (Burnside-Lawry & Carvalho, 2016), participation (Faga-Watson & Burchell, 2016), and shared values about essential functions (Copeland, et al., 2020). Understanding how society perceives extreme heat and prioritising the criteria for evaluating heat strategies is, therefore, a critical step to align public concern with institutional priorities in resilience planning.

This study develops a resilience assessment framework that combines survey-based scenario elicitation with stakeholder workshops. Together, they provide insights into how extreme heat scenarios are interpreted, what uncertainties shape those interpretations, and how decision values are negotiated. The study thus lays a theoretical and interpretive foundation for empirical validation and the co-production of knowledge and action in heat resilience planning.

Framework Design

The framework (Figure 1) embraces the polyvocality of resilience (Comes, 2016) and builds on resilience scholarship that views assessment not only as a technical exercise but also as a social process shaped by perceptions, uncertainties, and contested values (Hatt, 2013). By

sequencing surveys and deliberative workshops, it operationalises this perspective into a transferable method for resilience assessment.

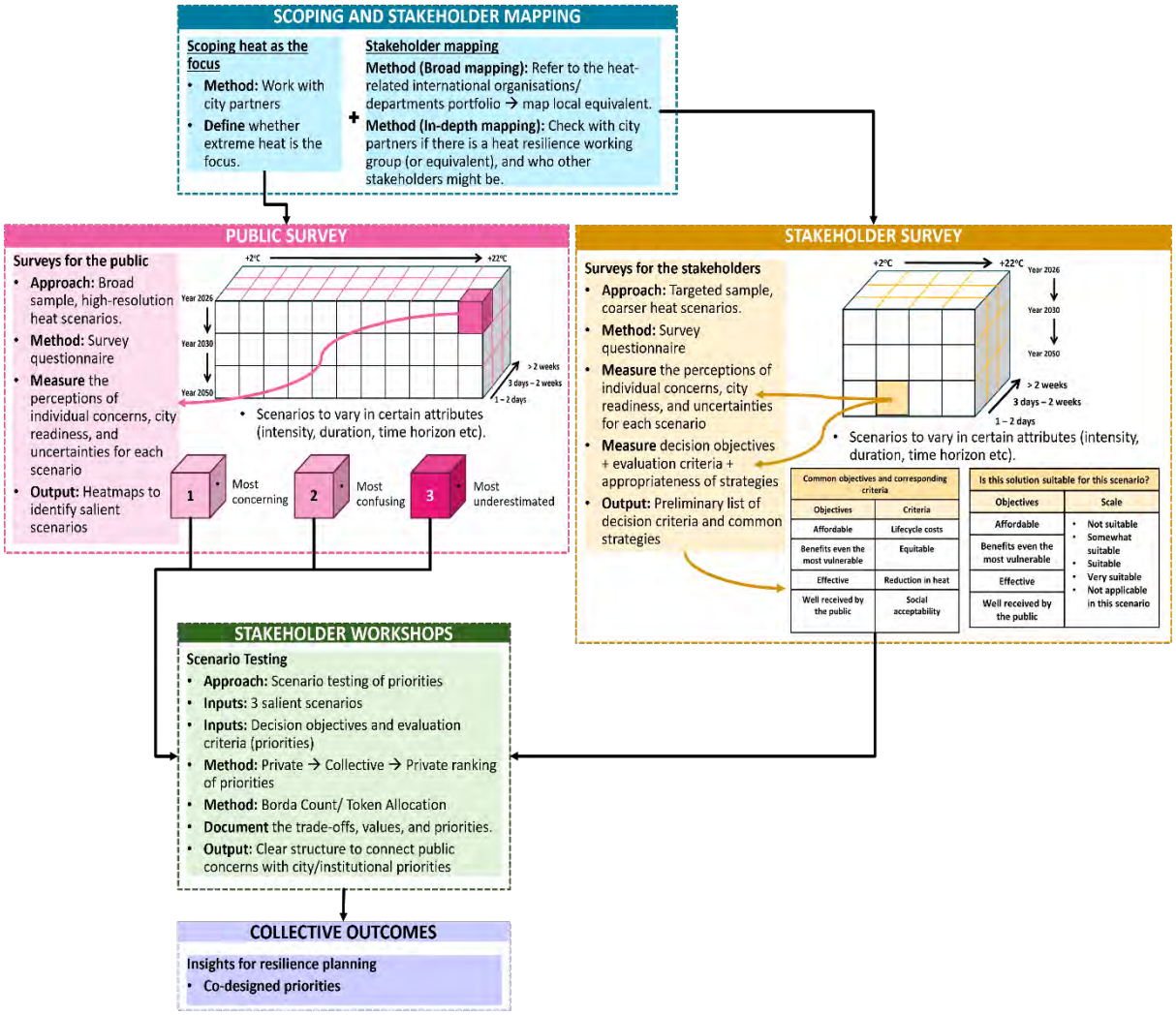


Figure 1: Framework for linking societal perceptions and decision priorities through co-designed processes, culminating in co-designed priorities and a shared basis for resilience planning.

The framework comprises four phases: (i) scoping and stakeholder mapping, (ii) public surveys of concerns, readiness, and uncertainties, (iii) stakeholder surveys on objectives, evaluating criteria, and strategy appropriateness, and (iv) workshops where scenarios and criteria are deliberated through individual and grouped prioritisation. Outputs from each phase feed into the next, and the framework links public perceptions with institutional priorities to provide a transferable structure for resilience planning. The final box indicates the framework's output — synthesised priorities and decision-relevant insights — rather than being a process phase.

Scoping and stakeholder mapping

Local research partners help identify whether extreme heat or an adjacent hazard (e.g., air pollution) is most salient for local resilience planning. Stakeholders are mapped by aligning international players with heat-related portfolios (Global Heat Health Information Network, 2025) with their local counterparts. With inputs from research partners, the mapping ensures

diverse representation across institutional, sectoral, and community perspectives. Early mapping secures relevance and fosters ownership, empowering participants as active contributors to resilience planning (Dushkova & Ivlieva, 2024).

Structured Survey

Surveys, built around hypothetical but plausible extreme heat scenarios, capture how extreme heat scenarios are perceived for personal concern, institutional readiness, and sources of uncertainty. We deployed surveys across cities in different Köppen-Geiger climates (Beck, et al., 2018) to assess variations beyond a single context.

Perceived concerns and readiness are measured via a 4-point scale, with an explicit "Not sure/ Don't know" category to reduce satisficing and agnostic responses with false midpoint responses (Sturgis, Roberts, & Smith, 2012) and to capture uncertainty as a resilience construct (Lorenz, 2013). Respondents also explain sources for uncertainties (e.g., unfamiliarity, insufficient knowledge), allowing direct policy insights (Smith & Stern, 2011; Moure, Jacobsen, & Smith-Hall, 2023), such as improving knowledge/ information/ communication gaps (Ghosh, Sen, & Frietsch, 2023) to bolster heat resilience. The survey also captures respondents' prior heat hazard experiences to assess whether direct experience or psychological proximity modulates concerns (Konisky, Hughes, & Kaylor, 2016).

Heatmaps visualise patterns of concerns, readiness, and uncertainty, highlighting salient scenarios that are disproportionately concerning (high concern, low readiness), confusing (divergence in concerns and readiness/ high uncertainties), and underestimated (low concern, high impacts based on scientific evidence).

Stakeholder Surveys

Stakeholder surveys repeat the concern–readiness–uncertainty elicitations at coarser scenario resolution but extend to include: (i) criteria for evaluating strategies, and (ii) appropriateness of common strategies given those criteria. These outputs inform workshop design.

Stakeholder Workshops

The salient scenarios serve as the empirical basis for the stakeholder workshops to test how stakeholders' preferences for criteria evolve. Importantly, the workshops do not focus on choosing specific heat strategies (e.g., intensifying urban greenery), but focus on clarifying the evaluation criteria, which may include life-cycle assessment (Subal, Braunschweig, & Hellweg, 2024), equity (Chu & Cannon, 2021), feasibility, and social acceptance (Jones & Clark, 2014).

The split allows stakeholders to reflect on the underlying values and trade-offs without being anchored to specific strategies. While pre-selected strategies may help stakeholders visualise decisions more concretely, they also risk introducing anchoring bias (Furnham & Boo, 2011) that carries into later evaluations. Premature commitments may also lead to maladaptation (Schipper, 2020) – a critical trap in resilience planning, where strategies can worsen long-term vulnerability or limit flexibility to future extremes (Rachunok & Nateghi, 2021). By

emphasizing criteria over strategies, the framework avoids the trap and provides a foundation for robust evaluation when more strategies are made known.

The workshops are also structured spaces to reveal discrepancies between public concerns and institutional priorities, and to map out where convergence and divergence emerge, through:

1. Private ranking of criteria: Reflects individual priorities and interpretations of the scenario.
2. Group deliberation: To exchange knowledge and negotiate. trade-offs, followed by a collective voting round.
3. Private re-reranking: Captures how personal concerns are refracted through institutional or collective processes.

The workshop deploys the Borda count (Emerson, 2011), to convert the ranking into points and tally to produce collective prioritisation. This captures the distribution of preferences without privileging only first choices. The Borda count is an example of how consensus may be operationalised within a workshop setting; it is not meant to be prescriptive. Some processes can unfold over long periods and extend beyond in-person interactions, thereby needing other consensus mechanisms.

Analysis and Results

Influence of Heat Experience

The framework links respondents' perceptions to their experiences of heat-related hazards. Testing how lived experiences shape concern and uncertainty allows the framework to incorporate psychological proximity as a factor in resilience assessment.

Dynamic Priorities

By embedding iterative ranking and deliberation, the framework allows for systematic testing of how priorities evolve, when convergence emerges, and divergence persists. Treating prioritisation as a process rather than a static input (e.g., as relative importance) makes the framework adaptable to different participatory resilience planning contexts.

Discussion and Conclusion

This paper establishes the theoretical foundation of a resilience assessment framework, which will be empirically tested prior to the conference, with cities like Barcelona and Antwerp providing initial comparative results. The framework will enable the translation of perceived concerns, readiness, and uncertainties into resilience planning. It offers both a comparative lens across cities and a practical template for participatory planning for climate extremes.

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Valuing water co-productively: A value-led approach to drought resilience in the eastern Netherlands

Christoph Euringer1,2*, Lara Wöhler1, Robert-Jan den Haan2, Rick Hogeboom1, Mascha van der Voort2, Markus Berger1

1. Multidisciplinary Water Management Group, Faculty of Engineering and Technology, University of Twente, Enschede, the Netherlands

2. Human Centred Design Group, Faculty of Engineering and Technology, University of Twente, Enschede, the Netherlands

Abstract

Droughts and water scarcity pose a major challenge for sustainable water management in the eastern Netherlands. The diversity of water users in the region leads to conflicting interests and values in water allocation and use, especially during times of drought. Water values often implicitly influence decisions on water management and water use. Making these values explicit therefore reveals both conflicting interests based on diverging values and opportunities for consensus and collaboration. Using a Q-methodology complemented by semi-structured interviews, representatives of local organizations involved in or affected by water management in the Twente region shared their prioritized water values. Assessing regional stakeholders' water values from an economic, environmental, and socio-cultural perspective provides insights into organizations' prioritization of functions that should be maintained when water becomes scarce and shows the potential to serve as input to further drought resilience assessments.

Keywords: Valuing water; water management; Q methodology; interview; drought resilience

Introduction

Water in sufficient quantity and quality is fundamental to sustaining life, enabling economic development, and maintaining healthy ecosystems. However, shifting precipitation patterns driven by climate change are contributing to the growing frequency and severity of extreme hydrological events worldwide, including both floods and droughts (IPCC, 2022) and increase the cumulative exposure of future generations to these hazards (Grant et al., 2025). These changes threaten the availability and reliability of freshwater resources across many regions and pose a growing risk to human and natural systems alike. As climate change intensifies and with it the frequency and severity of droughts, drought resilience has become a central concept in Europe's approach to water management (European Environment Agency, 2024; Toreti et al., 2024). This development is also reflected in the eastern Netherlands, especially in Twente, a region with high lying sandy soils and limited freshwater inflow from rivers, making it highly dependent on precipitation and groundwater (Bressers et al., 2016). Given the inseparable link between the Twente region's numerous water users and its water system, and the evident unilateral dependency between water users and the resource, the region is regarded as a socio-technical-environmental system. How available water is and how it is allocated in this system is implicitly influenced by how the resource is valued economically, ecologically, and socio-

culturally by its managers and consumers (Morgan & Orr, 2015). Yet these values, often neither quantified nor equally accessible, differ not only between periods of water abundance and drought, but also among the various actors in the system. This raises the question of how water values can be made explicit and contribute to fostering a drought resilient water system. To address this question, a framework for the participatory assessment of water values is applied in the Twente region. This strives towards a process of knowledge co-creation aimed at identifying prioritized water values in an effort to drive informed decision-making and raise awareness for drought-resilient water allocation.

The value of water

Valuing water has recently emerged as a paradigm in contemporary water management practice (Schulz et al., 2024a). It is grounded in the recognition that water provides a wide array of economic, ecological, and socio-cultural benefits (HLPW, 2017). Based on previous work, water values in this study are assessed in the categories of economic, environmental, and socio-cultural water values (Hellegers & van Halsema, 2019; Liu et al., 2024; Schulz et al., 2024a). Understanding and articulating these values is crucial for fostering communication and mutual understanding among water users and inform a more resilient water management. Past research has demonstrated that participatory approaches of valuing water not only promote awareness of differing stakeholder perspectives but can also enhance social interaction and strengthen collaborative action against shared risks such as drought (Garrick et al., 2017; Nikkels et al., 2021; Poplawsky et al., 2025). Making water values explicit provides insight into a shared decision-making process, can uncover hidden trade-offs, reconcile conflicting interests, and lead to more balanced and inclusive policy outcomes (Schulz et al., 2017; Hellegers & van Halsema, 2019; Schulz et al., 2024b). Rather than relying solely on economic efficiency metrics, water management challenges are reframed as complex, multi-stakeholder problems that require negotiation, value transparency, and collaborative planning (Hellegers & van Halsema, 2019).

Methodology

Q methodology is a valuable approach for assessing water values since it allows to systematically capture and interpret subjective opinions, beliefs, and priorities that may not always be easy for participants to articulate (Haeffner et al., 2025). The process of this method is presented in Figure 1. By having stakeholders sort statements about water uses during normal and drought conditions according to their level of agreement, this method structures diverse perspectives and highlights shared meanings (Ratchford et al., 2023). The Q methodology analysis then applies factor analysis to group viewpoints into clusters, distinguishing the differences that set them apart. However, the sorting exercise alone cannot fully explain the reasoning behind participants' choices (Gallagher and Porock, 2010). This is why semi-structured follow-up interviews are used to complement the findings.

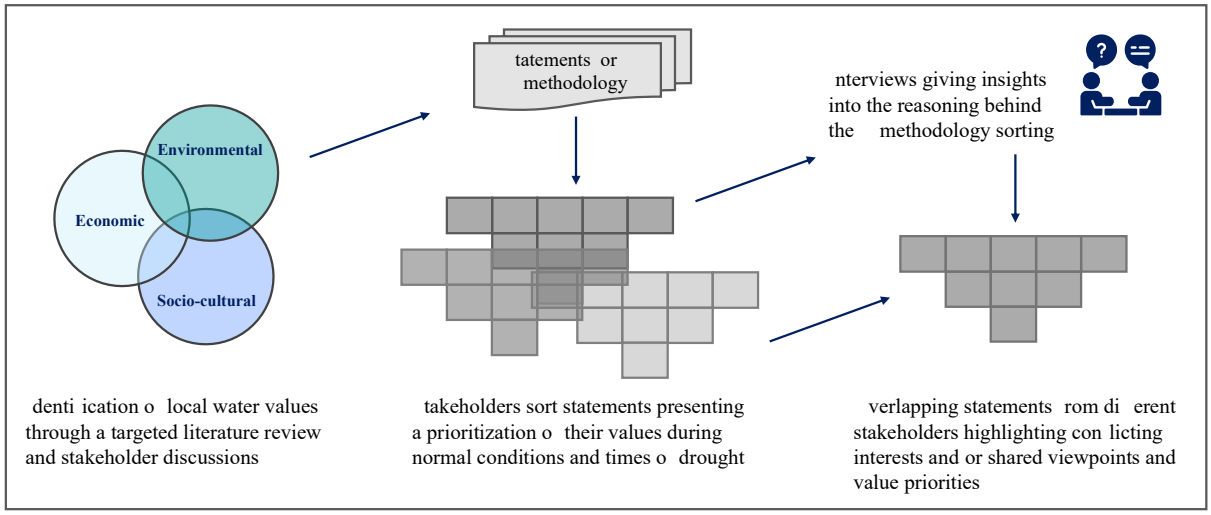


Figure 1: Assessing water values through the use of Q methodology complemented by expert interviews.

Expected results

The qualitative assessment of water values includes representatives from the regional industrial, agricultural, domestic, and environmental sectors as well as experts from research facilities. The prioritization of water values under normal conditions reflects current water allocation patterns in which the majority of water is allocated to the domestic sector followed by small and big businesses including agriculture. The water values under drought condition, however, reflect the allocation prioritization (*verdringingsreeks*) under water shortage according to the Dutch Ministerie van Infrastructuur en Waterstaat. This assessment uncovers the underlying values of water allocation and might indicate a collision of currently represented value distribution of some sectors and preferred allocation for future drought resilience. The factor analysis provides individual perspectives of values on the one hand, while offering statements of consensus on the other hand. Both are potential entry points of cooperation and collaboration. The combination of a Q methodology and interviews aims at providing deeper insights into why participants prioritized certain values, helping to clarify ambiguities, and uncovering subtle nuances in decision making that the statistical patterns of the Q method may not capture. Further, the results of the interviews give insights into potential policy or structural interventions that might be necessary to advance developing a drought resilient water system.

Conclusion

Co-productive valuing of water strengthens drought resilience by explicitly linking water management to the diverse values and priorities of stakeholders. In practice, this means representing the water system not as an objective reality, but as the combination of stakeholders' perceptions, thereby making value-laden choices of water use and allocation transparent (Biggs et al., 2015). By prioritizing water values under normal and drought conditions, actors reveal how decisions about water use and allocation are shaped, which in turn influence the region's drought resilience. This co-productive process helps identifying potential barriers to behavioral change, such as entrenched management practices, and creates

awareness of overlapping values that can form entry points for collaboration and future adaptations to reduced water availability and conflicts of interest (Helfgott et al., 2018).

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How climate resilient is the Maldives' water system? Insights from a socio-metabolic risk (SMR) analysis

Emily Voigt[1], Simron Singh[1], Kumaraswamy Ponnambalam[2], Nadhiya Abdulla[3], Shazla Mohamed[3], Shuaib Rasheed[3]

1 School of Environment, Enterprise and Development, University of Waterloo, Waterloo, Ontario, Canada, evoigt@uwaterloo.ca, simron.singh@uwaterloo.ca

2 Department of Systems Design Engineering, University of Waterloo, Waterloo, Ontario, Canada, ponnu@uwaterloo.ca 3 The Maldives National University, Malé, Maldives,

nadhiya.abdulla@mnu.edu.mv, shazla.mohamed@mnu.edu.mv, shuaib.rasheed@mnu.edu.mv

Abstract

Water metabolism is defined by patterns of water flowing into, within, and out of a socio-ecological system to meet societal needs. Patterns of water throughput may build resilience, or embody systemic risks that cascade across spatial, temporal and sectoral dimensions. A better understanding of these patterns and their associated risks can inform climate adaptation mechanisms, improving systemic resilience for climate vulnerable geographies such as Small Island Developing States (SIDS). These risks can be understood as *socio-metabolic risks* (SMR), a subset of systemic risks associated with critical resource availability, circulation, and the distribution of resultant costs and benefits. This study is the first attempt to develop a framework to analyze SMR associated with water metabolism in a SIDS, using the Greater Malé region in Maldives as a case. Quantitative water accounts are assembled and used to develop indicators focused on availability, access, consumption, and self-sufficiency. To capture varied and local perspectives on risk, data is collected from government agencies, industries and a household survey. The drivers and impacts of the determined system dynamics are explored through qualitative analysis using insights from expert interviews. A detailed system map is created presenting the function of the water systems in Malé and the SMR that accumulate and cascade throughout. Ultimately, this novel Hydro-SMR framework develops system level knowledge to understand and respond to water related risks, building resilience in the face of worsening climate change impacts.

Keywords: Socio-Metabolic Risk (SMR); Small Islands Developing States (SIDS); Water Metabolism; Water security; Climate Resilience

Introduction

Despite contributing less than 1% of greenhouse gas emissions globally, SIDS face some of the worst impacts of climate change including sea level rise, flooding and coastal erosion (IPCC, 2023). SIDS however should not only be recognized for their vulnerabilities, but also for their unique capacities to act as hubs for transformative sustainability science (Singh et al., 2020). The study of island social metabolism draws an analogy between biological metabolism and how a society organizes its material and energy stocks and flows to function (Singh et al., 2020). Building on this analogy, *socio-metabolic risks* (SMR) are systemic risks associated with certain stock and flow patterns of a critical resource like food, energy or water. Social metabolism and SMR offer a conceptual approach that allows the social and environmental impacts of resource use patterns to be studied systemically (Singh et al., 2022). The social metabolism research approach has been applied in island case studies using traditional industrial ecology methods such as material and energy flow analysis to assess the resilience and sustainability of resource use patterns (Camilleri-Fenech et al., 2018; Martin del Campo et al., 2023a; Noll et al., 2022). However, none have focussed on water metabolism in an island setting. This study fills this critical gap as SIDS grapple with acute water stress exacerbated by climate change. Taking Greater Malé region (capital of Maldives) as a case, we further develop the SMR framework to analyze risks associated with water metabolism and refer to it as Hydro-SMR. Malé is a low-lying island ~3 metres above sea level with an area of only 6.6 km^2

(Maldives Bureau of Statistics, 2025; World Bank Group 2024). The population of 209,707 accounts for 41% of the national population and potable water resources are limited (Maldives Bureau of Statistics, 2025). Understanding the water metabolism of Malé can be seen as the first step to identify opportunities for reconfiguring resource use patterns to promote resilience and adapt to climate extremes.

Methodology

This study compiles water accounts for Greater Malé using the System of Environmental and Economic Accounting (SEEA-Water) framework (Department of Economic and Social Affairs, 2012). A survey is used to gather data on household water use and access. Together with data from industries and government agencies, this data is used to develop indicators across the dimensions of availability, access, self-sufficiency and consumption. These are based on the assessment framework developed by Martin del Campo et al. (2023b) to operationalize the framework of SMR. To further develop the framework's capacity to represent the complexity of Malé's water metabolism, the access dimension is advanced to include indicators of affordability and reliability. The water accounts and derived indicators reveal system dynamics that are analysed to identify SMR. The consequences of these system dynamics and their subsequent risks will be further analysed and validated through semi-structured interviews with experts from across the water industry. Final analysis of results will integrate the quantitative and qualitative data through analysis of how qualitative interview data explains how quantitative system dynamics introduce or contribute to SMR throughout the system.

Results

This research is ongoing. Findings reveal system dynamics that produce systemic risks which in turn threaten resilience. These include a lack of diversity in freshwater sources, reliance on expensive bottled water, frequent flooding and a lack of available data around water consumption in key industries. A detailed system map is in development to present the function of the water systems in Greater Malé and the SMR that accumulate with potential for tipping points and cascading effects. These results are used to characterize the resilience of the system and identify areas in which resilience should be developed.

Discussion

This study builds on existing work to operationalize the framework of SMR, building evidence-based analysis of systemic risks and resilience. The potential of the framework is demonstrated through this case study which characterizes systemic risks and resilience present in the water system of Greater Malé in Maldives. This work assembles critical information on regional water system dynamics that can be used to inform policy and resilience building efforts. This development of an effective framework for evaluating SMR throughout the water system in Malé can act as a starting point for assessing water related risks on other SIDS which face similar challenges of data scarcity and limited access to freshwater resources. The combined qualitative and quantitative approaches produce useful quantitative indicators while also capturing varied and local perspectives. This method aims to avoid generalized conclusions in favour of specific and locally relevant analysis for building climate resilience.

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Monitoring water distribution systems for resilience using unknown input observability

Michaela Lestakova(1), Peter F. Pelz(2)
(1) Chair of Fluid Systems, TU Darmstadt, Germany, michaela.lestakova@tu-darmstadt.de
(2) Chair of Fluid Systems, TU Darmstadt, Germany, peter.pelz@tu-darmstadt.de

Abstract

Monitoring is a crucial function of resilient systems, including water distribution systems (WDSs). It plays an important role in identifying critical events and determining how to react well and fast. Assessing how well a WDS can be monitored should thus be an integral part of resilience assessment. However, a-priori metrics for assessing monitoring are missing. This contribution aims to close this gap by extending a previously proposed observability-based metric to consider demands and disturbances as unknown inputs, linking resilience engineering with concepts from control theory for WDSs.

Keywords: water distribution systems, resilience, control theory, observability, monitoring

Introduction

Resilient systems have the ability to anticipate, monitor, react to and learn from critical events. Critical events affect urban infrastructure systems, including water distribution systems (WDSs), in which they may be a result of ageing, progressing urbanization and extreme weather events expected to become more frequent due to climate change.

Monitoring plays an important role in identifying critical events and determining how to react well. Assessing how well a WDS can be monitored should thus be an integral part of resilience assessment. However, while considerable scientific attention has been given to finding suitable resilience metrics for WDSs, they mainly focus on anticipating and reacting, rather than monitoring.

Existing monitoring metrics rely on a-posteriori analysis, quantifying, for example, the detection time of a critical event such as leakage (Mounce et al., 2012; Romano et al., 2014), minimum detectable failure quantity value such as leakage outflow (Du et al., 2024), or the ability to localize a critical event in terms of distance (Romero-Ben et al., 2022) for a specific set of sensors.

A metric able to quantify how easy it is to monitor a system a-priori would allow embedding it in network design and analysis algorithms and resilience evaluation frameworks. It would help practitioners adjust existing networks towards improved resilience and design new networks so that they are inherently easy to monitor.

Recently, a new monitoring metric has been proposed for WDS based on the control-theoretic concept of observability. The underlying model of WDS considers demand as a known input. However, in real-world WDSs, exact values of demands are not known: while demands follow diurnal and seasonal patterns, they are subject not only to uncertainty but possibly also to extreme unexpected peaks or disruptions. In this contribution we revisit some concepts from

control theory that allow including demands as unknown inputs and considering disturbances such as pipe leakage or blockage.

Observability of WDS: A concept from control theory

Observability determines whether it is possible to reconstruct the trajectory temporal evolution of the internal states of a system from the knowledge of inputs and a given set of outputs (Montanari & Aguirre, 2020; van Gemert et al., 2024). Designed with low-dimensional systems in mind, classic control theory methods for assessing observability like the Kálmán rank test or the Hautus test are not feasible for large-scale systems such as WDSs (Montanari & Aguirre, 2020).

To address this issue, the concept of structural observability has been proposed. Structural observability works with the assumption that in a network modelled as a mathematical graph, the topology of the graph, i.e. the presence of edges between nodes, is known, but the edge weights are unknown (Jia et al., 2021). This corresponds well to a common problem in modelling of WDSs: the topology of the WDS is generally known, but the parameters defining the edges such as pipe roughness or even pipe lengths and diameters are often subject to uncertainty (van Gemert et al., 2024).

Designing a metric based on observability is challenging as observability is based on a crisp definition: the system either is or is not observable (Montanari & Aguirre, 2020).

This has motivated the use of minimal number of sensors that would render a WDS observable as a proxy to describing how well a system can be monitored. The evaluation of the monitoring metric thus becomes a minimum sensor placement problem.

Van Gemert et al. have shown how this method can be applied to WDSs modelled with the elastic water column model proposed by Zeng et al., 2022, for observing the state variables volume flow q and head h at every link and node, respectively. The pattern matrix corresponding to the system matrix of a WDS which captures its topology and the relationships between the state variables is

$$\mathcal{A}_{\mathrm{WDN}} = \begin{bmatrix} \mathcal{I} & \mathcal{A}_{\mathrm{inc}}^{T} \\ \mathcal{A}_{\mathrm{inc}} & \mathcal{D} \end{bmatrix} \qquad \text{Eq. 1}$$

such that the system matrix $A(x_0) \in \mathcal{P}(\mathcal{A}_{\mathrm{WDN}})$ (van Gemert et al., 2024). Above, $\mathcal{I} = \mathrm{diag}\{*\} \in \{0,*\}^{m\times m}$ (pattern identity matrix), $\mathcal{D} = \mathrm{diag}\{?\} \in \{0,?\}^{n\times n}$ (pattern discharge matrix), and $\mathcal{A}_{\mathrm{inc}} \in \{0,*\}^{n\times m}$.

The minimum number of sensors Z that would render the WDS observable is then found by designing a suitable measurement matrix $\mathcal{C}$. This problem is equivalent to finding a minimal zero forcing set for the suitable graph representation of $\mathcal{A}_{\mathrm{WDN}}$, denoted $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$, in which the vertices correspond to the state variables and the edges represent the relationships between them. The zero forcing problem can be solved using an integer program from Brimkov et al., the infection model (Brimkov et al., 2019; Jia et al., 2021), adapted to the color change rule used in the presented methodology.

Considering unknown demands and disturbances

In the method presented above, the demand term is assumed to be known; it is modelled as a known input. However, in infrastructure systems incl. WDSs, demand is usually volatile and not known precisely, even though it may follow specific diurnal or seasonal patterns. Unknown inputs can be modelled in linear time invariant systems as follows:

$$\dot{x}(t) = Ax(t) + Bu(t) + Dw(t)$$
$$y(t) = Cx(t), \qquad \text{Eq. 2}$$

where $x(t)$ is a vector of state variables, $u(t)$ the vector of known inputs, $w(t)$ the vector of unknown inputs, $y(t)$ the measurement vector and A, B, C, D the system matrix, control matrix, measurement matrix and unknown input matrix, respectively (Niederwieser, 2024). Just like for classical observability, criteria for the so-called strong observability under consideration of unknown inputs have been proposed. In this contribution, we would like to discuss the applicability of these conditions to WDSs for the purpose of monitoring, identification of disturbances and resilience assessment.

Conclusion

This contribution discusses observability-based metrics for assessing monitoring of WDSs. It shows that in order to consider demand and disturbances, it is necessary to be model them as unknown inputs rather than known inputs. Under these considerations, an existing metric based on classical observability criteria will be extended to account for unknown inputs. Moreover, it will be shown how unknown input observability can be exploited for the purpose of monitoring and identification of disturbances.

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Measuring Adaptation to Successive Disruptions in Multiple Performance Dimensions

Floris van Steijn[1], Nazli Yonca Aydin[1], Neelke Doorn[1], Tina Comes[1]
[1] Faculty of Technology, Policy and Management, TU Delft, Delft, The Netherlands, {F.P.vanSteijn, N.Y.Aydin, N.Doorn, T.Comes}@tudelft.nl

Abstract

Our societies are complex systems, combining social-economic, infrastructural, environmental, or health dimensions. Often, however, there are interactions between these different subsystems. In addition, in a world where poly-crises are increasingly common and disruptions are often prolonged, the disruption or the response to it often makes it impossible to contain the impact to just one (sub)system. When measuring the resilience to prolonged and recurring disruptions, it is therefore inadequate to measure a single or multiple performance dimensions in isolation. Methods that explicitly consider the interdependency and trade-offs between the different resilience dimensions are currently lacking. Therefore, we propose a method for measuring the adaptation in multiple performance dimensions and their co-evolution with the aim of understanding these interdependencies. We illustrate our methodology by applying it to the COVID-19 pandemic. A global, country-wise analysis is performed, with COVID-19 fatalities, economy and mental health as the three performance dimensions of choice. The results show the type and intensity of co-evolution of these performance dimensions.

Keywords: Resilience; Adaptation; Measurement; Poly-crisis; COVID-19

Introduction

Societies around the world have faced a growing number of crises that are not only severe but also prolonged and overlapping. These so-called *poly-crises* (e.g. pandemics, climate crisis and geopolitical instability) challenge traditional ways of thinking about resilience (Eisenberg et al., 2025). As a recent example, the COVID-19 pandemic has revealed how disruptions can unfold in waves, evolve over prolonged time periods, and affect people's lives in multiple dimensions simultaneously or in a cascading manner.

Resilience is commonly defined as the ability of a system to rapidly absorb, recover from, and adapt to disruptions (Mentges et al., 2023). Adaptation is increasingly recognized as a key element of resilience, starting out in fields like climate science and social-ecological systems (Walker et al., 2004). It refers to the capacity of a system to adjust its behavior in response to changing conditions. Importantly, adaptation is not always positive. Some systems may deteriorate over time, showing signs of fatigue, resource depletion, or policy failure. However, little attention to adaptation is given in the context of measuring resilience. Most post-hoc (engineering) resilience assessments focus on how systems respond to a single event (Bruneau et al., 2003). They often rely on single-shock resilience metrics such as the speed of recovery or the severity of impact.

Especially for poly-crises, this poses two problems. First, since disruptions are often prolonged or recurring, it is crucial to understand not only how systems respond to single disruptions, but also how they learn and adapt over longer periods of time. Second, in such highly-connected systems, with non-linear cause-effect relationships, effects ripple beyond the source of the disruption and overflow to other systems (Renn, 2021). This ties into a more general point about measuring the resilience of complex systems: performance cannot in terms of a single dimensions, since complex systems have several functions. This means that we need a better understanding of how multiple performance dimensions co-evolve. Therefore, multi-dimensional adaptation measurement that captures this co-evolution and allows to identify potential interactions and delays between different adaptation paths need to be added to the conventional toolboxes of measuring resilience.

These two points form the core of the proposed work: we propose to extend methods for measuring resilience to include *adaptation over successive disruptions* (1) while considering *multiple performance dimensions* (2).

We aim to illustrate this approach by applying it to the COVID-19 pandemic. Unlike a single, isolated event, COVID-19 was a global disruption that persisted for years and manifested differently across countries and regions. It strained healthcare systems, disrupted economies, and impacted mental health on a large scale. Importantly, it did not occur as one shock, but as a series of waves each requiring renewed responses and adaptations.

Method

To address this, we propose a method for quantifying adaptation of multiple performance dimensions. Rather than focusing on a single dimension like COVID-19 fatalities, we also take economic and mental health performance dimensions into account.

1. Physical Health: COVID-19 fatalities per million inhabitants as a direct measure of health impact. (*COVID-19 Data Set OWID*, n.d.)
2. Economy: GDP over time data (*Nominal Gross Domestic Product (GDP)*, n.d.)
3. Mental health: Anxiety and depression indicators capturing the broader societal effects of prolonged disruption. (Junchuan et al, 2020)

These dimensions were selected to represent different facets of resilience: immediate COVID-19-related health outcomes, economic effects and effects on mental well-being.

Our analysis begins by identifying individual COVID-19 waves for each country. Using publicly available data from 2020 to 2023, we apply curve-fitting techniques to detect distinct peaks in the time series of each performance dimensions. Each wave is treated as a separate disruption, allowing us to compute a resilience metric such as total performance loss (area under the curve).

To capture adaptation, we fit exponential learning curves to the sequence of disruptions for each country, and for each performance dimension. If a country learns from past waves, its

resilience should improve over the course of successive waves. Conversely, if it fails to adapt, resilience worsens.

The exponential function we use is:

$$f(t) = a \cdot e^{-bt} + c$$

Here, b represents the rate of learning (adaptation), and a + c (the magnitude of the curve at the start) represents the initial resilience level. A higher value of b indicates faster adaptation, while a lower or negative value suggests stagnation or decline. This model allows us to quantify adaptation in a way that is both interpretable and comparable.

Since adaptation is quantified for every performance dimension, this allows us to form multi-dimensional adaptation profiles of countries. For example, a country may adapt well in terms of COVID-19 fatalities, but worse in terms of mental health, or the other way around.

Conclusion

Our findings reveal significant variation in multi-dimensional adaptation profiles. Some countries showed strong improvement in managing fatalities, with each wave becoming less severe. Others maintained stable performance or even experienced worsening outcomes. Economic strain and mental health outcomes followed different trajectories, often revealing that it is difficult to keep disruptions in both dimensions limited, although some countries are better at managing this than others.

These methods and findings are important for future policy. First, future pandemics might face the same interdependencies, which pose similar problems for decision-makers. Secondly, these methods are a first step in identifying why some countries were better able to manage the pandemic across multiple performance dimensions than others.

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Graph Theory-Based Resilience Framework with Regionalized LCA Data to Quantify Sustainability-Resilience Trade-Offs in Agri-Food Systems

Joël Mongeon[1], Marilyne Chicoine[1,2], Miezah Ebenezer Kwofie[1]
1 Sustainable Food Systems Engineering Lab (SASEL), Department of Bioresource Engineering, Faculty of Agricultural and Environmental Science, McGill University, joel.mongeon@mail.mcgill.ca, marilyne.chicoine@mcgill.ca, ebenezer.kwofie@mcgill.ca
2 McGill Center for the Convergence of Health and Economics, Department of Marketing, Desautels Faculty of Management, McGill University

Abstract:

Global supply chains are increasingly expressed to disruptions, highlighting the need of advancing resilience alongside ever-focused sustainability outcomes. This study proposes a graph-theoretic approach that embeds Life Cycle Assessment (LCA) inventory data into an agri-food supply chain network analysis, enabling the joint evaluation of both sustainability and resilience performance. The palm oil value chain is assessed as a case study due to its complexity, economic significance, and sustainability controversies. Using graph theoretic measurements, and additional metrics across diversity, flexibility, robustness, and agility, the framework identifies pathways that reveal appropriate sustainability-resilience trade-offs. Certified and non-certified palm oil networks serve as the basis for comparison, to assess how governance and certification influence these trade-off outcomes. The analysis aims to reveal the convergence of resilience and sustainability and better contextualize the efforts to standardize value chains with rigorous sustainability regulations to simultaneously achieve value chain resilience.

Keywords: Supply Chain, Sustainability, Flexibility, Graph Theory, Trade-Off

Introduction

Globalization has prompted significant supply chain network structure, prompting industries to shift towards expanding offshoring production sites, often relying on single, optimized locations for significant global supplies (D'Ambrosio & Lavoratori, 2025). This creates supply chains that are increasingly interconnected yet fragile. In modern times, globalized supply chains have transitioned towards more sustainable practices amidst vulnerable climatic and anthropogenic patterns (Kareem et al., 2025). Extreme events such as the COVID-19 pandemic have exacerbated these issues, prompting for policy and industrial changes (Moosavi et al., 2022). As a result, supply chain resilience and is no longer optional.

In contrast to resilience, sustainability pressures, such as environmental, economic, and social dimensions, continue to reshape global supply chains. A significant requirement that has shifted global supply chain to more sustainable practices is the EU deforestation-free regulation (EUDR), which requires companies to prove that imported commodities are deforestation-free and legally produced (Verhaeghe & Ramcilovic-Suominen, 2024). The palm oil sector is a key commodity affected by this regulation, and at the forefront of sustainability and resilience intersections. It represents a widely consumed vegetable oil, yet faces challenges in deforestation, biodiversity, and regulatory scrutiny (Lieke et al., 2023). For palm oil

producers, the EUDR introduces new compliance burdens, data reporting requirements, and verification mechanisms, while simultaneously influencing market access and competitiveness (Van Noordwijk et al., 2025). In fact, studies have estimated that full enforcement of zero-deforestation agreements like the EUDR may reduce 40% of land allocated for palm oil (Damanhuri, 2023; Leijten et al., 2023; Reboah et al., 2024). For developing economies, in which most palm oil is produced, the transition towards heavier regulation may marginalize the current value chain infrastructure, leading to potentially more fragmented supplies (Van Noordwijk et al., 2025).

Methodology

The framework focuses on integrating both resilience and sustainability indicators within a unified network representation, which allows for simultaneous analysis of material flow robustness and environmental performance. To address this, the study develops a graph-based framework that integrates LCA and supply chain resilience analysis to address these challenges holistically. The framework encompasses three key components. First, a multi-layer weighted graph network is constructed, integrating nested weighted edges from material, emission, and economic flows generated from LCA inventory data collection. Second, resilience metrics are quantified across different value chain configurations, focusing on flexibility, robustness, diversity, and agility, which are derived from a combination of graph theoretic measures and additional stochastic metrics. Third, systematic comparisons of resilience scores with sustainability impact categories derived from LCA is conducted to evaluate the interplay between environmental performance and network resilience.

Case Study: Palm Oil Value Chains

The proposed framework is applied to palm oil value chains, which are emblematic of the tension between sustainability imperatives and resilience. Palm oil is not only a major source of edible oils, but also an essential input into cosmetics, biofuels and processed foods (Bausano et al., 2023). Yet, it remains scrutinized due to its association with deforestation and biodiversity loss (Lieke et al., 2023). This framework aims to compare Roundtable on Sustainable Palm Oil (RSPO)-certified chains with non-certified counterparts due to the emergence of regulatory frameworks such as the EUDR.

A value chain mapping assessment on palm oil value chains in select African countries were conducted to collect relevant data for the analysis. Primary data was collected from stakeholder interviews and surveys. This data is supported from an exploratory review of LCA and inventories from palm oil value chains across Indonesia and Malaysia. Color coding classifications were indicated based on key differentiating characteristics, ranging from fertilizer inputs to energy inputs, to identify value chain saturations in achieving sustainable and resilience trade-offs. The case study enables the analysis of key findings, highlighting critical nodes and bottlenecks across different value chain configurations in the palm oil value chain. Geographical differences are also explored, to better contextualize the differences.

By applying the approach to the palm oil value chain, the analysis highlights how certification schemes, governance structures, and evolving regulatory frameworks such as the EUDR influence both resilience and sustainability outcomes. It therefore serves as a basis for other commodities exposed to similar regulatory scrutiny, network topologies and related disruptions.

Conclusion

The study aims to reveal the convergence between resilience and sustainability across different value chain configurations and sustainability parameters. Graph theory enables the visualization of and quantification of systemic and economic flows, while LCA ensures environmental performance is embedded into decision-making. Therefore, this study demonstrates the value of combining graph theory and LCA to address the growing need for supply chains that are both resilient and sustainable. This nested representation provides new insights into the role of governance structures on network robustness and enables for the critical analysis of interventions that can mitigate cascading risks in supply chains. Additionally, the framework supports scenario analysis, allowing for proactive decision-making across different supply chain possibilities that can influence value chain outcomes. This research advances the knowledge for the curation of integrated decision-support tools that combine network analysis, LCA, and scenario modeling. Such approaches are urgently needed to guide industries and governments in navigating the uncertain futures of global trade, climate change, and sustainability transitions.

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A Practical Approach to Multiscale Resilience Modelling

Nicholas Currie,
Beyond Blue Ltd., United Kingdom,
nicholas.currie@beyondblue.tech

Abstract

In this paper, I outline an approach to resilience modelling for complex sociotechnical systems which can accommodate for both 1) systems under collaborative governance and 2) a lack of a supporting data ecosystem (i.e., a consistently structured body of data or associated data models). Following a brief introduction to the topic, I articulate the basic requirements of a multiscale resilience model (section 1), the challenges of implementing such models to assess the resilience of a system under collaborative governance (section 2) and outline an approach to developing resilience models which can overcome these challenges (section 3).

Keywords: resilience modelling, collaborative governance, multiscale models

Introduction

In the introduction, I articulate the central problem which the paper seeks to tackle. I begin by highlighting the frequently noted connection between resilience initiatives and systemic risk management. I point out that this connection ensures that a large proportion of the sociotechnical systems for which resilience initiatives are seen as proportionate are both 1) under collaborative governance and 2) seem to require resilience assessments to be conducted at multiple levels of the system. I then briefly summarize the associated challenges with collective action and how they make difficult any attempt at resilience modelling at multiple scales. Finally, I outline the shape of the paper and how it confronts these issues.

§1 – Multiscale Resilience Modelling

In this section, I begin by noting some of the key features of dynamical complex systems which are relevant when designing resilience models: 1) nonlinearity, 2) hierarchical composition, and 3) emergence. I argue that these characteristics render resilience modelling for complex systems problematic, especially given that much of the data available to support that modelling is micro data pertaining to different lower-level subsystems (e.g., critical assets). This introduces what I refer to as *the problem of data transformation* for resilience models. Namely, resilience models are required to convert micro data about subsystems into macro data about properties of the whole system without allowing model complexity to balloon. I urge that a viable solution to this problem can be found in the use of select multiscale resilience models. These are simpler but satisfactory representations of the system which decompose it into a small set of relevant subsystems which can manageably be modelled. Critically, I highlight that

in addition to enabling resilience assessment, models of this kind have the potential to serve as a framework for evaluating the resilience gain of proposed interventions.

§2 – Challenges for Resilience Modelling of Systems under Collaborative Governance

In this section, I begin by introducing some of the known issues associated with collaborative governance: divergent and often competing incentives, differences in the levels of available resources / priorities for their allocation, power imbalances, and different levels of maturity in understanding of the domain in question. I then connect these to challenges around the collective development and implementation of resilience models. Specifically, I argue that in cases where collaborative governance is involved, the following problems are liable to emerge.

1) Those parties looking to minimize the expense of their own resources to improving the resilience of the overall system may seek to free ride on others by presenting their contribution to system resilience as favorably as possible. These parties may withhold or misrepresent data or push for the adoption of a measurement framework which is favorable to them but not to the fidelity of the overall model.
2) Stakeholders may be unwilling to invest upfront the time and resource to generating new datasets to support resilience modelling. This limits the potential scope of resilience modelling efforts to any existing data and, in many cases, limits the fidelity of the model significantly.

§3 – An Iterative, Evolutionary Approach

In this section, I propose a solution to the problem framed in the previous. On the projected approach, development of a multiscale resilience model for a system under collaborative governance is possible through the iterative evolution of a low-fidelity three-tiered model. This model would have at its foundation a submodel for consuming the majority of the micro data available and converting it into a form which can support performance modelling of a handful of core subsystems under conditions of stress. Above this would sit a model of the performance of core subsystems which will enable assessments of their resilience. Finally, the outputs of these models would be used to feed a model of overall system performance under stress and, thereafter, an assessment of broader system resilience.

I argue that this approach has several key advantages. The first is that it is able to overcome the problem of data transformation. Another is that it places very few constraints on the data required. It is possible to develop a model of this kind which consumes a range of quite different micro data across the various subsystems and yet is still capable of generating system-level insights. Likewise, the conversion of this micro data into subsystem performance and resilience data can be supported by qualitative insights and expert judgement capture. It does not require the development of an additional highly structured dataset. Moreover, this approach minimizes the risk of free riders by making the data threshold requirements so low and the demands on stakeholders so minimal.

I then acknowledge that the downside of this initial model is its low level of realism. However, I go on to propose an approach to the iterative evolution of this model which can

enable far richer resilience insights over time. On this approach, the model is expanded in terms of both density (i.e., the number of subsystems modelled) and fidelity. The core focus for the latter is increased use of simulation in performance modelling, both at the level of subsystems and the macro system. If introduced in a manner that is sufficiently iterative and gradual, I argue that this drive towards greater use of simulation is liable to encourage stakeholders to develop a stronger, more focused and unified supporting data ecosystem without triggering the aforementioned issues of collective action associated with collaborative governance.

Structural vs. Nonstructural Roles in Seismic Resilience: AI-Based Managerial Trade-Offs in RC Frames

Sarhang Abdalrahman[1], Zanyar Mirzaei[2], Masoud Khalighi[2], Shayan Estifaei[3]
1 Environment Department of Halabja Province, Iraq, sarhang.mohammed@uok.ac.ir
2 Department of Civil Engineering, University of Kurdistan, Sanandaj, Iran, zanyar.mirzaei@uok.ac.ir, m.khalighi@uok.ac.ir
3 Delft University of Technology, Netherlands

Abstract

Earthquakes are distinct from many other hazards because they strike suddenly, occur with high uncertainty, and generate cascading consequences that extend beyond structural safety. Managing this risk requires more than structural performance-based design; it requires a more comprehensive perspective that considers both seismic resistance and long-term sustainability, including economic and environmental consequences.

Recent studies on seismic resilience have primarily concentrated on structural components and have insufficiently addressed nonstructural elements, even though these play a critical role in post-earthquake consequences. To address this gap, this study introduces an optimization framework for reinforced concrete (RC) moment frames that distinguishes structural and nonstructural contributions.

A wide range of RC frame design scenarios was analyzed in ETABS and used to train an artificial neural network (ANN) for rapid prediction of seismic losses across thousands of unseen alternatives. Multi-objective optimization then constructed Pareto frontiers to capture trade-offs between pre-earthquake design variables and post-earthquake sustainability losses. These trade-offs, covering structural and nonstructural systems, were condensed into a Decision Balance Index (DBI), a managerial metric that translates complex outcomes into a single value for decision support. The results show that structural and nonstructural systems interact to shape resilience and post-earthquake sustainability, while DBI enables project managers and policymakers to identify balanced design strategies without technical expertise. Moreover, ANN not only accelerates the exploration of design alternatives but also captures nonlinear dependencies and hidden patterns that conventional analyses often miss.

Keywords: Seismic resilience; RC frame buildings; Nonstructural components; Artificial Neural Network (ANN); Economic and environmental losses

Introduction

Earthquake resilience of buildings depends not only on their primary structural systems but also on the performance of nonstructural components which often drive repair costs, downtime, and Environmental Impact (EI) after seismic events (Taghavi & Miranda, 2003) (Challagulla, et al., 2023). Yet conventional frameworks have emphasized structural damage while overlooking these contributions, leading to incomplete evaluations of seismic losses,

particularly when sustainability objectives are considered (Dhakal, et al., 2016). Beyond this, resilience is shaped by detailing decisions, strategic processes, and material choices (Trejo & Barbosa, 2016), which are typically made to satisfy structural performance but are rarely assessed long-term sustainability consequences. Although some studies have attempted to integrate structural performance with sustainability objectives, most approaches remain partial and fragmented, because buildings are complex systems, and developing a holistic framework that simultaneously addresses seismic safety and life-cycle sustainability remains challenging (Abdurrahman, Mirzaei, & Khalighi, 2024) (Hasik, et al., 2018).

It is therefore essential to distinguish structural from nonstructural contributions when evaluating seismic performance, as this distinction clarifies their roles and supports design choices that balance safety with sustainability. Building on this motivation, the present study introduces an integrated methodology for RC frame buildings that formalizes trade-offs between pre-earthquake design variables and post-earthquake sustainability losses, condensing them into a DBI, enabling project managers and policymakers to identify balanced design strategies without technical expertise.

Proposed Framework for Seismic Loss Optimization

The proposed methodology integrates seismic modeling, fragility-based loss estimation, and AI-supported optimization into a framework that links structural and nonstructural performance with both economic and environmental impacts. This framework is designed to translate structural responses into sustainability-oriented decision metrics that guide managers and policymakers in resilient decision-making. As illustrated in Fig. 1, the process is organized into six stages. It begins with nonlinear seismic analysis of RC frame with infill systems, generating demands to establish fragility relationships. These fragility curves connect drift levels to probabilistic damage states, which are then used to quantify losses in terms of expected annual loss (EAL, USD/yr) and Environmental Impact (EI, kg CO_2/yr) (Gencturk, Hossain, & Lahourpour, 2016) (Hossain & Gencturk, 2014). To overcome the computational burden of repeated nonlinear simulations, an Artificial Neural Network surrogate is trained on simulation data, enabling rapid prediction of losses across thousands of alternative designs (de Lautour & Omenzetter, 2009) (Falcone, et al., 2022) (Kazemi, Asgarkhani, & Jankowski, 2023). Multi-objective optimization of these outcomes produces Pareto frontiers that capture the trade-offs between construction-phase and repair-phase impacts, which are further condensed into the DBI, a normalized 0–1 indicator obtained by normalizing construction- and repair-related impacts and measuring each scenario's distance from the ideal point. As the final stage, sensitivity analysis identifies the most influential design variables such as concrete strength, reinforcement ratios, infill stiffness, and damping, providing both explanatory insight and actionable guidance for sustainable seismic decision-making.

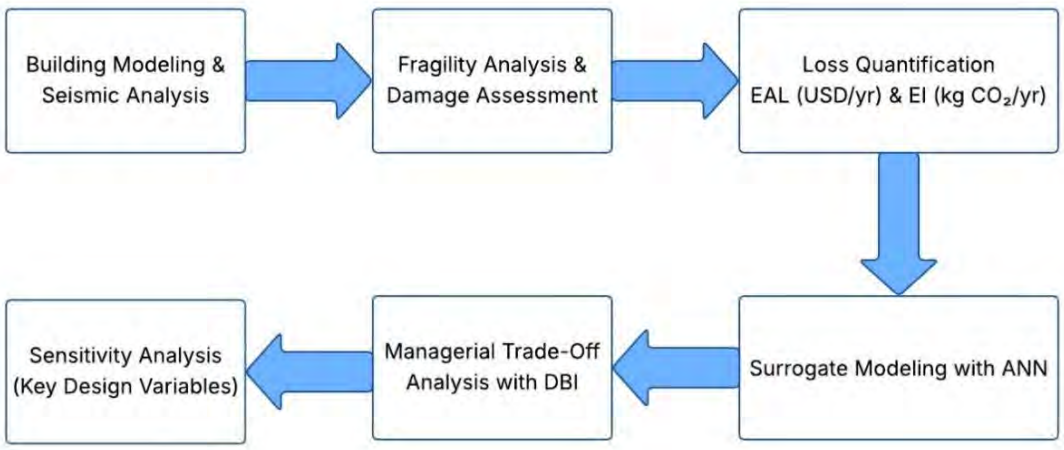


Figure 1. Proposed framework for seismic loss optimization in RC frame.

Illustrative RC Frame Case Study: Seismic Loss Optimization

A representative mid-rise RC moment-resisting frame is selected as the illustrative case. The building designed under generic international seismic provisions, includes structural elements and nonstructural systems, ensuring that drift-sensitive losses are captured. Nonlinear analyses in ETABS under multiple seismic intensity measures provide interstory drifts, which are translated into fragility curves for structural and nonstructural components. Repair quantities and CO_2 emission factors are then mapped to compute EAL and EI. Key design variables such as concrete strength, reinforcement ratios, infill stiffness, and damping are varied within realistic bounds to generate simulation data. An ANN surrogate is trained on this dataset, enabling rapid prediction of EAL and EI across thousands of unseen scenarios.

Conclusions

This study developed a resilience–sustainability optimization framework for RC moment frames that distinguishes structural and nonstructural contributions to seismic losses. By linking design variables to repair demands, the framework quantifies EAL and EI, highlighting how alternative configurations shape construction- and repair-phase consequences. Surrogate modeling with ANN reduces the computational burden of nonlinear analyses, enabling the construction of Pareto frontiers that reveal trade-offs between pre-earthquake design variables and post-earthquake sustainability losses. These trade-offs are condensed into a DBI, which provides project managers and policymakers with an accessible decision-support tool. Sensitivity analysis identifies the most influential design variables such as concrete strength, reinforcement ratios, and infill stiffness, offering practical guidance for design and regulation. While the framework advances the integration of resilience and sustainability, this version is limited to economic and environmental losses; social dimensions such as downtime and functional recovery remain important directions for future research toward a holistic life-cycle perspective.

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Harmonizing Methods for Multi-Hazard Resilient Buildings: From Risk Matrices to Uncertainty-Based Frameworks

Simona Bianchi, Delft University of Technology, Netherlands, s.bianchi@tudelft.nl

Abstract

Climate-induced hazards are rapidly increasing with climate change, yet the built environment remains ill-equipped to cope. Developing sustainable climate adaptation requires buildings that are resilient to diverse hazards. However, current design and assessment approaches rarely consider multi-hazard resilience, often leading to costly and environmentally unsustainable solutions. Harmonizing design criteria and methodologies to address multiple extreme events is therefore essential. This study examines and proposes methods, ranging from simplified to more advanced, for supporting resilience design decisions. It introduces multi-domain loss-based matrices based on economic, environmental and social impacts to design buildings exposed to climate extremes, such as heatwaves, hail and flooding, and their interactions. Furthermore, the study develops a probabilistic framework to integrate heat vulnerability with physical vulnerability, enabling informed decision-making by considering uncertainties in hazards, building properties, modelling and potential consequences.

Keywords: Climate Resilience; Multi-Hazard; Performance-based Design; Risk Assessment; Decision Making

Introduction

Global development goals and existing guidelines stress the urgency of resource-efficient climate adaptation, which could contribute up to around 30% of the global mitigation required by 2030-2050 to limit temperature rise (IUCN 2022). Yet, no established approach currently exists for designing sustainable climate resilient buildings. While resilience-based design methods are emerging, they mainly target infrastructure and rely on qualitative indicators or single-hazard objectives (e.g., Cimellaro et al. 2016; Duarte et al. 2022). The recent Arup guidelines (Arup 2023) represent a first step toward resilience design for buildings, but they define resilience levels only in terms of damage under single hazards such as earthquakes, floods or windstorms. This underscores the urgent need for holistic design approaches that integrate safety, functionality and sustainability objectives.

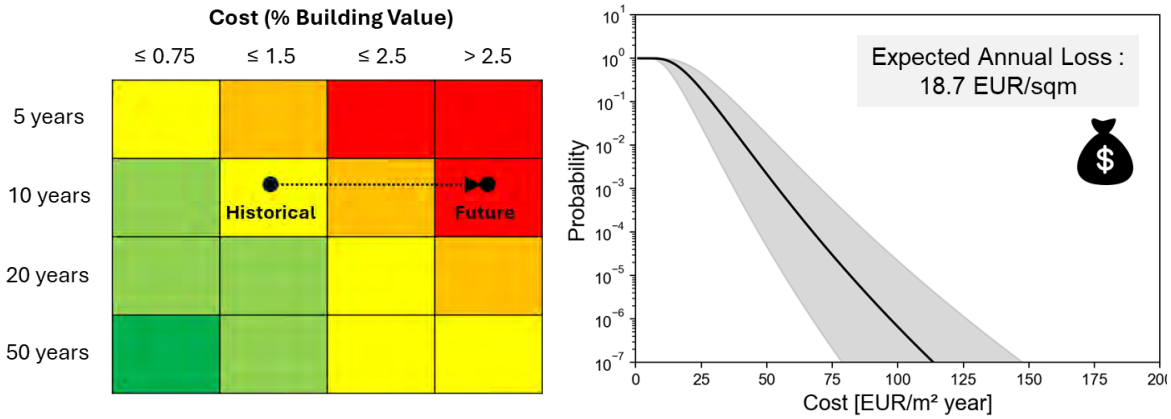
For retrofit and design investment decisions, quantifying the consequences of extreme events is crucial and should be embedded in early-stage design frameworks. This has led to a growing interest in multi-risk assessment methods that capture hazard interactions and/or physical vulnerabilities (e.g., Argyroudis et al. 2020; Iannacone et al. 2023). However, these methods do not account for heat-related impacts due to the absence of vulnerability models. Recently, initial definitions of heat resilience and preliminary attempts to measure heat fragility have begun to emerge in the overheating and energy domain (e.g., Homaei et al. 2021; Szagri et al.

2022). Given the urgency of the issue, mathematical functions should be defined to describe heat vulnerability and to establish a probabilistic framework for quantifying heat risk and resilience.

This study develops both practical and advanced approaches to support multi-hazard resilience design and assessment of buildings. First, a semi-quantitative loss-based design approach is introduced, incorporating new holistic resilience aspects (safety, well-being, cost, emissions) through risk matrices. Second, a quantitative probabilistic-based method is proposed for heat risk modelling. This framework embeds uncertainties from climate, buildings and occupants, and enables to integrate heat with other hazards to quantify building resilience considering both physical and heat vulnerabilities.

Multi-domain matrices

Risk matrices that integrate hazards and consequences are valuable tools for guiding building design and retrofit against climate-induced extremes. To move beyond single-dimension performance, this study identifies multi-domain (physical, economic, social, environmental) and multi-phase (response, recovery) resilience indicators, and examines their interaction with sustainability measures (overheating risk, global warming potential). These indicators can be combined into a multi-criteria index using weighted sums or products, where the weights reflect project priorities or stakeholder preferences (Bianchi et al. 2023, 2025). Scoring schemes, such as climate resilience classes, further enhance transparency in evaluation. Loss-based matrices can be developed for each dimension, with quantitative thresholds informed by policy measures, technical guidelines or experimental data. For instance, Figure 1a illustrates a heat-stress risk matrix that defines consequence functions (operational energy cost based, with thresholds defined based on Calvi et al. 2016) to capture the effects of current and future extreme heat.



(a) (b)

Figure 1. Example of (a) heat risk matrix based on energy cost, and (b) probabilistic energy loss curve for a multi-story building.

These matrices can be used to define performance targets for the building response and recovery phases after extreme events, and they can be applied to various climate-induced hazards and their interactions. By adopting a scenario-based approach, multi-hazard sequences over a building's lifespan (e.g., a heatwave occurring during post-flood repairs) can be modeled

to produce time-dependent resilience-based matrices that incorporate design targets for resource-efficient and resilient buildings.

Probabilistic risk modelling

To support robust decision-making, a quantitative risk assessment approach can be employed. For each climate-induced event, a probabilistic framework can be established by integrating all key components (hazard analysis, building analysis, fragility analysis, loss analysis), each influenced by specific sources of uncertainty. This enables the derivation of performance measures relevant to stakeholder decisions, such as financial loss, casualties, environmental impact.

Following the Performance-Based Earthquake Engineering approach (Cornell and Krawinkler 2000; Porter 2003), this study develops a novel mathematical framework for heat risk assessment, incorporating: 1) hazard curves derived from historical and projected weather data; 2) building response modeling accounting for uncertainties in material and geometric properties, construction details and occupant behavior; 3) fragility curves including uncertainty in performance thresholds; 4) loss computation, capturing human response variability and economic factors such as market prices. This probabilistic approach allows the development of heat vulnerability models (e.g., Figure 1b, for an Italian pre-1970 multi-story reinforced concrete building archetype) to quantify heat-related risk. Risk is calculated by combining the probability of hazard, vulnerability and exposure, where exposure includes factors such as the number of affected occupants and the surrounding urban context. This produces a dimensionless risk value, which is useful for scenario comparisons and sensitivity analyses but can be difficult to communicate to stakeholders. To improve interpretability, risk is expressed using exceedance probability curves and associated metrics. These include the Expected Annual Loss (EAL), which underpins financial risk assessments and informs mitigation strategies such as insurance premiums, and the Probable Maximum Loss (PML), representing a selected quantile (e.g., 90%) of the loss distribution.

The development of this approach demonstrates the potential to harmonize assessment methods across multiple hazard types. It enables integration of heat risk into multi-hazard frameworks that consider both independent events and sequences over a building's lifetime, allowing computation of life-cycle resilience and expected holistic losses.

Conclusions

This study addresses the need for holistic building design by developing practical and advanced approaches for multi-hazard resilience assessment. A semi-quantitative, loss-based design framework was introduced, incorporating multi-domain and multi-phase performance indicators through risk matrices, enabling designers to define performance targets and compare technological solutions. A probabilistic framework was also developed to generate heat vulnerability curves and quantify heat-related risk, therefore enabling integration with other climate hazards to estimate life-cycle resilience and overall losses.

The proposed approach offers a structured methodology for guiding investment decisions, supporting resource-efficient resilient buildings. It is adaptable to different building types, stakeholder priorities and urban contexts, and facilitates comparison of alternative building configurations. While comprehensive, generalizing the approach to all climates, building types,

or socio-economic contexts may require site-specific data and calibration. Future work will focus on integrating additional hazard types (e.g., fire, storms) and refining heat vulnerability models with empirical data to enhance applicability and robustness.

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Author

Prof. Dr. rer. nat. Martina Piefke

Affiliations

Neurobiology and Genetics of Behaviour Unit, Faculty of Health, Witten/Herdecke University

Scientific Director of the Working Group on Security Research and Security Practice at Witten/Herdecke University

Scientific and Managing Director of the Institute of Cognitive Sciences and Security Strategies (IKOWIS GmbH)

Title

Human factors resilience: methods of assessment and training of resilience in security agencies and organisations

Introduction

In the human factors domain, resilience is the capacity to adapt to challenges, recover quickly from difficulties, and bounce back from adversity. It' does not refer to avoiding hardship. Rather, it depicts resources of developing the ability to cope with stress, trauma, and setbacks. Resilience permits individuals and social communities to maintain psychological well-being in the face of hardship. Resilience can be learned and strengthened by suitable training and mindset shifts.

Soldiers, policemen and action forces of other security agencies and organisations are put in charge of the task to protect resilience of social systems. Therefore, they need to be equipped with high and professional levels and stability of resilient mindset and behaviour. We here introduce a multidisciplinary and multimodal method for the training and strengthening of resilience in action forces of security agencies and organisations. We expect that or multimodal approach may help to frame and stabilize professional resilience in security agencies and organizations.

Methods

We apply multimodal training of resilience in theory and practise on the instrumental, cognitive, and regenerative levels across ten weeks. On the instrumental level, individuals and teams within action force unities learn to work on external stressors, aiming at stressor modification where possible, and adapting to stressors in cases where a modification of external factors cannot be implemented. On the cognitive level, two dimensions are targeted. Firstly, internal stress enhancers are dealt with. Individual patterns of thought and motives are considered, identified, and modified in cases where they turn out to act as adverse stress enhancing key players. Modifications focus on cognitive forces of stress

reduction and constitution of stable stress resilience. Secondly, basic cognitive functions are trained, thereby focusing on functions that support resilient planning and execution of actions in critical situations and operation phases. These are mainly cognitive control and flexibility, attention, and working memory. On the regenerative level, we focus on physical activities, relaxation, and leisure time. The concept is illustrated in Figure 1.

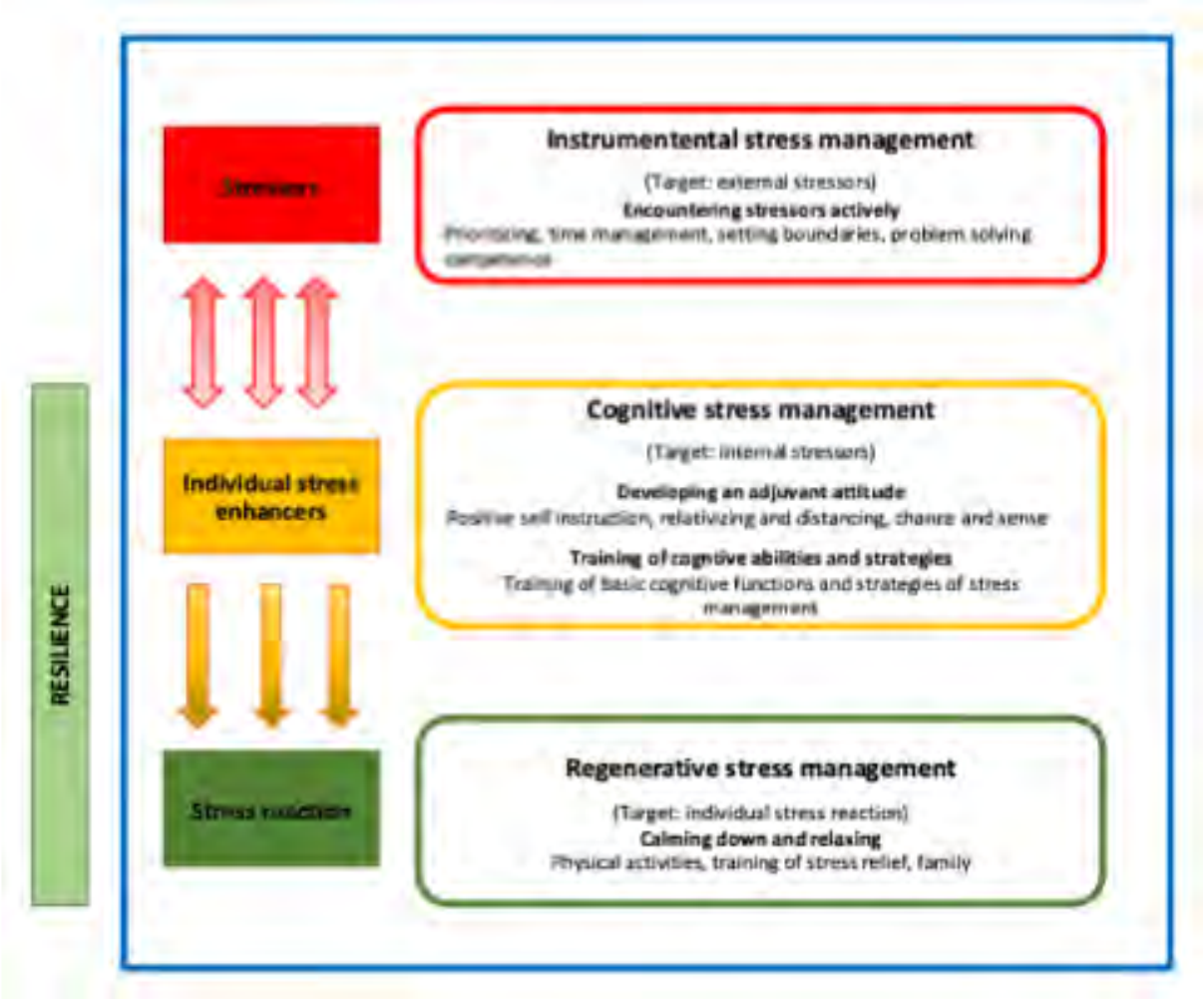


Figure 1. Concept of multimodal training of resilience

Results

Preliminary data show that members of security agencies and organizations may profit from multimodal training of resilience especially in the fields of cognitive operation strategies and focused attention resources. Moreover, results show post-operational physical and mental health benefits from this type of preventive training interventions.

Conclusion

Our multimodal training of resilience is a low-threshold approach, which can be integrated in routine qualification and advanced training of members of security agencies and organizations. Since the development and stabilization of resilience is based on changes in patterns of thinking and behaviour, a basic long-term training across at least several weeks and follow-up training interventions are required. We propose that our training approach is an efficient tool for the establishment of human factors resilience in professional operation areas.

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Explore Aspirations and Capabilities theory in migration in Moroccan Oases under drought: An Agent-Based Approach

Thanh Thi Nguyen [(1)], Bright Oluwatomilola Olunusi [(2)], Adham Badawy [(2)], Andrew Reid Bell [(2)]
1 University of Kassel, Germany
2 Department of Global Development, Cornell University, USA

Abstract

This paper introduces Oaspire – "Moroccan **Oas**is under Migration, As**pi**ration, Drought", an agent-based model (ABM) designed to explore migration in Moroccan oases through the aspiration–capability framework. Unlike household-based models, Oaspire simulates individuals with differentiated roles, savings, aspirations, and social connections. Implemented in NetLogo and following the ODD+ protocol, the model captures how drought, labor division, and peer influence interact to shape migration. Results reveal threshold-driven mobility, capability bottlenecks, and intra-household divergence. By linking behavioral theory with socio-ecological processes, the model contributes insights into resilience, vulnerability, and trade-offs in fragile oasis systems.

Keywords: migration; agent-based modeling; aspirations; resilience; Moroccan oases

Introduction

Migration in oasis systems is driven by intertwined socio-economic and ecological dynamics. Moroccan oases, particularly in High Atlas and Anti Atlas, face severe pressures from climate change, agricultural decline, and rural–urban migration. Traditional models often reduce migration to economic push–pull logics, neglecting subjective, social, and intra-household dimensions. The aspiration–capability framework (de Haas, 2021) emphasizes that migration depends on both an individual's desire to move and the means to practice it. This theory is especially relevant in Moroccan oases, where aspirations and opportunities vary sharply between genders, generations, and household roles. Responding to calls to integrate behavioral complexity in migration modeling (Schrieks et al., 2021; An et al., 2021), we present Oaspire, a NetLogo-based ABM that simulates migration as emergent from individual aspirations, capabilities, and interactions within socio-ecological contexts. By shifting the unit of analysis from households to individuals, the model reveals trade-offs and synergies affecting resilience in fragile landscapes.

Methods

The "**Oaspire**: Moroccan **Oas**is under Migration, A**spi**ration, Drought" model builds on the aspiration–capability framework, recognizing three states: (1) aspiration without capability (frustrated migrants), (2) capability without aspiration (settled individuals), and (3) aspiration with capability (potential migrants). This aligns with Sen's capability approach and highlights the interplay of economic, social, and psychological factors.

Theoretical framework

The model builds on the aspiration–capability framework, recognizing three states: (1) aspiration without capability (frustrated migrants), (2) capability without aspiration (settled

individuals), and (3) aspiration with capability (potential migrants). This aligns with Sen's capability approach and highlights the interplay of economic, social, and psychological factors.

Model design

Oaspire was implemented in NetLogo following the ODD+ protocol. Agents represent individual household members distinguished by age, gender, labor role, savings, aspiration level, and social connections. Patches represent farmland with fertility and crop type; links capture social ties within and across households.

Processes include:

- Seasonality: alternating wet and dry seasons.
- Labor allocation and income generation.
- Aspiration growth through social influence and peer comparison.
- Savings accumulation with stochastic losses.
- Environmental shocks: drought reduces yield.
- Migration decisions: short-term labor migration or permanent migration if aspiration > 0.9 and savings > 150.

Scenarios and simulation

Simulations were run for 200 ticks (seasons), replicated 50 times across four scenarios:

1. Baseline: no drought, low aspirator influence.
2. Drought: frequent yield shocks ($p = 0.4$).
3. High aspirator density: strong peer influence.
4. Combined stress: drought and aspirator density

Results and discussion

First results show migration patterns emerged in all scenarios, though rates and timing varied. Under the baseline, about 5% of individuals migrated by tick 200, reflecting a low but steady rate of mobility. The drought scenario doubled migration (~11%), showing that environmental stress reduces income and accelerates mobility. High aspirator density created early but slower-rising migration, suggesting that peer influence generates rapid aspiration growth but eventually stabilizes. The combined stress scenario produced the highest migration (~15%) and earlier departures, underlining the reinforcing effects of environmental and social pressures.

These outcomes highlight the interaction between structural triggers and social influence. While drought clearly reduced yields and income, aspiration was primarily shaped by social contact, supporting arguments that migration is as much a relational process as an economic or ecological one. Intra-household divergence was also evident: younger members with higher aspirations often migrated earlier, while older individuals with strong attachment remained immobile despite financial capability.

Household labor dynamics further illustrate resilience trade-offs. Outmigration of working-age adults weakened agricultural capacity and increased vulnerability, especially in households dependent on senior or child labor. By contrast, households with more balanced labor portfolios coped better with drought and labor loss. Migration thus simultaneously reduced household resilience while potentially enhancing individual resilience through livelihood diversification. A key insight is the threshold nature of migration. Many individuals reached high aspiration but lacked sufficient savings, becoming frustrated potential migrants. Others accumulated savings but never developed the aspiration to leave, remaining settled. Migration occurred mainly when aspiration and capability converged, producing nonlinear outcomes. This finding resonates with de Haas's (2021) argument that hardship alone does not guarantee mobility and explains why some individuals stay behind under similar conditions.

Overall, Oaspire demonstrates that migration cannot be adequately understood using household-level or linear economic models. Individual agency, social influence, and threshold dynamics all shape mobility in fragile oases. At the system level, these dynamics reveal trade-offs: migration may erode local agricultural labor but contribute to broader socio-economic resilience through remittances and demographic change

Conclusion and outlooks

Oaspire operationalizes the aspiration–capability framework in Moroccan oases, offering a new tool to study migration under environmental uncertainty. By simulating individual-level aspirations, savings, and social interactions, the model demonstrates that migration is not solely a response to poverty or drought but emerges from complex behavioral processes.

The findings highlight the importance of combining behavioral theory with agent-based modeling to assess resilience in socio-ecological systems. Future work will extend the model sensitively analysis and scenario implementation to include remittances, gendered migration outcomes, and policy interventions.

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Optimizing Project Resilience: Balancing Costs and Benefits

Seyed Ashkan Zarghami
Australian National University, Canberra, Australia
ashkan.zarghami@anu.edu.au

Abstract

Although the concept of resilience has been discussed since the 1970s, it has gained substantial prominence across various disciplines in recent years, particularly in response to cascading disruptions such as pandemics, geopolitical conflicts, and financial crises (Champlin et al., 2023). While there is no universal definition of resilience, most converge on the idea of building system capabilities that minimize the negative impacts of disruptions, enable rapid response, and support recovery to a steady or even improved state (Duchek, 2020). Projects serve as prime examples of socio-technical systems, as they involve complex interactions between diverse stakeholders (social elements) and technology (technical elements) (Zarghami & Zwikael, 2025). Building resilience in projects, however, often entails substantial costs such as maintaining reserve resources, building redundancies into supply chains, or introducing backup systems that demand additional financial and managerial effort. A further complexity is that resilience in complex socio-technical systems, such as projects, does not operate in isolation (Mehvar et al., 2021). Strengthening one dimension of resilience often requires compromises in others, making it essential to use tools that capture trade-offs and synergies to help decision-makers weigh competing priorities under conditions of uncertainty. Specifically, it becomes essential to make informed decisions about the optimal level of resilience, striking a balance between the investments required and the benefits gained, particularly given the resource-scarce nature of most projects. This decision-making process ensures that the costs of resilience are effectively offset by the reduced risk of project failure in the face of disruptions. Despite the growing recognition of its importance, the literature has yet to develop a model that optimizes project resilience by explicitly balancing costs and benefits. This research addresses this gap by introducing the concepts of resilience cost (measured as the value of contingency reserves allocated to manage disruptions) and resilience worth (measured as the benefits derived from reducing delays in project completion) (Zarghami, 2025). Accordingly, this research adopts a three-step approach. First, the resilience cost is constructed by combining the contingency reserve, which covers resilience to known-unknown events identified in the project risk register, with the management reserve, which addresses resilience to unknown-unknown events. Second, the resilience worth is estimated by calculating the penalty costs avoided through improved resilience. Third, the total cost curve is developed by integrating both resilience cost and resilience worth. The minimum point of this curve represents the optimal level of resilience, where investment is most efficiently balanced against the benefits gained (Farzin, 2022). To validate its practical relevance, the proposed model is applied to a real-world project. By integrating resilience cost–worth assessments into project planning, this research provides both a practical tool for decision-makers and fresh theoretical insights into the role of resilience in project-based decision-making.

Keywords: Decision-making; Optimization; Project; Resilience

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Assessing Social Resilience through Archetypes: Methodology and Insights from Singapore

Renate Schubert[1], Mijie Li[2], Adam Roberts[2], Jonas Joerin[2]
1 Department for Social Sciences and Humanities, ETH Zurich, schubert@econ.gess.ethz.ch
2 Future Resilient Systems, Singapore-ETH Centre, Singapore

Abstract

Understanding social resilience in urban populations is essential for effective governance and disaster/crisis preparedness. This study introduces a framework for assessing social resilience through social archetypes, defined by shared capacities and perceptions, and examines how social resilience performance shifts under potential disruptions. Using survey data from Singapore at both national and town levels, we identify three archetypes with distinct social resilience profiles and demonstrate that high resilience under normal conditions does not always predict superior performance during disruptions. These findings provide insights for tailoring interventions to enhance community resilience.

Keywords: social resilience; archetype analysis; profiling; disruption scenarios; resilience assessment

Introduction

Cities are complex, densely populated systems where residents face a range of potential stressors, from natural hazards such as heat waves, hurricanes, floods etc., often resulting from global climate change to social disruptions caused by economic instability, the danger of job loss, a strong influx of foreigners, cyber-attacks etc. Social resilience, i.e., social coherence of citizens, mutual support, well-functioning social networks as well as trust in other citizens and in leaders is essential for societies to thrive even under adverse conditions. Understanding social resilience is essential for effective urban governance before, during and after a crisis and for disaster preparedness. Of particular interest is how static or dynamic social resilience is in the population. It is, hence, important to know how societal groups that perform well under normal conditions react with an increase or decrease of social resilience when a crisis occurs, and whether less socially engaged groups are able to activate latent capacities to adapt and support each other. Understanding these dynamics is critical for designing interventions and policies that strengthen community resilience in diverse urban population groups.

We introduce a novel framework for assessing social resilience using social archetypes: clustering groups of individuals through shared attributes beyond socio-demographic or socio-economic characteristics. This approach enables a more nuanced understanding of social resilience performance and its dynamic shifts under potential disruptions. Unlike traditional approaches that focus primarily on socio-economic or socio-demographic characteristics, our methodology incorporates psychographic dimensions, such as individual capacities and perceptions, which are relevant for social resilience performance and tend to be rather stable over time and may be well suited for identifying groups that react in similar and predictable ways to social resilience enhancing measures.

National Survey

We conducted a national survey in Singapore (2'500 participants) and applied a k-means clustering analysis to identify social archetypes based on psychological resilience and collectivistic orientation. We then examined how these archetypes perform in terms of social resilience under "normal" conditions and in response to vignettes of disruption scenarios. To analyse the respective social resilience performances, we used indicators and sub-indicators that are well-known from the literature, like social cohesion, social support, social networks and vertical trust. The three social archetypes we identified were:

- **Archetype 1: The Optimistic Leaders**: individuals with high psychological resilience and collectivistic orientation.
- **Archetype 2: The Engaged Connectors**: citizens with high collectivistic orientation and with low psychological resilience.
- **Archetype 3: The Reserved Individualists**: individuals with rather low psychological resilience and with a rather individualistic value orientation.

Analysing the social resilience performance scores of the three archetypes, it turns out that under normal conditions, Archetypes 1 and 2 exhibited stronger social resilience, with higher levels of social cohesion, social networks, social support and vertical ties compared with Archetype 3. However, when presented with a hypothetical future disruption, like, for instance, intense heat waves, economic turmoil, or strong foreigner influx, a notable shift occurred: Archetype 3 performed more positively, whereas Archetype 1 showed reduced scores for vertical ties and social cohesion. Archetype 2 showed reduced scores for vertical trust and social cohesion. These findings highlight that high resilience under "normal" conditions does not necessarily predict superior performance under disruptive conditions, and that less engaged groups can reveal unexpected adaptive capacities when challenged.

From the methodology perspective it is interesting to see that socio-demographic and/or socio-economic attributes do not correlate in a consistent way with the three social archetypes we identified and seem to contribute less to explaining social resilience shifts occurring under disruption scenarios.

Two Towns Survey

To validate these findings from the national level, we conducted additional surveys in two Singaporean towns, Bukit Merah (a rather traditional and very centrally located community) and Punggol (a rather new town at the northern edge of Singapore). Results from these localised surveys corroborate the national-level patterns. By using the cluster centroids from the national survey, participants in the two towns were grouped into the three archetypes without any misclassification errors. A more robust test of using the two dimensions of psychological resilience and collectivistic orientation from the national survey but allowing new clusters to form showed very similar results as obtained for the national level, with three clusters being identified for each of the two towns, and only minor misclassification errors. When examining the social archetypes' social resilience performance, results were in line with the national survey. Given that we had chosen two very different communities, our results seem to confirm

that the three social archetypes which we identified capture consistent resilience performance trends across different community contexts.

Conclusion

Our study demonstrates the value of social archetypes as an innovative assessment framework for social resilience performance. By identifying social archetypes based on rather stable attributes, that are relevant for the resilience related context, we were able to identify which societal groups are more vulnerable or more adaptive in the face of disruptions. Such knowledge helps tailoring interventions to different societal groups, hereby helping to strengthen the overall social bonds, enhance adaptive capacity, and foster cohesive communities. Our study contributes to the field of resilience assessment by offering a replicable, theory-driven method for linking rather stable psychographic traits to social resilience outcomes, bridging the gap between theoretical frameworks and practical applications in urban governance and disaster preparedness.

A Lens for Resilience: Applying the Sociotechnical Ecosystem Framework to Complex Adaptive Systems

Sevan Gerard MA, BS, EMT-P, NCEE (a,b,c) a. Disaster Health Institute, Inc., USA; sevan@disaster.health b. Paracelsus Medical University, Center for Disaster Health and Research, Austria c. World Association for Disaster and Emergency Medicine (WADEM) – Europe Chapter Orcid ID: 0009-0001-0202-970X

Abstract

Originally developed as a conceptual lens for analyzing identity formation and social behavior in the context of conflict and terrorism, the sociotechnical ecosystem framework (STEF) offers a powerful, transdisciplinary approach to understanding resilience in complex adaptive systems. In today's era of cascading disruptions, spanning governance, economy, infrastructure, and institutional life, the line between social behavior and technicity has become increasingly blurred. This framework responds by offering a structural lens through which systems can be interpreted holistically, capturing both their material and behavioral dynamics.

The framework comprises five interacting domains, namely artifacts, mobility, communication, information, and networks, that together constitute the operational and symbolic structures of any sociotechnical system. As a lens rather than a fixed model, it avoids rigid quantification and instead supports situated, context-sensitive assessments that reveal how systems adapt, reorganize, and sustain coherence under stress. Sociotechnical systems evolve through the interplay, shifting and transfer of operative value between domains.

By focusing on interdependencies, relational flows, and evolving configurations rather than discrete outcomes or static metrics, the sociotechnical ecosystem lens facilitates the co-construction of resilience assessments in diverse contexts, from urban governance and economic continuity to infrastructure and organizational systems. It helps practitioners and scholars surface latent fragilities and adaptive capacities embedded in the social-technological continuum.

In an age where disruption is the norm and certainty the exception, this lens offers a way to see systems not as bounded entities, but as ecosystems of evolving sociotechnical meaning, behavior, and structure, making STEF a versatile tool for next-generation resilience assessment.

Keywords: Sociotechnical Ecosystem; Complex Adaptive Systems; Behavioral-Identity Dynamics; Resilience Mapping; Transdisciplinary Systems Analysis

INTRODUCTION

Resilience is no longer a luxury for systems operating in relatively stable environments. In our current era of perpetual crisis, marked by pandemics, ecological breakdowns, social fragmentation, and institutional volatility, resilience must be a fundamental design principle. However, many resilience assessment tools rely on fixed indicators, checklist logic, or sector-specific metrics that fail to reflect the real-world complexity and dynamic interdependence of sociotechnical systems (Tan, 2021).

This paper introduces the sociotechnical ecosystem framework as a lens for assessing resilience across complex adaptive systems. Initially developed by Gerard (2017) to explore how identity and behavior are shaped by technological environments in the context of terrorism and conflict, the framework has since evolved into a scalable and structurally grounded assessment methodology. It is based on the premise that resilience is not a property of isolated units, but of evolving relationships between technological and social subsystems. The concept of technicity is important to the framework because it captures the way technological forms and practices shape and mediate human activity, creating conditions in which the technical and the social become inseparable. Drawing from Ellul's insight that technology possesses an autonomous logic influencing culture and behavior (Ellul, 1964), and further elaborated by Simondon (2011) and Stiegler (1998), technicity underscores how resilience must be understood not only as adaptation to shocks, but as the capacity to navigate systems where technology actively co-produces social dynamics.

METHODOLOGY

Rooted in complexity science and sociotechnical systems theory, the sociotechnical ecosystem framework is informed by three key intellectual traditions:

1. Complex Adaptive Systems (CAS): Resilience has been described as a higher order description of system dynamics (Srinivasan and Kumar, 2015), and is understood as an emergent property of systems capable of reorganization, learning, and maintaining coherence in the face of disruption.

2. Social Identity Theory and Technoself Studies: Systems are not only technical or structural; they are made of social meaning, narrative, and identity, shaped by the technological environment and give rise to a technoself (Luppicini, 2013).

3. Sociotechnical Systems Theory: Technical artifacts and human behaviors co-evolve, making it impossible to cleanly separate "social" from "technological" domains in modern systems (Trist, 1981).

The framework bridges these domains by providing an integrated structure for observing and analyzing how systems behave under conditions of uncertainty and transformation.

The Five Domains of the Sociotechnical Ecosystem Framework

The lens is built on five essential, indivisible and interdependent domains:

- Artifacts – The physical and digital object, tools, infrastructure, and materials that constitute the physical base of a system.

- Mobility – The capacity for movement and distribution of people, resources, services, information or data across time and space.

- Communication – The formal and informal signaling systems through which networks exchange, coordinate and integrate information.

- Information – The content, knowledge structures, and epistemic conditions that inform value determination, decision-making, and perception.

- Networks – The organizational, relational, and institutional structures that mediate interactions and create boundaries of hierarchy, inclusion and exclusion.

These domains are not siloed indicators; they are overlapping sifts that reveal different facets of system functioning, vulnerability and interdependence, and together establish the tides of emergent resilience, adaptation and innovation of systems.

Application Across Systems

Originally applied to identity formation and recruitment patterns within extremist sociotechnical environments (e.g., the Islamic State's online media and mobilization ecosystem)(Gerard, 2017), the framework has since been translated into a general systems methodology. It enables practitioners to trace how shocks propagate across domains and how systems adapt or collapse as a result.

For example:

- In urban systems (artifacts), the model can assess the resilience of transport infrastructure not just through redundancy of routes (mobility), but how digital signaling (communication), governance hierarchies (networks), and public trust (information) shape adaptive responses during disruption.

- In corporate systems (networks), it can highlight how employee coordination (communication) and supply chain agility (mobility) interact with digital infrastructure (artifacts) and institutional culture (information) to determine business continuity.

- In governance systems (networks), the framework allows analysts to examine how misinformation (information) on social media (artifact) and fragmented institutional trust (communication) undermine adaptive capacity during social upheaval or crisis.

The sociotechnical ecosystem lens thus facilitates multi-domain sensemaking, enabling both diagnostic and generative functions in resilience assessment, where effective redundancy is often represented in multiple different domains.

Advantages Over Indicator-Based Approaches

Most resilience assessments focus on static capacities (e.g., the number of beds in a hospital, or miles of fiber optic cable) or linear performance measures. These approaches are often blind to the emergent and relational nature of adaptive capacity. The sociotechnical ecosystem framework, by contrast:

- Embraces complexity by focusing on inter-domain interactions and adaptive shifts between those domains (for example innovating from traditional banking to online banking by eliminating mobility requirements).
- Supports co-creation by aligning analysis with practitioner knowledge and local context.
- Avoids false precision by resisting reduction to rigid scoring or benchmarking.
- Enables dynamic mapping of how resilience capacities shift over time.

Rather than asking "how resilient is system X," the framework encourages the question: "How do the dynamics across artifacts, mobility, communication, information, and networks produce (or erode) resilience in this context?" revealing dominant vulnerabilities and opportunities for resilient innovation.

DISCUSSION

The sociotechnical ecosystem is not a tool in the traditional sense—it is a lens. It does not prescribe what to see, but provides structure for seeing the complexity that is often missed. It is especially useful in systems where traditional boundaries are dissolving: between digital and physical, public and private, and individual and institution.

Its greatest strength lies in its flexibility and capacity to generate insights across contexts without sacrificing structural rigor. As a method, it invites stakeholders to participate in resilience assessment as active agents, making it not only a diagnostic framework, but a vehicle for system learning and transformation.

The lens does not aim to replace existing structured risk assessment methodologies or frameworks. Rather, it seeks to enhance the researcher's capacity to account for the full range of dynamic agents within a system. By doing so, it helps to identify sources of weakness or fragility, support adaptive thinking, and illuminate the complex interactions that generate emergent resilience, while also highlighting the vulnerabilities that erode system stability.

CONCLUSION

In an age of accelerating disruption and complexity, there is a growing need for resilience assessment methodologies that are both theoretically grounded and practically usable across domains. The sociotechnical ecosystem framework provides a powerful lens through which complex systems can be understood, assessed, and designed for greater adaptability.

Originally conceived as a tool for analyzing sociotechnical identity in conflict environments, it now serves as a general method for evaluating the resilience of any system where technology and human behavior are inseparable. In doing so, it meets the central challenge of

improving and refining resilience assessment methods by moving beyond reductionism and toward situated, transdisciplinary, and complexity-informed ecosystem assessment practices.

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Assessing Regional Drought Resilience: Crossing Sectoral and Federal Borders

Maren Jabs[1] Lara Wöhler[1] Joanne Vinke-de Kruijf[1] Maarten S. Krol[1]
University of Twente
m.jabs@utwente.nl, l.wohler@utwente.nl, joanne.vinke@utwente.nl, m.s.krol@utwente.nl

Abstract

In response to the predicted increase in frequency and intensity of drought events and the resulting threats to agriculture, ecosystem health, and other system components, multidisciplinary strategies are required to build drought resilient socio-ecological-technical systems (SETs). An assessment tool that represents this comprehensive and holistic view is currently missing. To support decision-makers and practitioners through a practice-oriented approach, this research therefore aims to develop an innovative indicator framework for integrated drought resilience assessments at regional level. By covering parameters such as resilience phase or SETs dimension, the assessment results shall inform and activate relevant actors to implement drought resilience measures, that are tailored to the identified weaknesses of their region. To ensure credible, salient, legitimate and feasible design and assessment processes, as well as actionable results, the framework development is based on existing literature, expert interviews and workshops with regional stakeholders. The framework is applied in the transboundary Dutch German context as part of the Interreg DIWA project. Recognising the transboundary nature of this study area as well as numerous global river catchments, this research explicitly accounts for transboundary governance collaborations. By integrating multidisciplinary parameters and emphasising stakeholder co-development, this research presents a resilience assessment method, that assists effective drought resilience actions. It shall therefore support the preparedness for more frequent and intense droughts, while promoting sustainable, collaborative, and adaptable approaches to resilience.

Drought Resilience; Multidisciplinary; Co-development; Resilience assessments; SETS

Introduction

In times of accelerating climate change, weather extremes such as floods and droughts increasingly affect all parts of the world. In Central and Western Europe, however, the risk of drought is often underestimated due to generally ample precipitation (Hänsel et al., 2019). This is especially true for the Netherlands, where adaptation measures have traditionally focused on flood protection (Bartholomeus et al., 2023). The creeping nature of droughts, which complicates the identification of exact timeframes and impacts, has been adding to this bias (Wilhite, Svoboda & Hayes, 2007; Wilhite & Vanyarkho, 2000). As a result, recent events – such as the prolonged drought of 2018-2020 – severely hit a drought-vulnerable country (Bartholomeus et al., 2023).

The often long-term consequences of droughts include effects on water resources, agriculture, and the economy (e.g. Ding, Hayes & Widhal, 2011; Hlavinka et al, 2009; Ross & Lott, 2003), calling for integrated, multidisciplinary action. A guiding concept in the context of climate adaptation is ‘resilience’, understood as a system’s ability to withstand, recover from, and adapt to disturbances (Helfgott, 2018; Walker et al., 2002). Resilience is therefore a dynamic, evolutionary process (Boschma, 2014; Christopherson, Michie & Tyler, 2010; Meerow, Newell & Stults, 2016; Simmie & Martin, 2012), where adaptability and transformability are as crucial as short-term recovery (Boschma, 2014).

Suitable and legitimate strategies for building resilience require an ongoing process of co-discovery, involving scientists, policymakers, and practitioners (Helfgott, 2018; Walker et al., 2002). By emphasising such collaborations, the Interreg project ‘DIWA’ (Drought Strategies in Water Management) responds to the growing threat of drought in the Dutch German border region by fostering transboundary resilinece strategies, reflecting realities common to many catchments worldwide.

While resilience assessment frameworks exist, they mainly address floods, urban systems, or communities (e.g. Sharifi, 2016; Tayyab et al., 2021; Tong, 2021). A comprehensive framework tailored to drought is lacking. Moreover, research on drought resilience neglects practice- and solution-oriented approaches (Hagenlocher et al., 2019), as well as concepts specifically targeting transboundary drought management. Embedded in DIWA, this research contributes an innovative, solution-oriented approach designed to support regional resilience action.

Methodology

Designed to inform practitioners and decision-makers of their region’s status of drought resilience, the framework is developed to warrant the following criteria: credibility, salience, legitimacy, and feasibility. In practice, this means grounding the framework in current scientific knowledge (credibility), ensuring relevance to decision-makers (salience), reflecting diverse stakeholder values (legitimacy), and remain practically applicable (feasibility) (Cash et al., 2003; van Oudenhoven et al., 2018).

To achieve this, the development followed a three-step process (Fig. 1). Starting from the definition of goals and requirements, scientific and grey literature informed an initial, credible framework strucutre. Focus lay here on both existing frameworks and indicators, and on literature on design parameters and processes.

Interviews with experts in systemic drought research, resilience assessments, and stakeholder interaction then added missing perspectives to the project and checked the current version for the four design criteria. The revised framework and assessment procedure were then applied in a number of case-studies in the Dutch German border region. To cover different aspects of SETs, each case-study area included natural, agricultural, commercial and residential areas. Supported by stakeholders, which also represented different disciplines within society (waterboards, farmers, industry, nature conservation, governments), a set of workshops ensured additional validation, particularly for legitimacy, salience and feasibility.

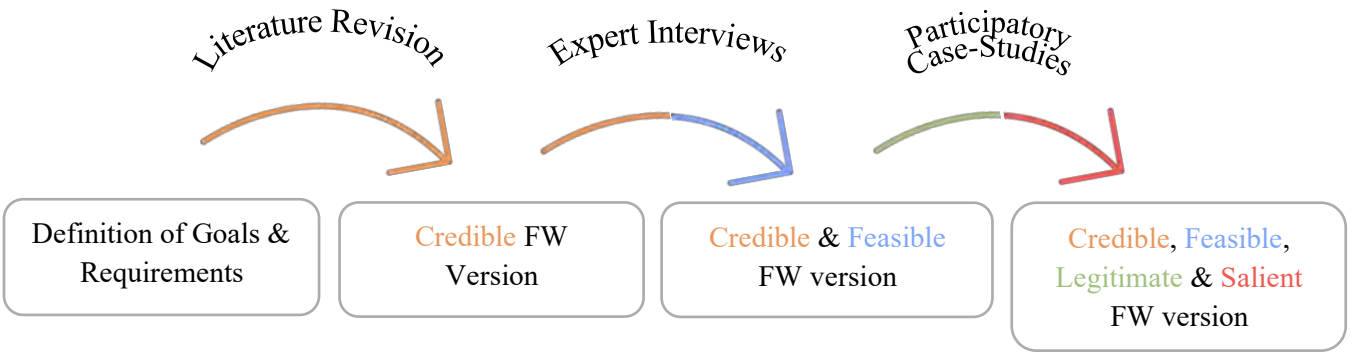


Figure 1: Design process for creating a credible (yellow), salient (red), legitimate (green) and feasible (blue) drought resilience assessment framework (FW).

Results

Throughout the different development stages, all four design qualities – credibility, salience, legitimacy, and feasibility– were addressed, resulting in an indicator-based framework for applications at the NUTS3 level (EU administrative division for statistics). By setting clear boundaries, and allowing for repeatability at different points in time and monitoring of change, these choices make the framework and its' application suitable for an increasing understanding of regional drought resilience.

Indicators are organised in a four-level structure (Fig. 2). Overarching the strucutre, five 'dimensions' (Natural, Infrastructural, Economic, Institutional, Human) capture the multidisciplinary character of social-ecological-technical-systems (SETS). Inspired by the United Nations Convention to Combat Desertification (UNCCD), this supports the credibility of the assessments. Credibility is further supported by selecting only indicators that contribute to a comprehensive resilience understanding, through i.e. different resilience phases. By accounting for data availability in the assessment process, the feasibility of the selection is ensured. To strengthen salient and legitimate results, the framework is designed as a living tool, that is adaptable to regional needs in close collaboration with relevant stakeholders. This flexibility fosters ownership, accounts for transboundary realities, and thereby encourages cross-boundary collaboration. Including a sorting and filtering system (e.g. by sector, assessment level, or topic) further increases salience, legitimacy and feasibility, as well as the usability by practitioners. Textual descriptions of the assessment results are complemented by a four-stage colour-coded visualisation of the results and arrows indicating change since the last assessment. This offers a clear overview of strengths and weaknesses and enabling comparison over time.

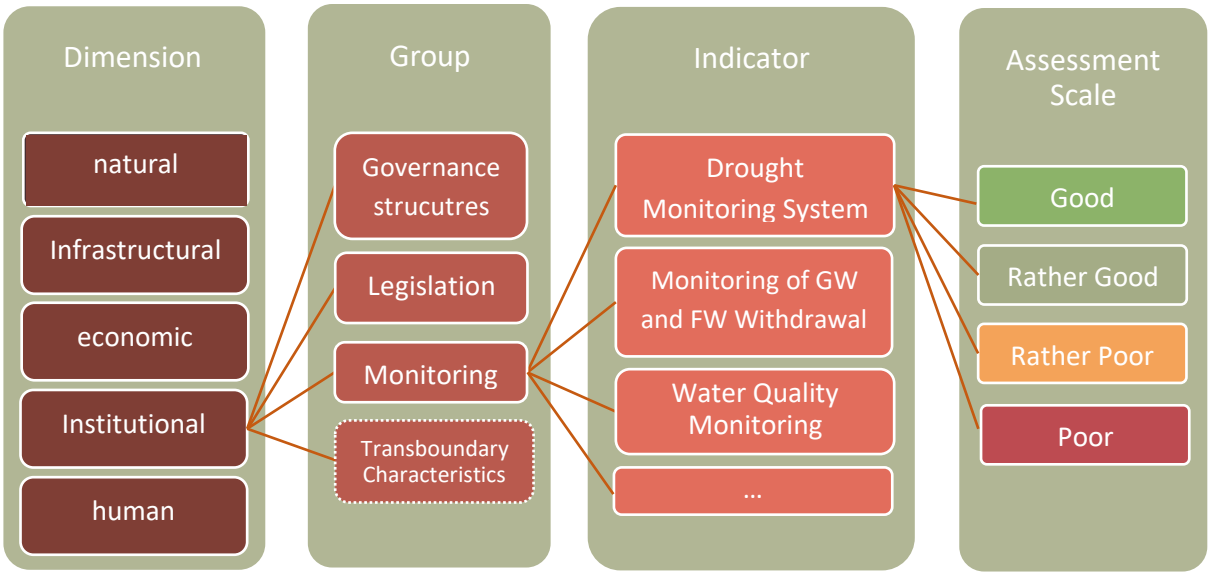


Figure 2: Scheme of Drought Resilience Assessment Framework

The framework has been designed for applications that are not scientifically supervised, but guided by relevant governance parties, such as regional waterboards of municipalities. After being initiated, the application follows a three-step procedure: 1) a stakeholder workshops, in which the framework is adapted to their regional needs; 2) data collection and indicator assessment; 3) a second stakeholder workshop to present results, reflect on the framework's performance and ideally discuss action points to improve drought resilience. For the present study this application procedure was followed for the selected case studies in the Dutch German border region. While we focus on the framework development in the presented results, exemplary outcomes of the framework application, and hence the drought resilience in the case region are showcased as well.

Conclusion

The resulting framework offers a credible, salient, legitimate and feasible tool, that allows stakeholder-driven assessments of drought resilience at the regional scale. By combining a clear structure with adaptable, participatory application, it supports both monitoring and action. Applied in case studies in the Dutch German border region, it has proven to foster ownership, highlight regional vulnerabilities, and encourage collaboration, ultimately contributing to more resilient water management.

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11. Digital Resilience

Optimization under Attack: Resilience, Vulnerability, and the Path to Collapse

Amal Aldawsari[1,2,*], Evangelos Pournaras[1]
1 School of Computer Science, University of Leeds, Leeds, UK
2 College of Computer Science and Engineering, University of Hail, Hail, Saudi Arabia

Abstract

Resilience is a critical property of distributed combinatorial discrete-choice optimization systems operating under adversarial disruptions. This study analyzes how such systems are affected by adversarial agents, focusing on performance degradation and collapse dynamics. Using real-world datasets and simulating over 100 million scenarios, we systematically evaluate how adversarial density and behavioral severity influence system performance and Pareto optimality. The resulting dataset reveals when system remains resilient and when adversarial conditions lead to vulnerability or collapse, informing self-healing and fault-tolerant strategies in socio-technical infrastructures.

Keywords:Distributed optimization; Multi-agent optimization; Adversarial resilience; Vulnerability; System collapse.

Introduction

Distributed optimization plays a central role in modern socio-technical systems such as smart grids, transportation, and participatory sensing, where multiple autonomous agents coordinate decisions without centralized control (Boyd et al., 2011; Yang et al., 2019; Lan et al., 2023). These systems are increasingly deployed in dynamic and large-scale infrastructures, making them highly susceptible to adversarial agents that manipulate information or degrade overall performance (Gupta et al., 2020; Ravi et al., 2019; Sundaram et al., 2018).

Prior research on distributed optimization has focused mainly on continuous decision spaces and cooperative settings, proposing Byzantine-resilient methods (Sundaram et al., 2018; Su et al., 2020) and trust-based strategies (Yemini et al., 2022; Du et al., 2023). However, the resilience of combinatorial discrete-choice multi-agent optimization remains underexplored.

This work addresses this gap by analyzing the resilience of distributed discrete-choice optimization systems under adversarial influence. Using large-scale simulations based on real-world datasets, we investigate how adversarial density and behavioral severity influence system performance. Our findings reveal distinct operational phases where systems transition from resilience to vulnerability and ultimately to collapse, providing insights for designing adaptive and fault-tolerant strategies.

Methodology

Resilience in distributed optimization is essential for maintaining system performance under adversarial conditions, where adversarial agents can disrupt operations, degrade efficiency, and increase vulnerability. We study how adversarial density and behavioral severity influence

system transitions between resilience, vulnerability, and collapse. To capture these dynamics, we propose a generic adversarial distributed optimization model tailored to discrete-choice scenarios. Each agent selects one plan from a finite set of alternatives, balancing personal discomfort against system-wide inefficiency. Agents are divided into legitimate, who align with collective goals, and adversarial, who prioritize personal benefit. By systematically varying the proportion and severity of adversarial agents, the model spans behaviors from fully cooperative to fully selfish.

The proposed adversarial model is implemented within the I-EPOS (Iterative Economic Planning and Optimized Selections) framework (Pournaras et al., 2024), a scalable distributed optimization algorithm extended here to support heterogeneous agent behaviors. We evaluate three real-world domains, energy demand coordination (1000 agents), data-sharing privacy (72 agents), and voting systems (266 agents), through more than 100 million simulated scenarios across 30 levels of adversarial severity and varying adversarial densities. System performance is assessed using three key metrics: (i) inefficiency cost, the deviation of the global outcome from optimal performance; (ii) discomfort cost, the deviation from agents' preferred plans; and (iii) compromise cost, the additional discomfort imposed on legitimate agents. We further analyze Pareto optimality to identify trade-offs between discomfort and inefficiency, and apply a multi-Otsu thresholding method to classify operational states into resilience, vulnerability, and collapse.

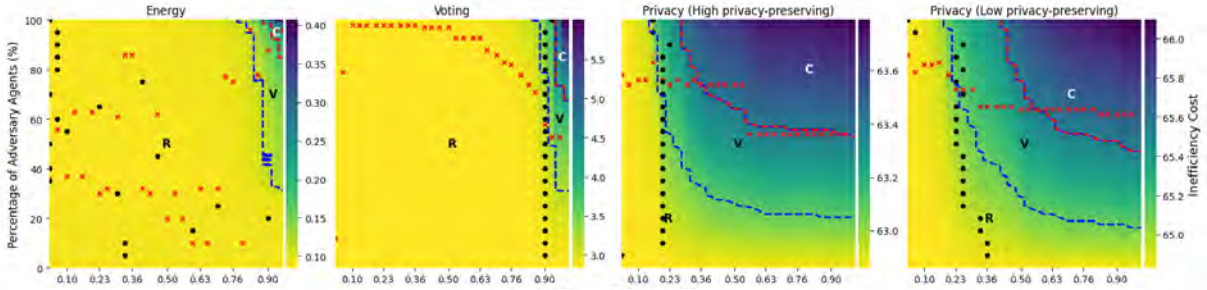
Results and Discussion

Figure 1 illustrates inefficiency, discomfort, and compromised discomfort under varying adversarial scales and severities, showing thresholds for resilience, vulnerability, and collapse, with Pareto knees. In Figure 1(a), inefficiency remains low up to 30–50% adversaries and $\beta < 0.7$; beyond this, energy and voting remain about 90% resilient, while privacy collapses earlier at 20–30% adversarial density. Figure 1(b) shows discomfort declining as adversarial influence grows: energy and voting drop sharply only near collapse, while privacy deteriorates earlier ($\beta > 0.3$, > 60% adversaries). Figure 1(c) highlights that legitimate agents' compromise costs remain low under mild attacks but rise steeply at high adversarial densities, especially in privacy datasets (>80–90%).

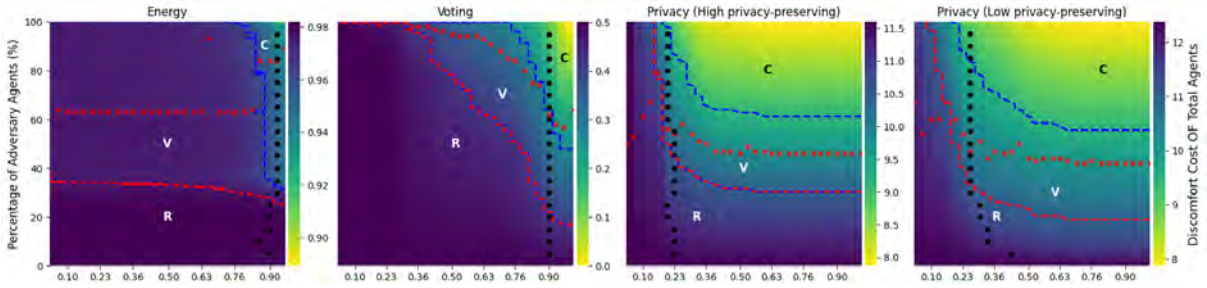
Across all domains, a resilience lag emerges: inefficiency appears stable while discomfort and compromise already signal vulnerability, making agent-level metrics early-warning indicators of collapse. Overall, resilience depends on both adversarial scale and severity, varying by scenario. While systems often remain resilient under high adversarial influence, this comes at the expense of legitimate agents bearing growing discomfort. Most Pareto-optimal trade-offs lie within the resilience region, though extreme scales extend into vulnerability and collapse.

Conclusion

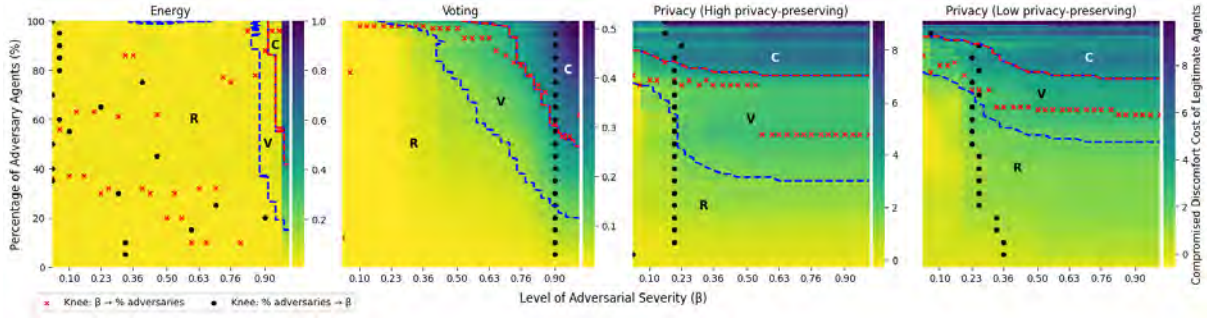
This study analyzed resilience, vulnerability, and collapse in distributed optimization under adversarial conditions, identifying thresholds where systems transition from stability to failure. A key contribution is a benchmark dataset from over 100 million experiments, enabling reproducible research. While the current evaluation focuses on static adversarial severity and hierarchical structures, future work will explore dynamic adversarial strategies, alternative topologies, and adaptive mitigation mechanisms to further strengthen system robustness.



(a). Inefficiency costs



(b). Discomfort costs



(c). Compromised discomfort costs for legitimate agents

Figure 1. Inefficiency, discomfort, and compromised discomfort across adversary scales and severities in energy, voting, and privacy datasets, with Pareto knees and resilience (R), vulnerability (V), and collapse (C) thresholds.

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Quantum Information and Communications Technologies Ecosystems as Drivers of Digital Resilience: Case Study of the Netherlands

Shamira Ahmed, TU Delft, s.ahmed-1@tudelft.nl

Abstract

Advances in Quantum Information and Communication Technology (QICT), including the Quantum Internet, Post-Quantum Cryptography (PQC), Quantum Computing, and Quantum Key Distribution (QKD), to name a few, are redefining the conditions of digital resilience by transforming both global technical and governance standards for information communication technologies (ICT). Advancements in QICT promise not only to secure systems enabled by ICT against quantum-enabled threats but also to enable reconfigurable, adaptive, and critical infrastructures and public services, in the Netherlands.

This paper explores how Dutch innovation ecosystems, anchored by national programs, drive digital resilience through the deployment of QICT. Using a scoping review and strategic case analysis, the study highlights how collaborative infrastructure, ethical governance, and adaptive strategies underpin secure transformation across public and private sectors.

The objective of the study is to enrich digital resilience literature by examining if and how QICT and overall digital transformation empower innovation ecosystems not just for technological advancement and economic competitiveness but for participatory, justice-oriented, and environmentally sustainable change, in the digital age.

Keywords: Quantum Information and Communication Technologies; Digital Resilience; Innovation Ecosystems.

Introduction

Advances in Quantum Information and Communication Technology (QICT), including the Quantum Internet, Post-Quantum Cryptography (PQC), Quantum Computing, and Quantum Key Distribution (QKD are fundamentally reshaping the conditions for the digital economy and society worldwide and particularly in the Netherlands (OECD, 2025; NAQT, 2019).

Digital resilience within the context of QICT can be understood as the capacity of systems, organizations, and societies to anticipate, withstand, and adapt to threats and disruptions arising from quantum-enabled advancements, namely quantum computing's capacity to break current cryptographic defenses and quantum communication's impact on secure information channels (Ramya et al., 2025). It not only means technical ability to defend against and recover from cyberattacks, but also proactive preparation and migration to quantum-resistant technologies (such as post-quantum cryptography), agile governance, and continual innovation in digital security architectures (WEF, 2025; Van den Broek et al., 2024; ITU, 2024).

Furthermore , the Dutch Quantum Innovation Ecosystem (QDNL) aims to safeguard critical infrastructure, advance strategic sectors, and create sustainable societal impact (NAQT, 2019). Central to Dutch vision is fostering digital resilience anticipating and responding to quantum-

enabled cyber threats, operational disruptions, and the ethical implications of emerging technologies (QDNL, 2019).

Traditional firm-level studies of digital resilience and transformation often focus exclusively on organizational assets, risk management, and cyber defense (Liao et al., 2024) or a specific ecosystem (Codara and Sgobbi, 2023). By contrast, adopting an innovation ecosystem lens reveals broader, interconnected dynamics: multiple public, private, and academic actors co-create infrastructure, standards, and policy, collectively enabling transformative adaptation, knowledge exchange, and resilience to server the public interests (Stahl, 2021; Granstrand & Holgersson, 2020).

While there is emerging literature on frameworks that support digital ecosystems and socio-technical-ecological (STE) trajectories (Florek-Paszkowsk & Ujwary-Gil, 2025;Gorelova et al., 2025). Digital resilience scholarship has yet to fully theorise how QICT fits within STE pathways. This paper attempts to address the aforementioned gap by analysing Dutch QICT initiatives that focus on enhancing digital resilience in the public sector, the research focuses on the dynamic mechanisms and synergies that connect digital transformation with sustainable innovation ecosystems.

In addition, while most emerging literature highlights that digitally resilient systems emerge from well-integrated ICT infrastructure and transformational capacities, shaped by human, organizational, and institutional factors (Codara and Sgobbi, 2023; Liao et al., 2024), an innovation ecosystem lens on emerging digital technologies (EDT), such as QICT will facilitate exploration of systemic adaptation beyond fragmented, firm-level strategies. Adopting an innovation ecosystem lens, enhances the study by revealing how actors, enablers, endowments, and capabilities collaborate to develop, adapt, and deploy QICT to enable digital resilience (Stahl, 2021; Granstrand & Holgersson, 2020).

While firm-level research focuses narrowly on individual organizational capabilities, assets, and risk management strategies, often optimizing internal digital resilience through technology adoption and cyber defense; the ecosystem approach captures systemic, multi-actor dynamics across public, private, and academic sectors (Liao et al., 2024). It investigates how networks of organizations interact, share resources, co-develop standards, and influence policy, thus enabling collective adaptation and transformative change (Stahl, 2021; Granstrand & Holgersson, 2020

Research Design/Methodology

The research adopts a data-driven mixed methods approach combining systematic literature review and qualitative case studies. The following methods will be explored:

Literature Review: Peer-reviewed articles, sectoral reports, and policy documents will be systematically identified, screened, and synthesized based on explicit criteria for relevance to QICT, digital resilience, and Dutch innovation ecosystem.

Case Study Selection: Three key Dutch initiatives will be analysed :

(i) PQC migration in public administration,
(ii) Implementation of QKD for city and port infrastructure, and
(iii) Metropolitan-scale quantum network rollouts (Van den Broek et al., 2024)

Data Collection:

(i) Semi-structured interviews with municipal IT managers, national policymakers, and QICT researchers.
(ii) Impact tracing across municipal-university partnerships and national innovation platforms.

Contribution

This study contributes to both resilience theory and innovation ecosystem literature in three ways:

(i) **Conceptual enrichment:** It advances digital resilience beyond technical robustness by embedding QICT within **STE trajectories**

(ii) **Empirical evidence:** Dutch QICT case studies can demonstrate if and how collaborative governance can enhance human-centered ethical and societal values in innovation ecosystems.

(iii) **Policy relevance:** Findings provide actionable insights for national and municipal policymakers on the importance of ensuring resilience strategies are socially embedded with existing ICT enabled ecosystems.

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Resilient Emergency Response in Human-AI Teams: A Systematic Review of Information Prioritization Strategies and Metrics

Isabel Florence Franke[1], C. Natalie van der Wal[1], Tina Comes[1]
1 Faculty of Technology, Policy and Management, TU Delft, Delft, The Netherlands,
i.f.franke@tudelft.nl, C.N.vanderWal@tudelft.nl, T.Comes@tudelft.nl

Abstract

Crowd crises demand rapid, high-stakes decisions under uncertainty, where the right information can mean the difference between escalation and resolution. Traditional information streams have undergone significant changes since the introduction of Artificial Intelligence (AI) as a tool for sensemaking and decision support. Yet, it remains unclear exactly *how* AI implementation affects information prioritization in heterogeneous, high-pressure teams. Information Value Theory (IVT; Howard, 1966) established the Value of Information (VoI) as a means to assess whether the benefit of reduced decision uncertainty justifies the cost of acquiring additional information. In emergency response, VoI cannot be reduced to the oftentimes static and monetized formulations. As a first step to dynamically decide what information matters most, for whom, and when, we performed a systematic literature review to investigate how information prioritization strategies and information metrics have been used across Multi-Actor Systems (MAS) including humans, artificial agents, and human-AI collaborations. This work offers a foundation for future empirical validation and system design to enhance digital resilience in emergency response Human-AI Teams (HATs) operating under uncertainty, time pressure, and high stakes.

Keywords: Human-AI Teams; Emergency Response; Value of Information; Information Prioritization; Digital Resilience

Introduction

While often peaceful, crowd gatherings can quickly escalate into crises. For example, high densities of people can result in catastrophic crowd crushes, as tragically demonstrated during the Love Parade (2010), Astroworld festival (2021), and the Halloween Crowd Crush in Seoul (2022). These events illustrate how small disruptions in dense environments can cascade into emergencies. Simple technical solutions, however, cease to be applicable in complex socio-technical systems, in which humans and technologies are highly interconnected and information circulates across multiple actors and institutions (Comes, 2024). Where decision-makers must respond under time pressure, uncertainty, and high stakes, *cognitive and moral overload* (Ishmaev et al., 2021; Jarke-Neuert & Lohse, 2022) may amplify the use of heuristics and biased reasoning (Alison et al., 2013; Chandler & Sweller, 1991; Tversky & Kahneman, 1981).

AI has the potential to expand human capabilities by integrating real-time information to monitor, analyze and predict threats such as critical densities and evacuation bottlenecks (e.g.,

Haghani et al., 2023). Yet, novel risks like automation biases, altered team dynamics, and overreliance on AI

recommendations, can reduce decision-making effectiveness (Carter & Wynne, 2024). In addition, strong interdependencies between different crowd management actors—involving police forces, firefighters, medical services, event organizers, municipal authorities, and progressively artificial agents—can lead to role insecurities and a lack of communication. One way to support the formation of resilient Human-AI collaborations for emergency response begins at analyzing how the acquisition, analysis, and distribution of information is used to make sense of evolving situations. Robust theoretical foundations are needed to optimize the system's design for sending relevant information, to the right actor, at the right time.

We argue that the Value of Information (VoI) can provide such a foundation. Originating in decision theory, Information Value Theory (IVT; Howard, 1966) provides a means to measure whether additional information meaningfully reduces uncertainty relative to its cost (Howard, 1966; Raiffa & Schlaifer, 1961). Traditionally, this has been operationalized through cost-benefit assessments, with the assumption that perfect information is available. In contrast, crisis information is incomplete, ambiguous, and delayed. Its utility is only realized once decisions unfold. Despite the wide range of fields and applications that have examined information value and priority in Multi-Actor Systems (MAS) (e.g., Mutlag et al., 2020; Sarne & Grosz, 2013; Wong-Parodi & Small, 2021), there is still limited understanding of how the various theories and concepts relate to each other to guide information prioritization in crowd management. Conventional VoI approaches often fail to capture the actor- and context-sensitive prioritizations that reflect distinct goals, values, and organizational hierarchies within such systems. To address this gap, we propose an adaptive conceptualization of VoI that supports actors in re-prioritizing relevant information across shifting operational phases.

Contribution

We contribute a systematic literature review comparing information prioritization strategies and metrics used in Multi-Actor Systems (MAS) to uncover the core mechanisms and factors shaping time-critical information sharing facilitated by AI. We adopted a broad focus, spanning mathematics, AI, medicine, environmental-, social-, computer-, and decision sciences, among others. This transdisciplinary approach is suited and necessary to tailor adaptive prioritization strategies to the needs of emergency response Human-AI Teams (HATs). The findings stress the importance of training simulations for testing AI-supported real-time information prioritization and debriefing units. The identification of systemic vulnerabilities thereby supports the development of a framework that buffers against cognitive and moral overload. This work offers a foundation to translate information value qualities into a resilient AI-based information-support system enabling effective interventions for and the prevention of evolving emergencies.

Method and Analytical Strategy

The review follows the PRISMA protocol (Page et al., 2021) to explore how information prioritization is formalized and operationalized in MAS. Figure 1 depicts the initial literature subset, screening criteria and process flow.

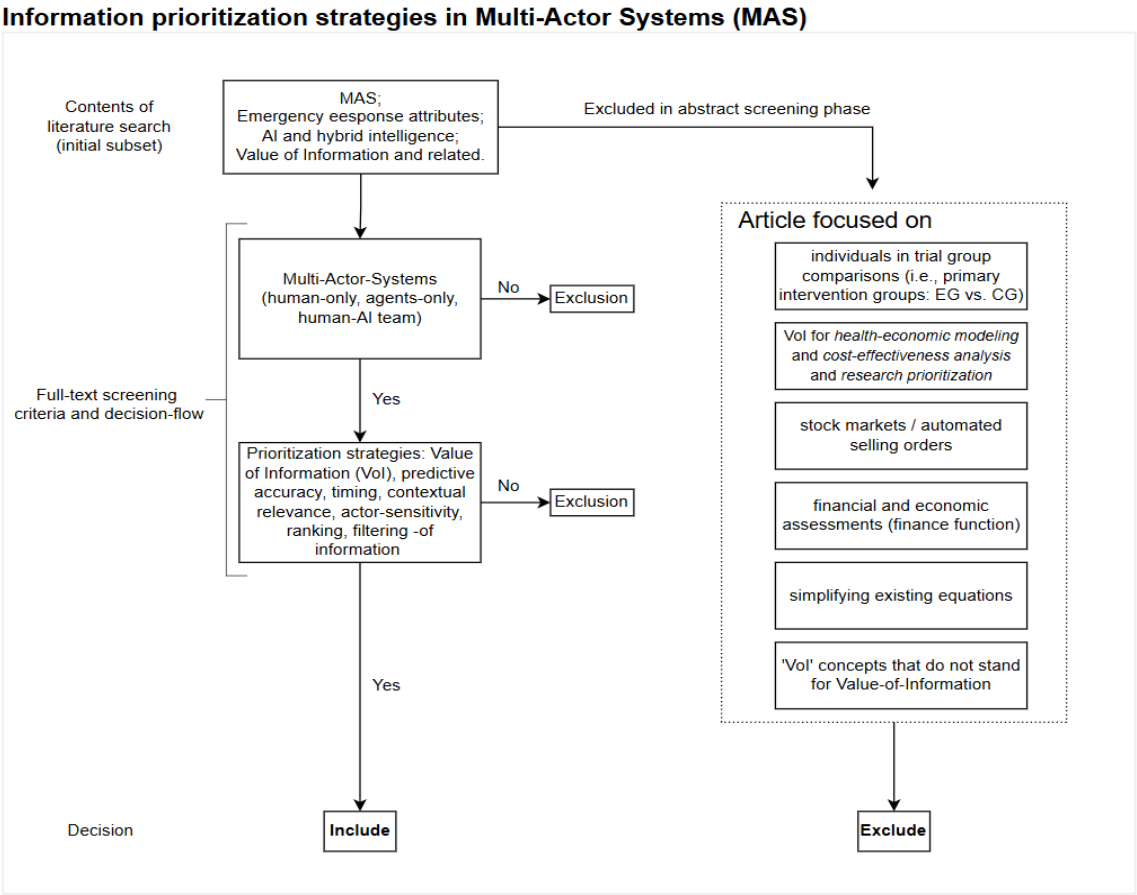


Figure 1. Eligibility Criteria and Process Flow

The included studies are analyzed using a mixed-methods approach. First, a descriptive layer outlines the strategies and metrics used to prioritize information within MAS. We categorize MAS into Human-AI, Human-only, or AI-only and examine addressed emergency response attributes (e.g., timeliness, uncertainty, high-stakes). Second, a thematic layer supports the interpretation of findings through the lens of resilience thinking (Bhamra et al., 2011; Caldwell, 2014; Weng et al., 2023) and applies them to emergency response:

- **who** prioritizes (human, AI, hybrid),
- **what** is prioritized (alerts, contextual data, meta-information),
- **how** is prioritization operationalized (information metrics),
- and **why** (reduce information overload and delay).

Lastly, we identify how MAS dynamics can influence information prioritization (e.g., distributed knowledge, value misalignments) and discuss how challenges addressed by these systems —such

as cognitive overload, value misalignment, and delayed responses—connect to and address the needs of emergency response HATs.

The outcomes of the review will be presented at the conference, where key dimensions of information value are used to illustrate gaps across MAS domains (e.g., shifting priorities, non-linear information flows).

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REC: Resilient Edge Computing in Emergency Scenarios

Markus Sommer[1], Philipp Jahn[1], Leon Wimbes[1], Artur Sterz[2], Bernd Freisleben[1]
1 Philipps-Universität Marburg, {msommer, jahnph, wimbes, freisleb}@informatik.uni-marburg.de

2 tRackIT Systems GmbH, sterz@trackit.systems

Abstract

This paper introduces REC, a novel resilient edge computing platform for emergency scenarios where cloud infrastructure may be unreliable. REC combines serverless computing with resilience and locality, enabling diverse parties to join their resources into a distributed network for crisis recovery. It uses WebAssembly for platform-agnostic code execution and a distributed key-value store for data persistence. REC has multiple node types (brokers, executors, datastores, clients) that orchestrate job execution and data management. Key features include self-healing, job parallelization, and flexible node discovery.

Keywords: resilient edge computing; serverless computing; WebAssembly

Introduction

Due to global instability caused by natural disasters and conflicts, we need new, distributed, and resilient computing solutions. Centralized computing, which consolidates resources efficiently, is susceptible to single-point-of-failure vulnerabilities. In contrast, resilient distributed systems disperse resources and maintain operational continuity even when components fail. *Serverless computing* and *Function-as-a-Service* (*FaaS*), which provide abstractions to server administration and software deployment, are popular examples.

Major service providers like *Amazon AWS* and *Google Compute Cloud* offer these services at competitive costs using extensive datacenter networks. This approach provides macro-level redundancy (e.g., deployment options in North America, Europe, Asia) but does not address local resilience issues. In scenarios where local communication infrastructure fails (e.g., major emergencies like floods, earthquakes, or wildfires), these services often become inaccessible, forcing affected populations to rely on local resources until external communication options are restored. In this regard, there are several proposals to develop resilient *FaaS* implementations (Baresi & Filgueira Mendonca 2019; Ristov et al. 2022).

To address this issue, we propose *REC*, a novel and resilient edge computing platform that adapts serverless computing to local mesh networks. REC provides an abstraction layer for rapid code deployment and data storage, similar to traditional *FaaS* offerings. *REC* is a distributed infrastructure with nodes spread throughout the network, maintaining operational continuity in the event of node failures or network partitioning.

REC operates without a central controlling entity, allowing various parties to manage cooperative nodes that efficiently share computing resources with the population affected by the crisis. Users can dispatch computational jobs to the network without knowing the underlying network topology. The system manages data storage and retrieval, automatically providing necessary data to jobs and storing job outputs for future use.

Design

In an emergency, the local network hosting *REC* may be unstable, since various emergencies may damage the network backbone. Nodes may join or leave the network due to device mobility or limited backup power. Therefore, *REC* must handle changing network topologies.

Nodes. *REC* has four distinct node types, each with unique network abilities. Multiple instances of each node type can be hosted in the network. Figure 1 illustrates a typical city network with *REC*. *REC* aggregates and shares computing resources among various parties, including institutions with access to "big iron" hardware and individuals contributing personal hardware.

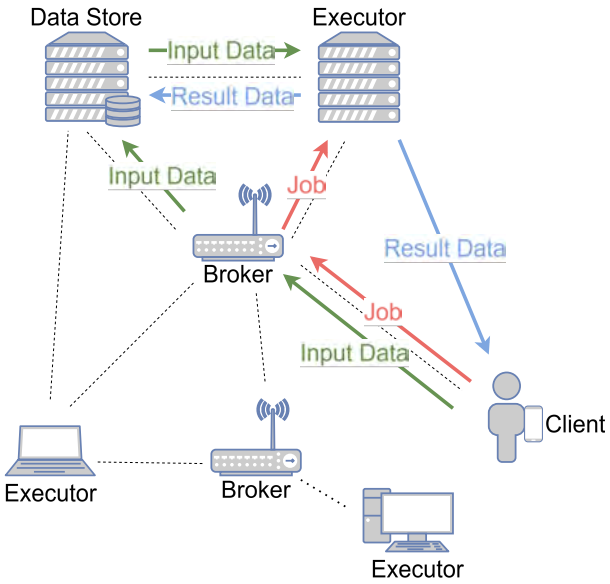


Figure 1. The architecture of REC

Broker nodes manage other nodes and connect them. Multiple brokers should be active to prevent catastrophic disruptions from single node failures. Each broker can have multiple connected datastores and forward, store, and retrieve requests for other nodes. Brokers also manage executors and select executors for submitted jobs. Brokers are placed on highly connected nodes, such as local network backbone machines or interconnected mesh routers.

Executor nodes execute WebAssembly code and are managed by one broker. When a job is submitted, relevant data is pulled from datastores, the job is executed, and the result is sent to a datastore and client. Participants with powerful hardware should consider running executor

nodes. Possible operators include local institutions with large servers or individuals with powerful hardware.

Datastore nodes store data required for job execution and results. Job results can be used as input for another job, enabling pipelining. Participants with large storage should consider running datastore nodes. Possible operators include institutions with local data centers or individuals willing to share capacity on their home NAS.

Client nodes, running on user's hardware, interact with REC. They allow users to submit jobs and retrieve results.

Jobs. To ensure platform-/architecture-agnosticism while optimizing computing resources, we use WebAssembly. WebAssembly programs can be written in various high-level languages and compiled to WebAssembly bytecode, which is executed by a WebAssembly runtime. WebAssembly is supported by major web browsers with their own WebAssembly runtimes, as well as many standalone runtimes written in various languages with different feature sets.

Data. We designed REC based on *named data networking* (Zhang et al. 2014). This led to the addition of the datastore node type, which provides data persistence within the network. Data is organized in a distributed key-value store, with each piece of data having a unique hierarchical name. Each key can have multiple subkeys. Queuing a key returns its content and all its subkeys. Jobs can specify an arbitrary list of keys as arguments. *REC* retrieves the data for the specified names and provides it to the job for execution. The job creator does not need to know the data's location; *REC* handles discovery and transmission. The result of a job is stored as a key-value pair in the network.

Node discovery. Finding peers for *REC* is a challenge during setup, since a new node does not know the locations or addresses of other nodes. To form a network and allow new nodes to join, we implemented a resilient peer discovery protocol. When a new node enters the LAN, it checks if at least one broker is present. If so, it can connect as an executor or a datastore. To increase resilience, a node might also start a broker to avoid a single-point-of-failure, even after network partitions.

Implementation

Our proof-of-concept implementation is written in *Python*. Since *wasmtime*[1], the most mature WebAssembly runtime, runs only on x86-64 machines, our implementation is currently limited to this architecture. Our code is published under a permissive open-source license[2].

Experimental Evaluation

To evaluate REC, we used a machine learning-based audio classification algorithm trained to recognize over 70 urban sounds. This workload approximates a useful task in an urban

[1] https://wasmtime.dev/
[2] Link to be inserted after the end of review process

emergency scenario. Recognizing urban sound profiles can help first responders. For example, the algorithm can differentiate between human speech, laughing, and screaming, so a location with many screaming voices may warrant investigation. The algorithm requires frequency-domain values, which are obtained from a preparation job that transforms compressed audio to frequency values. These are then passed to the audio classification program.

Our experimental evaluation shows that while REC introduces some performance overhead compared to native execution, it compensates this by enabling parallel processing. This capability can yield significant speedups in computational tasks, which is particularly beneficial in resource-constrained emergency scenarios.

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12. Digital Foundations Of Resilient Built Environments

Digital Twins in Flood Resilience: Potential, Challenges and Reliability for Urban Applications

Erica Arango, Maria Nogal and Ranjith K. Soman
Department of Materials, Mechanics, Management, and Design, Delft University of Technology, Delft, 2629, The Netherlands

Abstract

Cities are facing an increase in natural disaster, aggravated by climate change, causing severe damage to critical infrastructures. Digital Twins (DTs), emerged as promising tools to enhance resilience by enabling disaster management and policy support. This work examines the role of DTs in strengthening urban flood resilience, drawing on insights from the Resilience HydroTwin Project, which develops city-scale behavioral DTs in The Netherlands and India. Potential benefits include improved situational awareness during and prior disaster, scenario testing, operational optimization, and enhanced stakeholder engagement. However, significant challenges remain for their reliable adoption, emphasizing the need for interdisciplinary collaboration, transparent governance, and long-term commitment from the developers and stakeholders to ensure their implementation.

Keywords: Digital Twins; Urban Flood Resilience; Critical Infrastructures; Data Integration; Socio-Technical Systems.

Introduction

Societies are facing increasing uncertainty, as natural hazards, pandemics, and military conflicts can disrupt them at any moment. When it comes to natural hazards, climate change are increasingly aggravated them, introducing new and complex challenges. For example, in 2021 historic flash floods devastated parts of Western Europe, causing dozens of fatalities (Endendijk et al. 2023). Critical infrastructure, which provide essential services to society, are particularly vulnerable to such impacts. Ensuring their resilience, and enhance system capabilities against future incidents, is therefore a crucial task in mitigating the consequences of disasters.

Addressing these uncertainties requires innovative methods capable of identifying, predicting, and analyzing potential impacts, supporting crisis management, and formulating effective adaptation. Among the emerging approaches, Digital Twins (DTs) stand out as particularly promising. “DTs, defined as virtual replicas of physical systems such as cities and their critical infrastructures, enable the simulation of system behavior to enhance understanding and support management (Brucherseifer et al., 2021). In the context of urban flood resilience, DTs can provide right-time feedback for situational awareness, enable rapid forecasting, and support both planning and operations (Gebhard et al., 2025), thereby strengthening the resilience of critical infrastructures.

DTs have been applied in industries such as construction, manufacturing (e.g., Sacks et al., 2020, Soman et al., 2025), and energy (e.g., Yu et al., 2022), their use for enhancing the resilience of cities and critical infrastructures is still recent, and their limitations remain

insufficiently explored. This paper examines the potential of DTs in the context of urban flood resilience, framed through the Resilient Hydrotwin Project, which is developing a comprehensive behavioral digital twin at city-scale, integrating multiple system models to provide insights for disaster response and planning. We discuss how the DT concept can be applied to interconnected infrastructures in Chennai (India) and Rotterdam (Netherlands) and discuss the main challenges of implementation, including data scarcity, computational demands, and cross-sectoral integration, while also accounting for human behavior and governance to support a more holistic perspective on urban resilience.

Potential of a behavioral DT for Rotterdam and Chennai

The Resilience Hydrotwin project aims to develop a virtual abstraction of real-world urban systems by integrating behavioral, hydrological, transportation, water resource management, and governance frameworks into a comprehensive city-scale platform that provides right-time insights for disaster response and planning. This integration enables both project locations, Rotterdam and Chennai, serve as living labs to assess the feasibility of operational DTs to assess flood hazards under sea-level rise and extreme rainfall, while both serve as a platform for engaging local stakeholders through visualization and scenario-based workshops.

Potential benefits emerging from these applications include:

- Improved situational awareness. Analysis of sensor data and visualization tools enable faster and more informed decision-making in both the preparedness and response phases of flood events (Gebhard et al., 2025).
- Scenario testing and planning. The project explores structural and non-structural interventions under climate and land-use change scenarios, supporting urban planning and investment prioritization. DTs support rapid decision-making and facilitate “what-if” scenario exploration for resilience planning, emergency response, and early warning applications.
- Behavioral integration. The role of people and social systems in digital twins remains poorly explored (Nochta et al., 2021). To address this gap, the project built a Behavioral DT models to consider human actors and their interactions with technical systems during flood events, supporting both emergency response and recovery, and enabling the evaluation of soft adaptation measures for more comprehensive resilience planning.
- Operational optimization. In Chennai, high-resolution rainfall and hydrological data are coupled with hydraulic models to enable anticipatory flood responses, allowing real-time control of reservoirs and pumps to reduce flood extents, lower operational costs, and enhance system robustness.
- Stakeholder engagement. Immersive visualization environments allow decision-makers and communities to interact with scenarios, fostering participatory resilience planning.

Challenges, Limitations, and Technical Requirements

The project face several challenges and requirements for the effective deployment of urban flood-oriented DTs:

i. Technical requirements. Data ownership and sharing frameworks pose challenges when multiple organizations are involved in the DT. It also requires significant computational resources (cloud/HPC), while building a simulation platform demands sophisticated software to manage communication between subsystems. Licensing restrictions and missing interfaces can be avoid using open access software (Gebhard et al., 2025).
ii. Systems integration challenges. Harmonizing heterogeneous data sources and governance actors are critical factor for the DT creation. Integrating hydraulic and traffic models introduces further challenges such as spatial and temporal mismatches, and (3) data conversion issues (Rajeev, 2025).
iii. Operational and governance limitations. The value of DTs depends on their alignment with user workflows. In this case, the project emphasizes stakeholder co-design and participatory workshops to ensure outputs meet decision-makers' needs, which add level of complexity. On the other hand, sustaining DT platforms requires interdisciplinary expertise (hydrology, GIS, data science, governance), ongoing calibration, and adequate institutional support.
iv. Uncertainty and model limitations. Predictive uncertainty remains an inherent constraint, stemming from hydrological/hydraulic models and meteorological forecasts. The fidelity of DTs, ensuring that the virtual twin reflects and reliably predicts the real system, remains a research frontier.
v. Complexity of urban systems. Cities are adaptive socio-technical environments with non-linear interactions and emergent behaviors. Addressing this requires complexity-science approaches that integrate data-driven, scenario-based, and socio-environmental dimensions (Caldarelli et al., 2023). Part of this is addressed through the integration of behavioral DT, but since city dynamics are constantly evolving, capturing their full complexity remains a challenge.

To what extent can cities rely on DTs?

To use DTs as decision-support tools for urban flooding, certain conditions must be met: (1) adequate spatial and sensor data are available or supplemented by additional inputs; (2) stakeholders are engaged in co-designing use cases; and (3) sufficient resources are dedicated to validation, data pipelines, and maintenance. Validation is essential yet challenging, as it depends on the intended use and clearly defined requirements. Evidence from the Rotterdam case highlights that progress requires both technical and social advances. On the technical side, robust workflows such as real-time raster-to-network translation, empirically calibrated depth–speed curves, and automated data exchange pipelines are key to operational readiness (Rajeev, 2025). On the social side, addressing cognitive gaps, fragmented governance structures, and interpersonal dynamics is equally critical, as DTs alone cannot bridge disciplinary silos or build trust among actors (Yaren, 2025). Thus, rather than validating the DT as a whole, confidence can be built incrementally through subsystem functions (e.g., data acquisition, simulation, decision support), provided these are embedded within institutional and collaborative frameworks that support their effective use.

Conclusions

Digital Twins hold great potential to support urban flood resilience by integrating diverse data sources, simulating complex interactions, and proving participatory decision-making. While technical, methodological, and governance challenges remain, these can be addressed through careful planning, iterative validation, and focused attention on socio-technical interactions. DTs can complement traditional forecasting and emergency protocols, providing valuable insights for decision-making. Sustained investment in data infrastructure, interdisciplinary expertise, and stakeholder engagement will enable DTs to realize their full potential as effective tools for crisis preparedness and urban resilience.

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Simulation-Informed Learning for Surrogate Models of Infrastructure Resilience

Hamed Hafeznia[1,2] and Bryan T. Adey[1,2]

[1] Institute of Construction and Infrastructure Management, ETH Zurich, Switzerland
[2] Future Cities Laboratory Global, Singapore-ETH Centre, Singapore
hamed.hafeznia@sec.ethz.ch
adey@ibi.baug.ethz.ch

Abstract

Enhancing the resilience of critical infrastructure systems is crucial to mitigate the socioeconomic costs of climate change. Resilience assessment requires carrying out many stress tests, which are computationally intensive. To address this challenge, this research study utilized ML-based surrogate models to predict the performance of transport infrastructure during flood events. To generate training datasets for the surrogate models, a stress test framework was employed to assess the resilience of a transport infrastructure case study in Switzerland. The simulation datasets include 27 variables involved in the stress testing. After analysing the correlation of both the raw and log-transformed datasets, four target variables were selected: restoration time, direct costs, indirect costs, and total length of inundated roads. Therefore, four individual XGBoost models were trained. The results showed that the developed surrogate models have high predictive performance. Increasing the number of training samples can help surrogate models identify more patterns in simulation datasets and improve their generalization.

Keywords: Surrogate model; infrastructure; Stress test; Resilience; Machine learning

Introduction

Critical infrastructure systems are increasingly susceptible to hazards related to climate change (Hafeznia & Stojadinović, 2023; Younesi et al., 2020). Enhancing the resilience of infrastructure systems, such as transportation, energy, and water, is essential to mitigate the negative impacts of extreme hydroclimatic events (Ahmadi et al., 2021; Kong et al., 2021). Stress testing is one of the methodologies used to assess the resilience of transport infrastructure against potential disruptive events (Adey et al., 2024). Stress tests are designed to simulate the impacts of hazards on infrastructure assets and evaluate the overall performance of the transport infrastructure during disruptions. The complexity of hazard models and the existence of many assets within transportation networks require performing a considerable number of computationally intensive simulations (Nasrazadani et al., 2025). Considering the importance of resilience enhancement for transport infrastructure in the face of climate change,

exploring numerous stress scenarios is inevitable. Developing surrogate models for complex infrastructure networks can be an effective solution to the computational challenges. This research study aims to develop a comprehensive Machine Learning (ML) pipeline to utilize the simulation results for creating surrogate models of transport infrastructure.

Resilience stress test framework

To create surrogate models for assessing the resilience of the transport infrastructure to hydroclimatic hazards, a simulation-based stress test framework developed by Hackl et al., (2018) was employed to generate the required data for the learning process of the surrogate models. For this paper, the stress test framework was utilised to evaluate the resilience of transport infrastructure in Chur, Switzerland, for 1247 flood scenarios with a 10-year return period.

Regression model training with XGBoost

The role of surrogate models in this study is to predict target outcomes based on input features derived from the simulation results. This study's learning task involves a regression problem. To this end, XGBoost was employed as a regression-based machine learning algorithm to predict target values such as cost and restoration time for transport infrastructure affected by floods. A comprehensive XGBoost pipeline was designed in Python for structured data and enhanced with data preprocessing, correlation analysis, feature engineering, automated overfitting detection, SHAP (SHapley Additive exPlanations) explainability, and automated pruning.

Using a systematic approach, 27 variables were identified within simulation datasets that can be features or targets for surrogate models. To analyse the relationships between the model parameters, Pearson correlation matrices for both the raw and log-transformed variables were computed. The correlation analysis was visualized with heatmaps. Figure 1 displays the correlation values for the raw datasets.

In the next step, four target variables and their respective feature sets were chosen to develop the surrogate models. Target variables were direct costs, indirect costs, restoration time, and the total length of inundated roads. Accordingly, four single-target XGBoost regression models were developed.

To capture nonlinearities between parameters in the stress test, each regression model created multiple feature representations, including raw, polynomial, log-transformed, and pairwise combinations. *RandomizedSearchCV* was applied to tune the hyperparameters of the XGBoost model. Standard regression metrics (R^2, MAE, and RMSE) were used to assess the performance of the models, and the difference between R^2_{Train} and R^2_{Test} indicates the allowable overfitting gap. Table 1 presents the performance of trained models for each target variable.

The results show that the developed XGBoost models perform well in predicting four target variables, especially the direct costs trained model, which has a minimal overfitting gap, indicating the robustness of the model.

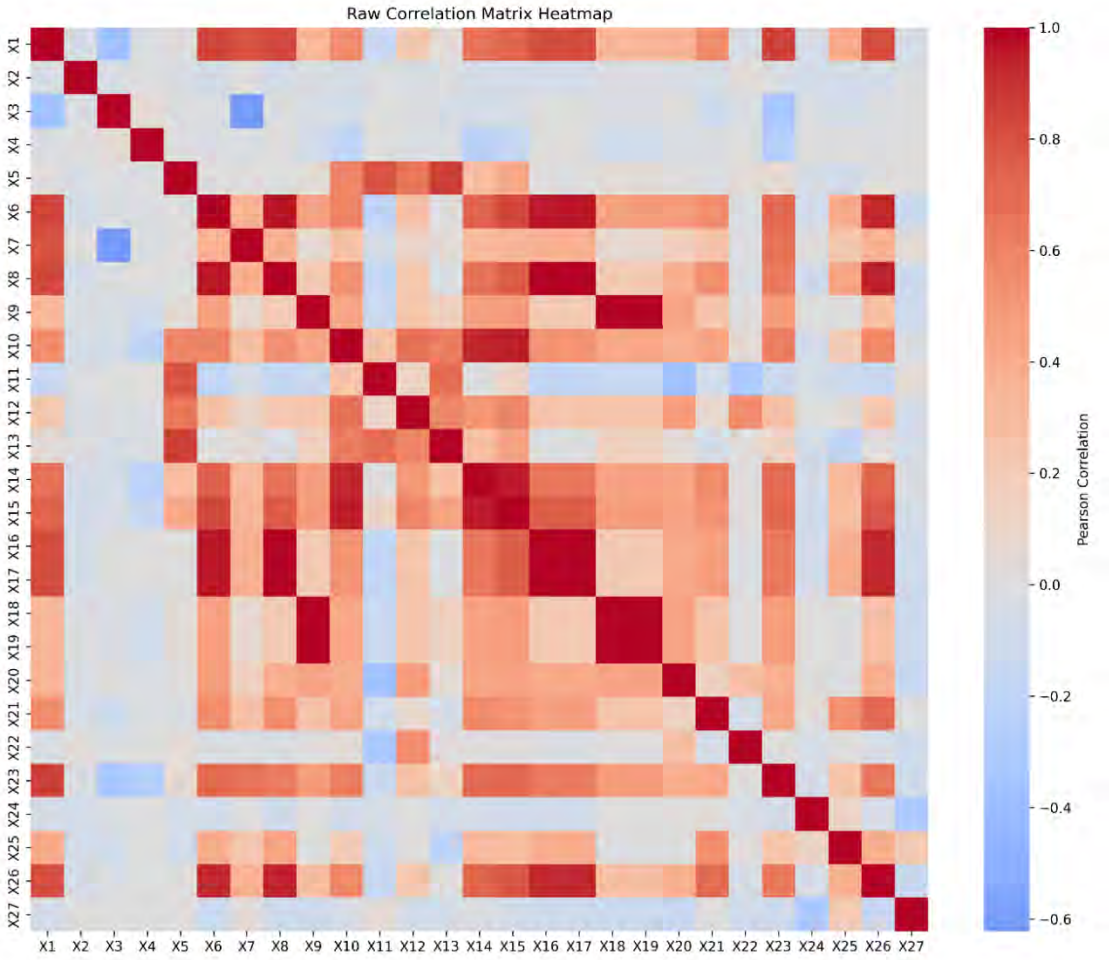


Figure 1. The correlation matrix for the raw datasets of 27 variables.

The high R^2_{Train} value indicates that the surrogate models fit the training data very accurately. However, the small drop in R^2_{Test} and $R^2_{CV\_Mean}$ values for restoration time and indirect costs suggests mild overfitting and variability in the model's performance for those two targets across various data partitions. To enhance the robustness of the XGBoost models and decrease the overfitting gap, it is recommended to carry out more stress test scenarios to gather more training data, which helps the surrogate model identify more patterns in the datasets.

Table 1. The summary of model performance for each target variable.

Target	**R^2_{Test}**	**R^2_{Train}**	**$R^2_{CV\_Mean}$**	**Overfit gap > 0.15**	**Feature engineering**
Restoration time	0.897	0.910	0.866	No	Top SHAP features
Direct costs	0.996	0.999	0.995	No	Top SHAP features
Indirect costs	0.921	0.979	0.852	No	All engineered features
Total length of inundated roads	0.963	0.977	0.914	No	All engineered features

Conclusion

The resilience assessment of interconnected infrastructure systems involves performing many stress tests, which can be computationally expensive. As discussed, ML-based surrogate models can resolve this challenge by learning the relationships between different parameters in the infrastructure resilience model and significantly reduce computation time, from several hours for a single stress test to just a few seconds.

Acknowledgements

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Advancing Network Modelling for Flood Resilience Assessment of Urban Rail Transit under Power Dependencies

Wei Bi[1], Bryan Adey[2]

Institute of Construction and Infrastructure Management, ETH Zurich, Switzerland

1 wb316@cam.ac.uk, 2 adey@ibi.baug.ethz.ch

Abstract

Urban rail transit systems (URTSs) rely critically on electricity, yet both transport and power assets are highly exposed to surface water flood risks. This dependency introduces additional vulnerability and therefore warrants explicit consideration in system resilience evaluations. This study aims to develop an advanced and computationally efficient complex network model that integrates power dependencies into URTS flood resilience assessment, accounting for service disruptions from direct transport asset flooding, cascading effects arising from power asset failures, and the subsequent dynamic recovery process. The methodology is demonstrated through a case study of the London Underground, which is stress-tested by flood events of varying extents and climate scenarios. The results highlight how system dependencies undermine resilience under evolving climate risks and provide evidence to support resilience planning and adaptation for URTSs.

Keywords: Urban rail transit; flood resilience assessment; complex network modelling; system dependencies; climate change

Introduction

Modern transport infrastructure faces challenges that are different from those encountered by the pioneering engineers who built them in earlier centuries. Two pressing challenges are the increasing water-related hazard risks posed by climate change (IPCC, 2023) and the growing system dependencies among various domains due to electrification and digitalisation (Pant et al., 2024). Multimodal urban rail transit systems (URTSs)—such as metros, light rail, and trams—are socio-technical systems that exemplify such complexities and are vulnerable to climate hazard risks. In recent years, notable metro flooding incidents have occurred in several cities, including New York in 2012, 2021, and 2023, Brussels in 2016, Sydney in 2020, London and Zhengzhou in 2021, Milan, Madrid, and Hong Kong in 2023, Valencia in 2024, and Paris in 2025, with observed significant equipment damage, extensive service suspension, and even passenger fatalities due to carriages being trapped in flooded tunnels.

Rainfall-induced surface water flooding disrupts URTS operations not only by inundating rail tracks and making them unsafe to travel through, but also by short-circuiting power supplies and damaging signalling equipment. These dependencies on power and communication systems introduce additional vulnerability to URTSs, exposing the network to cascading failures and prolonged service disruptions. Incorporating these dependencies into URTS flood resilience evaluations is therefore essential to accurately capture system-wide risks. To date, only a small number of studies have applied data-driven methods for infrastructure interdependency analyses (Sun et al., 2022). Goldbeck et al. (2019) proposed a dynamic

network flow model to analyse the resilience of London's metro and power networks. Ilalokhoin et al. (2023) developed a network flow model to assess the resilience of the Great Britain's railway network, accounting for interdependences between track, train, electricity, signalling, and telecoms. While both studies serve as good starting points, they analyse resilience under stochastic asset failures and do not address flood events or climate change impacts, leaving a notable gap in understanding system dependences for estimating flood resilience and addressing climate risks with data-driven models (Pant et al., 2024).

To (1) account for system dependencies and complex dynamics into data-driven infrastructure resilience analysis and (2) estimate system flood resilience under evolving climate risks, this study advances complex network modelling for URTS flood resilience evaluation, particular under power dependencies. The model simulates service disruptions caused by direct station and track flooding, cascading effects arising from power asset failures, and the subsequent dynamic recovery process. The methodology is demonstrated through a case study of the London Underground under flood events of varying extents and climate scenarios. The assessment results provide insights into the criticality of system dependencies in eroding system resilience under evolving climate risks and offer evidence to inform resilience planning and climate adaptation for URTSs.

This is ongoing work, and if the submission is accepted, the detailed methodology and anticipated case study results will be presented at the conference.

Acknowledgements

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Digital Twins for Resilience – Adaptation of Buildings to Thawing Permafrost

Matthew Joyner, PhD, PE [1]; Margaret Kurth [2]; and Kevin Bjella, PE [3]
[1] US Army Engineer Research and Development Center, United States, matthew.d.joyner@usace.army.mil
[2] US Army Engineer Research and Development Center, United States, margaret.h.kurth@usace.army.mil
[3] US Army Engineer Research and Development Center, United States, kevin.bjella@usace.army.mil

Abstract

The ability to adapt to changes is a crucial component of resilience that is often overlooked in design of structures. Thawing permafrost represents a serious and evolving threat to structures in cold regions, primarily due to the ground subsidence that it causes. This subsidence in turn leads to differential settlement – which occurs when one portion of a building's foundation subsides more than another, causing the structure above to experience excessive stresses and strains. Although permafrost thaw is generally expected to increase into the future, the rate and spatial distribution of that increase is highly uncertain, often leading to overly conservative design decisions aimed at mitigating worst-case thaw scenarios that may ultimately never materialize. This research proposes an alternative to this over-conservatism which leverages an adaptive design strategy, operationalized through a Digital Twin framework. In this approach, a moderately conservative design is accepted, provided that it is equipped with a sensor-enabled Digital Twin to monitor and adapt to differential settlements as needed through releveling of the foundation. The primary objective of this research is to develop a systematic methodology by which engineers and decision makers can explore the cost and resilience tradeoffs associated with such an approach and, if deemed feasible, configure the optimal sensor arrangement for the Digital Twin. This configuration is done by comparing the up-front and life cycle costs for a given sensor configuration with the associated benefits – assessed through stochastic simulations of the structure's performance over a 50-year service life. Expected-value-of-information (EVoI) analysis is used to quantitatively assess the value of a given sensor configuration accounting for uncertainty in permafrost thaw as well as the load and resistance parameters of the structure. Benefits considered in the analysis include 1) Economic value (ΔC): repair costs for thaw settlement damages that were avoided due to sensor-triggered adaptations; 2) Time value (Δt): reduction in risk exposure time due to improved adaptation timing enabled by sensor data; and 3) Reliability value (ΔR): avoided reliability deficit at the end of the structure's service life due to sensor-triggered adaptations. This work is intended to serve as an initial step toward broader implementation of adaptation-based design using Digital Twins, which can be applied to other infrastructure systems and other natural hazards of gradually increasing severity..

Keywords: Digital Twins, resilience, permafrost, structural reliability, Arctic
480

13. Best Practices And Innovation Potential For Enhancing Urban Resilience

Resilience-oriented Value of Structural Health Monitoring for Infrastructure systems

Huangbin Liang[1], Beatriz Moya[2], Francisco Chinesta[3], Eleni Chatzi[4]
[1] Singapore-ETH Centre, Singapore, huangbin.liang@sec.ethz.ch
[2] ENSAM Institute of Technology, France, beatriz.moya_garcia@ensam.eu
[3] ENSAM Institute of Technology, France, Francisco.CHINESTA@ensam.eu
[4] ETH Zurich, Switzerland, chatzi@ibk.baug.ethz.ch

Abstract

Post-disaster recovery of critical infrastructure is essential to societal resilience. While Structural Health Monitoring (SHM) systems offer promise in improving damage assessment, their system-level impact remains difficult to quantify. This study proposes a probabilistic simulation framework to assess the value of SHM in supporting the resilience of electric power networks (EPNs) following seismic events. By integrating fragility modeling, inspection quality, and dynamic repair simulation, the framework compares multiple monitoring scenarios—ranging from manual inspection to full SHM deployment—using a resilience metric based on functionality restoration. Results show that improved damage perception from SHM can reduce loss of resilience by over 20%, highlighting its strategic importance in post-disaster infrastructure management.

Keywords: resilience; electric power networks; value of information; seismic structural health monitoring; post-earthquake recovery

Introduction

Electric power networks (EPNs) are essential to post-disaster recovery, yet their functionality is often compromised by earthquake-induced damage. Conventional post-event inspections are time-consuming and prone to uncertainty, leading to inefficient recovery and prolonged outages. Structural Health Monitoring (SHM) offers a data-driven alternative by enabling near real-time assessment of damage states [1-3]. However, given the cost and complexity of SHM deployment, a critical question remains: What is the quantifiable value of SHM in enhancing the system-level resilience of infrastructure?

To answer this, we propose a resilience-oriented value of information (VoI) framework that models the decision impact of SHM under uncertain damage and recovery scenarios. We focus on seismic damage in power systems and assess the value of SHM in accelerating recovery and improving resilience metrics [4].

Methodology

2.1 Framework Overview

The proposed simulation framework captures the full cycle of infrastructure resilience assessment under earthquake events. It consists of the following key modules:

1) Seismic Scenario Generation: Earthquake intensities are sampled using earthquake event-based ground motion prediction equations (GMPEs) [5].

2) Damage Simulation: Component-level fragility curves convert seismic intensity into probabilistic damage states [6-7].

3) Damage Perception Modelling: We represent damage identification using confusion matrices to simulate the accuracy of manual or SHM-based inspection.

4) Repair Simulation: A dynamic queuing model with constrained repair resources is used to simulate the component-wise recovery process.

5) Functionality Evaluation: System functionality is assessed via islanding analysis and DC optimal power flow (DCOPF) modeling [8].

6) Resilience Quantification: The Lack of Resilience (LoR) metric is computed as the area under the normalized functionality-time curve [9].

2.2 SHM Value Modelling

To simulate the effect of SHM, we model four types of monitoring scenarios:

- No SHM (Baseline): Random manual inspection with low detection accuracy.
- SSHM–Full: All components are monitored with high accuracy and immediate data availability.
- SSHM–Partial: Only a subset of components is instrumented.
- SSHM–Delayed: Accurate information becomes available after a time delay (e.g., due to processing or communication lag).

Each scenario is represented by a specific confusion matrix reflecting true positive (TPR) and false positive (FPR) rates.

2.3 Monte Carlo Simulation

The entire process is repeated over multiple Monte Carlo runs to account for uncertainties in seismic intensity, damage realization, perception error, and recovery dynamics. For each run, the LoR metric is computed, and the average performance across scenarios is compared to evaluate the resilience improvement due to SHM.

Case Study: IEEE 24-Bus Test System

We demonstrate the framework using the IEEE 24-bus system shown in Figure 1, modified to include realistic component types (e.g., substations, generators, load units, bus nodes). Fragility parameters and recovery parameters are collected based on available empirical and analytical studies, as provided in Tables 1 and 2. To realistically capture the uncertainty related to damage perception during post-earthquake assessment, a unified tridiagonal confusion matrix is adopted for both inspection-based and SSHM-based assessments.

$$\boldsymbol{C} = \begin{bmatrix} \frac{1+a}{2} & \frac{1-a}{2} & 0 & 0 & 0 \\ \frac{1-a}{2} & a & \frac{1-a}{2} & 0 & 0 \\ 0 & \frac{1-a}{2} & a & \frac{1-a}{2} & 0 \\ 0 & 0 & \frac{1-a}{2} & a & \frac{1-a}{2} \\ 0 & 0 & 0 & \frac{1-a}{2} & \frac{1+a}{2} \end{bmatrix} \quad (1)$$

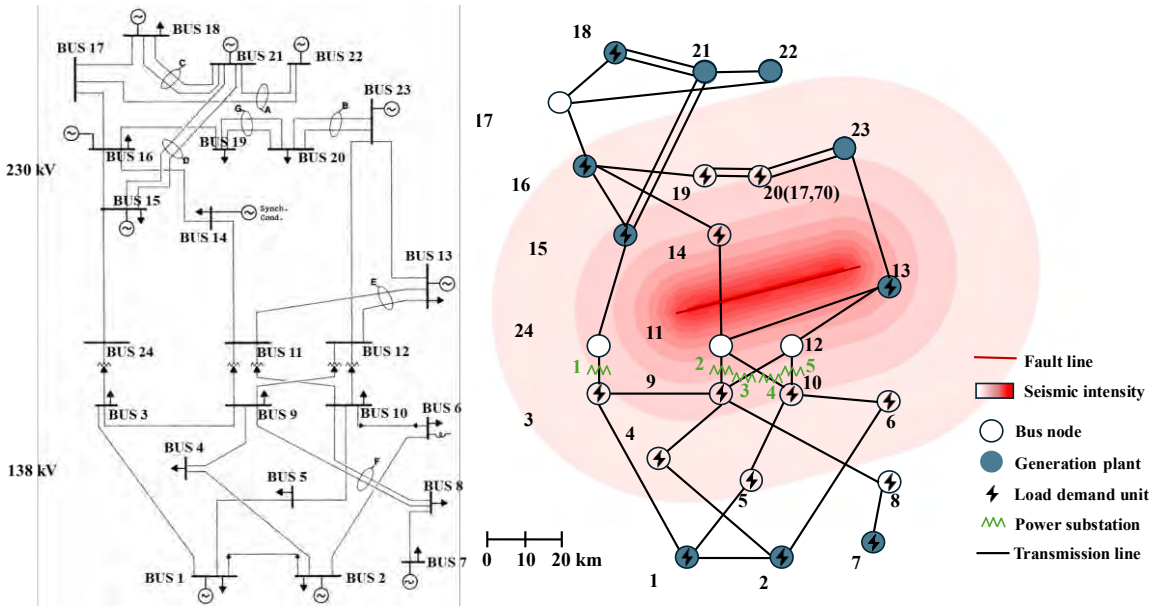
For the case of inspection-based assessment, we set a = 0.70 to represent typical field reconnaissance accuracy and apply a 2-day information delay before perceived damage data become available for repair scheduling to reflect inspection logistics. For SSHM-based assessments, we use a = 0.90 to capture their higher precision, with immediate assessment data availability (0-day delay) representing real-time damage perception.

Table 1 Seismic fragility parameters for different EPN components

Damage	Bus node		Generation plant		Load unit		Substation	
state	θ(g)	β	θ(g)	β	θ(g)	β	θ(g)	β
Slight	0.13	0.65	0.10	0.60	0.24	0.25	0.10	0.60
Moderate	0.26	0.50	0.22	0.55	0.33	0.20	0.20	0.50
Extensive	0.34	0.40	0.49	0.50	0.58	0.15	0.30	0.40
Complete	0.74	0.40	0.79	0.50	0.89	0.15	0.50	0.40

Table 2 Repair duration parameters for different EPN components (units: day)

Damage	Bus node		Generation plant		Load unit		Substation	
state	μ	σ	μ	σ	μ	σ	μ	σ
Slight	0.8	0.4	0.5	0.1	0.3	0.2	1.0	0.5
Moderate	2.5	1.0	3.6	3.6	1.0	0.5	3.0	1.5
Extensive	5.5	2.0	22.0	21.0	3.0	1.5	7.0	3.5
Complete	7.0	3.0	65.0	30.0	7.0	3.0	30.0	15.0

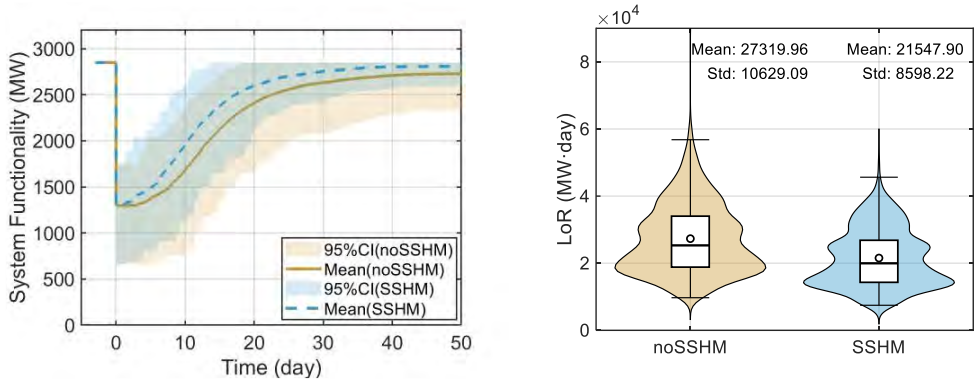


(a) (b)

Figure 1. Illustrated IEEE 24-bus RTS (a) one-line diagram; (b) abstracted network configuration diagram subjected to an earthquake scenario with a strike-slip fault line (dashed red) defined by two endpoints at coordinates (0, 50) and (40, 60). The red shaded contours represent the seismic intensity field, with darker zones indicating higher seismic intensity. The geographic coordinates of bus nodes (hollow circle) are indicated in parentheses. Generation plants, load units, and substations are denoted by blue circles, lightning symbols, and green polylines, respectively.

Results and discussion

To capture the combined effects of hazard and perception uncertainties, 100 damage scenarios were generated using stochastic ground motions and fragility models, with 100 recovery simulations per scenario under both inspection-based and SSHM-assisted assumptions (10,000 total per method). As shown in Figure 2(a), hazard variability significantly broadens recovery uncertainty, yet SSHM consistently accelerates recovery with reduced variance. The final system functionality averages 98.6% with SSHM, compared to 95.6% without—a 3.0% improvement due to enhanced damage awareness. Figure 2(b) shows LoR distributions: SSHM achieves a mean LoR of MW ·day std: versus MW ·day std: in the baseline, reflecting a 21.0% reduction in expected loss and a 20.6% drop in uncertainty. These results emphasize SSHM's critical role in improving both resilience outcomes and the reliability of recovery forecasts under diverse seismic impacts.



(a) (b)

Figure 2. (a) Time evolution of mean system functionality with 95% confidence intervals across the 10000 MC simulations; (b) violin plots of LoR distributions highlighting reduced mean and variability with SSHM-assisted damage perception compared to inspection-based assessment.

Conclusion

This study presents a probabilistic, resilience-oriented simulation framework to quantify the value of SHM in post-earthquake infrastructure recovery. By simulating damage perception, repair scheduling, and system functionality, we demonstrate that SHM substantially reduces recovery time and improves resilience metrics. This approach provides a transparent and quantitative basis for sensor deployment decisions and resilience-informed infrastructure design.

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Dynamic and interactive modeling of social resilience to flood impacts in the Mekong River Basin

Liang Emlyn Yang[1,2]

1 Department of Geography, Ludwig Maximilian University of Munich (LMU), Munich, Germany

2 John A. Paulson School of Engineering and Applied Science (SEAS), Harvard University, Cambridge 02138, MA, USA

Abstract

Most flood-related research emphasizes risks, losses, and vulnerabilities, often portraying communities as victims of disaster. However, this narrow focus overlooks the crucial question of how communities actively maintain resilience in flood-prone environments. The ERC-funded STORIES project places community resilience at the center of its investigation, using the Mekong River Basin as a key case where millions of people have long lived with seasonal floods. Our research explores how communities develop resilience by building elevated homes, adapting agricultural calendars, and engaging in community-based water governance. We combine historical analysis, field-based case studies, and agent-based modeling to trace how these security strategies have evolved over time and space. The Mekong's flood resilience is not just technical or economic—it is deeply rooted in social networks, trust, cultural identity, and institutional arrangements that support mutual aid and risk sharing. Community security, in this context, means more than protection from immediate harm; it reflects a capacity to adapt, preserve autonomy, and maintain a sense of continuity amid environmental uncertainty. By foregrounding community resilience, the shift in perspective—from managing disaster impacts to enhancing community resilience —provides a more just and sustainable foundation for climate adaptation in the Mekong and beyond.

Keywords: Flood resilience, community resilience, flood adaptation, resilience measures, spatial-temporal dynamics, Mekong river

Enhancing Urban Flood Resilience through Governance and Institutional Innovations: A Case Study of Can Tho City, Vietnam

Thanh Phuoc Ho, Nguyen Trung Ly, Van Pham Dang Tri, Matthias Garschagen, Liang Emlyn Yang

Abstract

Climate change and rapid urbanization have intensified flood risks in many cities worldwide, particularly in low-lying regions. The Vietnamese Mekong Delta is highly vulnerable, with urban areas such as Can Tho City experiencing both seasonal riverine flooding and localized urban inundation from heavy rainfall. Despite these challenges, Can Tho has emerged as a pioneering case of urban flood resilience, largely driven by governance and institutional innovations. This study presents empirical findings from Ninh Kieu District, the city's urban core, based on 10 in-depth interviews with government officials and surveys of over 160 residents. A mixed-methods approach combining qualitative and statistical analysis was employed to identify and assess the effectiveness of flood management strategies. Results highlight several major innovations. The ODA-funded Can Tho Urban Development and Resilience Project (DA3) has delivered more than 10 km of embankments, floodgates, pumping stations, and tidal sluices. Furthermore, the WD6 urban dike project has played a critical role in expanding protective infrastructure, reinforcing Can Tho's long-term flood defense system. Recent evaluations confirmed that, for the first time, key districts remained flood-free during peak tidal surges, significantly improving mobility, business continuity, and public confidence. Moreover, the Flood Risk Management Information System (FRMIS) provides real-time data on rainfall, salinity, and water levels, enabling proactive flood control through integrated monitoring and adaptive operations. Additionally, complementary policy frameworks such as Plan 181/KH-UBND and Project 553 have strengthened community awareness, risk communication, and disaster preparedness, reflecting a governance shift toward community-based resilience building. Survey results reinforce these findings from the public perspective: 90% of respondents felt their neighborhoods were now well protected, 80% reported their households no longer experienced flooding, and 85% expressed satisfaction with project implementation. These findings highlight the pivotal role of governance and institutional innovations in shaping Can Tho's resilience pathway, showing how governance reforms and institutional arrangements can jointly foster adaptive, long-term flood resilience in rapidly urbanizing areas. This case study illustrates that urban flood resilience is most effective when infrastructure investments are complemented by policy instruments and information systems. Together, these measures provide valuable lessons for other flood-prone cities globally seeking to enhance adaptive capacity and safeguard urban development.

Keywords: Urban resilience, flood governance, institutional innovations, climate adaptation, Vietnamese Mekong Delta

A Review of Global and Indian Frameworks for Urban Flood Resilience

Aashly V S[1], Deepty Jain[1], Diana Contreras Mojica[2]
[1] Transportation Research and Injury Prevention Centre (TRIPP), Indian Institute of Technology Delhi, India, aashlyvs@gmail.com, djain@tripp.iitd.ac.in
[2] School of Earth and Environmental Sciences, Cardiff University, United Kingdom, ContrerasMojicaD@cardiff.ac.uk

Abstract

Despite the increasing frequency of resilience-oriented strategies in global urban flood risk management frameworks, the integration of social equity, inclusion, and mobility considerations remains challenging. Global frameworks acknowledge these vulnerabilities, but often generically, and actual implementation fails to address local needs. India's resilience planning predominantly focuses on physical initiatives such as building embankments, levees, floodwalls, and hazard mapping, but with a limited integration of the two components of risk: Exposure and vulnerability. Also, less importance is given to social aspects and transportation networks as essential strategies for improving resilience. This review examines the conceptualisation of exposure, vulnerability, and inclusion of the transportation sector within the urban resilience framework by comparing global and Indian policies. We further review the existing indicators used to measure exposure and vulnerability at different spatial scales.

Keywords: Urban Resilience; Transport Indicators; Risk; Exposure; Vulnerability

Introduction

Urban flooding refers to the rapid rise of floodwaters in urban areas, resulting in physical and social impacts (Alves et al., 2021). In cities, urbanisation increases catchment areas, raising flood peaks by 1.8 to 8 times compared to rural floods (NDMA, 2010). Due to increasing populations, climate change, and rising sea levels, the individuals at risk of flood disasters would exceed 2 billion by 2050 (M. Liu et al., 2024). Urban flooding also significantly impacts the serviceability of transport systems, causing travel disruptions. Climate change, rapid urbanisation, and inadequate governance are exacerbating the consequences globally, particularly in a Global South country like India.

Given the increasing risk of urban flooding and socio-economic disparities, there is a need to understand, assess, and manage flood risk components. This study provides a review of global and Indian urban flood resilience frameworks and indices used to assess exposure and vulnerability. By identifying gaps in current approaches in urban contexts, the study aims to help government agencies and policymakers improve the existing frameworks, addressing more context-specific challenges.

Method

This paper reviews global and Indian urban flood frameworks and indicators used for measuring exposure and vulnerability. Peer-reviewed articles, government reports, and policy papers on exposure, vulnerability, social equity, and transport integration are also reviewed. A total of 46 papers were selected for preliminary assessment based on the title and abstract; among those, 27 papers were fully reviewed based on relevance to the study. The selection of relevant studies is based on the application of exposure and vulnerability indicators, and integration of socio-economic aspects and the transport sector across national, regional, and local scales.

Evolution of Strategies

Flood management strategies have shifted from complete reliance on traditional methods such as construction of dams and levees to non-structural adaptive planning that includes recognising the role of governance structures and understanding local community knowledge (Katyal & Petrisor, 2011; Mai et al., 2020; Wang et al., 2020). This evolution gives an insight into a comprehensive understanding and increasing complexity of flood risks and resilience through the integration of local knowledge and stakeholder involvement. The studies recognise that top-down governance alone is not enough; community-based approaches are also to be considered at various stages of planning, implementation, and monitoring of disaster risk reduction (DRR) (Abid et al., 2024; Devkota et al., 2014; Singkran & Kandasamy, 2016). Dhiman et al. (2019) emphasised that flood risk management and adaptation strategies should include grassroots-level implementation and the use of technologies for flood adaptation planning in India. These perspectives together show that making cities resilient to floods requires a combination of structural changes, strong governance, technologies, and continuous community involvement.

Integration of Exposure and Vulnerability

In the existing research, exposure and vulnerability were frequently studied separately. Exposure was measured in terms of factors such as population and assets in flood zones, while vulnerability was measured by quantifying susceptibility to damage (Alam et al., 2018; Dullaart et al., 2021; Mitchell et al., 2022; Murali et al., 2020). However, such kind of assessments are most likely to underestimate combined risks, where vulnerabilities increase the consequences of exposure (Bui et al., 2023). For example, two homes exposed to the same flood depths could experience substantially different outcomes due to factors such as socioeconomic resilience and distance from evacuation routes. This indicates that an analysis of exposure alone is inadequate for a comprehensive understanding of risk. While several studies have integrated exposure and vulnerability to assess risk, such integration is less commonly done at finer spatial scales due to data availability.

Integration of Transportation

Transportation strategies are critical for flood resilience by ensuring accessibility, evacuation, and recovery, yet most global frameworks (IPCC, Sendai, WRI, MOVE, CVI) treat transport only generically, often limited to indicators like vehicle ownership (SVI, SoVI) (Duy et al., 2019; Y. Liu et al., 2022; Pregnolato et al., 2016). Despite the available evidence that accessibility, spatial connectivity, and mobility strongly influence recovery and resilience (Contreras et al., 2013; Gajanayake et al., 2018; Thakur & Mohanty, 2024) within the Indian context, transport indicators are rarely integrated into disaster risk management.

Conclusion

Urban flood resilience requires integrated frameworks that address exposure, vulnerability, an equitable society, and mobility. The study reviewed the existing literature and global flood assessment frameworks and identified critical gaps. Firstly, there is a limited understanding of exposure and vulnerability at a spatially finer scale governed by poor data availability, specifically in Indian cities. Additionally, exposure and vulnerability are frequently assessed separately, which underestimates risks and ignores how social and economic conditions

amplify flood impacts. Last, globally, there is a limited inclusion of transportation indicators in DRR frameworks, limiting assessment of transport strategies and inclusion of key factors, including accessibility, connectivity, and evacuation to reduce vulnerability during disasters.

The gaps in Indian and global contexts demand context-specific and socially inclusive responses. Resilient urban flood management requires local government structures and bottom-up approaches that incorporate vulnerable populations. It is observed that the framework and indexes often failed to address transport indicators in both the global and Indian scenarios. This review provides an outline for modifying urban flood resilience systems for reducing vulnerability of urban populations.

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It’s not just risk—It’s responsibility: changing drivers of home flood protection

Mikhail Sirenko[1], Tatiana Filatova[2]
1 Delft University of Technology, the Netherlands, M.Sirenko@tudelft.nl
2 Delft University of Technology, the Netherlands, T.Filatova@tudelft.nl

Private household adaptation is a critical yet underutilised element of flood resilience. Property-level measures might reduce up to 80% of damage if adopted in a timely manner. However, socio-behavioural factors serve as constraints to adaptation. Among them, a lack of risk awareness is considered a primary barrier. Empirical research typically relies on a single snapshot of data, implicitly assuming these factors are stable over time. Using two nationally representative survey waves from the Netherlands (2020 and 2023), we examine how factors of household intentions to implement six structural home-flood protection measures change. Counterintuitively, despite a major flood in 2021, by 2023, we find lower adaptation intentions (an 11.6 percentage point decline), lower flood worry, and reduced self-efficacy. This coincided with a marked shift in perceived responsibility for flood risk toward the government (12 percentage point increase), while the actual uptake of private adaptation measures remained low (2-5%). Regression analysis reveals a reordering of behavioural drivers: in 2020, prior flood experience, self-efficacy, and flood worry were the most prominent predictors, though perception of responsibility was also consistently significant. By 2023, perception of responsibility emerges as the strongest and most consistent predictor of intention to act (odds ratio 2.4), while the importance of flood experience and worry declines. These results suggest that household drivers for adaptation are volatile, relying not only on a household's experience and capacity to act but also on the understanding of shared responsibility between citizens and the state. "Empowering" households only with information about potential flood risk, while rationally sound, may not result in an intention to protect homes. Climate adaptation policy design that embraces private action must therefore include: clear responsibility framing, support for skills development and the efficacy of measures, targeted financial incentives, and adaptability to account for evolving public attitudes, even over short timeframes.

Allotment Gardens for Urban Resilience

Marcin Korecki, TU Delft, the Netherlands, mkorecki@tudelft.nl

Abstract

The aim of this work is to characterise and discuss allotment gardens' potential for increasing urban resilience in areas such as food security, health, and social cohesion. Both benefits and challenges are analysed and future research directions of specific relevance to the resilience community are proposed.

Keywords: Allotment Gardens; Urban Resilience; Food Security

Introduction

Allotment gardens are a common, albeit often hidden, feature of many European cities. Dating back to the 18th and 19th centuries, they boast a long tradition of urban farming and community emergence. The broader research community has paid attention to the allotment gardens in the context of the political and legal sphere, the ecology, spatial design, and social aspects (Bell et al., 2016; Guitart et al., 2012). Due to their potential for, among others, increasing food security of urban areas, the allotment gardens have recently started to attract attention of the resilience community (Winkler, 2025). Specifically, they are seen as increasing the resilience of socio-economic systems to climate change (Burchard-Dziubińska, 2021) and the stability of the food supply, when threatened by crises (Barthel et al., 2015).

Benefits & Challenges

A large number of allotment gardens' benefits has been demonstrated by scholarly work. These include: access to food (Castro et al., 2013), improved health (both mental and physical (Wood et al., 2016)), reduced crime, education, sustainability, preservation of cultural heritage, increased biodiversity and life satisfaction (Guitart et al., 2012). All of these advantages can be seen as increasing the overall resilience of a given urban area on several fronts. The most prominent is the allotment gardens' potential to increase the food security of the urban populations, who over the last century had drastically increased their reliance on outside food production and elongating supply chains. This increased food security is well attested, not only by theoretical research, but also by strong historical evidence. One such historical example is the allotment gardens' role in mitigating the food shortages in the 70s and 80s of the 20th century in Poland (Bellows, 2004). Another testament to their contribution to the overall urban resilience is the interest that they have generated during the pandemic as a stress-coping strategy (Janus et al., 2022).

Considering all those benefits a simple question comes to mind: if the allotment gardens are so good why aren't there more of them? While the benefits of allotment gardens appear well studied and supported by strong evidence the challenges that they face have attracted less attention. The primary limitation to the expansion of allotment gardens is the scarcity of available space in urban environments. Moreover, the space that remains viable is often competed for by a variety of public and private entities. Secondly, the quality of the food produced in urban environments may be lowered by exposure to pollutants that are commonly found in high densities in cities. Furthermore, in many countries, the allotment gardens operate, in principle. as private entities and the access to them may be restricted to the members of the community. This significantly limits their beneficence to the broader public and stunts their impact. The overall integration of the allotment gardens with the urban fabric may also pose challenges and further research is needed to work out specific spatial policies. All these issues need to be addressed and to some extent resolved before allotment gardens can be further expanded.

Future Directions

The most obvious research direction in the context of allotment gardens is the design of ways of addressing the aforementioned limitations. The research needs to be especially nuanced as the allotment gardens are not a uniform

system but differ across countries and cities. This also necessitates a concentrated effort of researchers across borders such that allotments in different countries and cities may be compared and the learnings from one place can flow to another. Due to their communal nature, the allotment gardens appear a perfect candidate for citizen science projects, where the garden users themselves can be engaged in the process of gathering, analysing and sharing data. Indeed, the gardeners themselves present a vast and rich repository of knowledge on urban farming. Informed by years of hands on experience they can be expected to hold valuable information on the suitability of crops and synergies between them in a given urban context. On the other hand, the gardeners may perhaps benefit from engaging with novel methods of cultivation such as permaculture techniques of Fukuoka Masanobu and others which seem particularly appropriate in the context of small, dense, urban plots (Fukuoka, 2009). The dynamics of development of existing gardens and their cellular structure gives an interesting opportunity to directly study the spatial self-organisation in the system through e.g. analysing what plants are planted where. Following the contemporary research trends allotment gardens' role in the sustainable and circular economy of the future is yet another direction of potential research. Lastly, the research could go beyond the gardens themselves to consider the implications for food security of less organised, wilder environments with high food generating potential, such as urban forests.

All in all, allotment gardens are a rich environment with great potential for increasing urban resilience in several key areas. In order to fully realise their potential more research is needed into the challenges that have so far stunted their expansion. Through the engagement of the academic community and the gardeners themselves in the spirit of citizen science much progress may be made in making the cities of the future more resilient.

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Prototype Litfaßsäule 4.0 – An integrated approach to building urban resilience

Joachim Schulze[1] Christine Quittkat[2] Michèle Knodt[3]
1 Technical University of Darmstadt, Germany, schulze@stadt.tu-darmstadt.de
2 Technical University of Darmstadt, Germany, quittkat@pg.tu-darmstadt.de
3 Technical University of Darmstadt, Germany, knodt@pg.tu-darmstadt.de

Abstract

Communication is a decisive part of disaster risk management (DRM). But in crisis scenarios like a blackout which lead to the disruption of mobile networks, internet, television and landline telephony maintaining communication is a major challenge. This paper introduces an innovative and unique prototype entitled *Litfaßsäule 4.0* that is self-sufficient and enables secure crisis communication in cities thus building this crucial dimension of urban resilience. The *Litfaßsäule 4.0* is an extension of existing advertising columns common in German cities and is exceptional not only in a technical sense but also from an urban planning perspective as it integrates critical infrastructure into the cityscape. The prototype has undergone testing in the city of Darmstadt during the summer of 2025 and was evaluated through an on-site survey. The results of this survey reflect the perception of the residents on the prototype and are presented in the concluding chapter of this paper.

Keywords: disaster risk management (DRM); urban resilience; crisis communication; Litfaßsäule; blackout

Introduction

A blackout poses a huge threat to modern cities, which rely on a complex network of interdependent infrastructures. Especially the breakdown of everyday communication technologies (Petermann et al., 2011) is a challenge impeding the authorities in their ability to inform the residents about the situation. Yet this is a necessity in crisis management (Bakker et al., 2018; Hanson et al., 2020). The recent blackout on the Iberian Peninsula has demonstrated how important information is to the population, with people gathering around car radios (AFP, 2025). The apparent lack of preparation for such an event on the one hand, and the excepted damage on the other, call for measures to improve crisis communication in a blackout scenario. This paper introduces a self-sufficient prototype communication tool that builds upon a historically established infrastructure found in German cities: the so called *Litfaßsäule*. It is not only a technical innovation but also demonstrates how crisis-related infrastructures can be well integrated into the cityscape.

Development and design of the prototype

The *Litfaßsäule* was invented at the end of the 18th century by Ernst Theodor Amandus Litfaß who was a renown Berlin based businessman and publisher. Litfaß was inspired by advertising columns found in Paris and London and after introducing substantial changes to the design,

above all the round shape, brought it to the market in Germany (Wahren, 1998). The *Litfaßsäule* quickly became established not only as an advertising space but also as a reliable source of information and is still present in German cities with an estimated number of 65,000 columns and can be considered one of the oldest and most iconic street furniture.



Figure 1 Mapping of columns in the city of Darmstadt

The history of the *Litfaßsäule* is the starting point to think about how it is suited to play a role in crisis communication. One of the first criteria is accessibility. In a blackout scenario, for example, residents will need to seek out information on foot because traffic comes to a standstill (Petermann et al., 2011). Thus, it is necessary to have an element well distributed and accessible. Mapping the 155 columns found in the city of Darmstadt reveals that the next *Litfaßsäule* is rarely more than 300 meters away and is usually located in busy places, e.g. public squares or intersections, making it easy to spot (Figure 1). This suitability is emphasized by an examination of the *Litfaßsäule's* construction. It is made of stacked concrete rings that enclose a rainproof interior of about five cubic meters, offering enough space to place the necessary technology while protecting it against vandalism. In addition, the capital of the column, at a height of four meters, ensures good visibility for displaying information. Last but not least, the high degree of public acceptance and the *Litfaßsäule's* history as a trustworthy source of information qualify it for use in the context of crisis communication.



Figure 2 Prototype at the Riegerplatz in Darmstadt (courtesy of Sascha Mannel)

Building on the original idea and the conceptual analysis described above, a prototype was developed in close cooperation with a leading Out of Home (OOH) advertiser. The design of the prototype integrates modern technology while maintaining the traditional appearance of the *Litfaßsäule* (Figure 2). Technically, it can continue operating for a minimum of 72 hours in the event of a blackout. The main components include three LED displays which show information or warnings as running text, a communication unit that enables the fire brigade to activate the column, and two photovoltaic panels and methanol fuel cell as energy sources. All components of the *Litfaßsäule 4.0* are integrated into the capital, which can be installed onto any existing *Litfaßsäule*. Maintenance is easily carried out by a counterweight system in the body of the column, which lifts the capital and enables access to the components.

On-site survey on public awareness and acceptance of the *Litfaßsäule 4.0*

To evaluate public awareness of the *Litfaßsäule 4.0*, assess acceptance of this new crisis communication medium, and identify design features that enhance its recognisability in emergencies, we conducted an on-site survey at the prototype installed at Riegerplatz, Darmstadt. A structured questionnaire was administered orally to passers-by, with responses entered directly into tablets. In early June 2025, a pre-test at the same location validated the questionnaire, checked technical requirements (internet connectivity for live data entry), and evaluated participants' willingness to respond.

The main survey took place on four dates in June and July 2025, with the digital display of the *Litfaßsäule 4.0* activated and showing the message: "*Litfaßsäule 4.0 – We would be delighted*

if you would take part in our survey". Of 121 individuals approached (by two student assistants and one senior researcher), 112 participated. The highest response rate occurred on 2 July 2025, coinciding with the weekly market at Riegerplatz.

The sample shows two location-related biases: (1) Academic bias: 54.46% held a university degree, and another 17.86% had the *Abitur* (university entrance qualification), reflecting the socio-demographic profile of the Martinsviertel neighbourhood. (2) Gender bias: 62.16% of respondents were women, likely due to the market day coinciding with one survey date. Findings indicate that 66% of respondents noticed the digital display, despite the column's familiarity in the urban landscape. Moreover, 68.75% regarded the crisis-only digital display as useful, while only 7.19% deemed it useless. Opinions on everyday design varied (**Error! Reference source not found.**): about 60% valued recognisability as a crisis information point; 30% considered special design unnecessary, one-third preferred colour coding, 13% favoured text/symbol alone, and 18% supported combining both. Five percent were undecided.

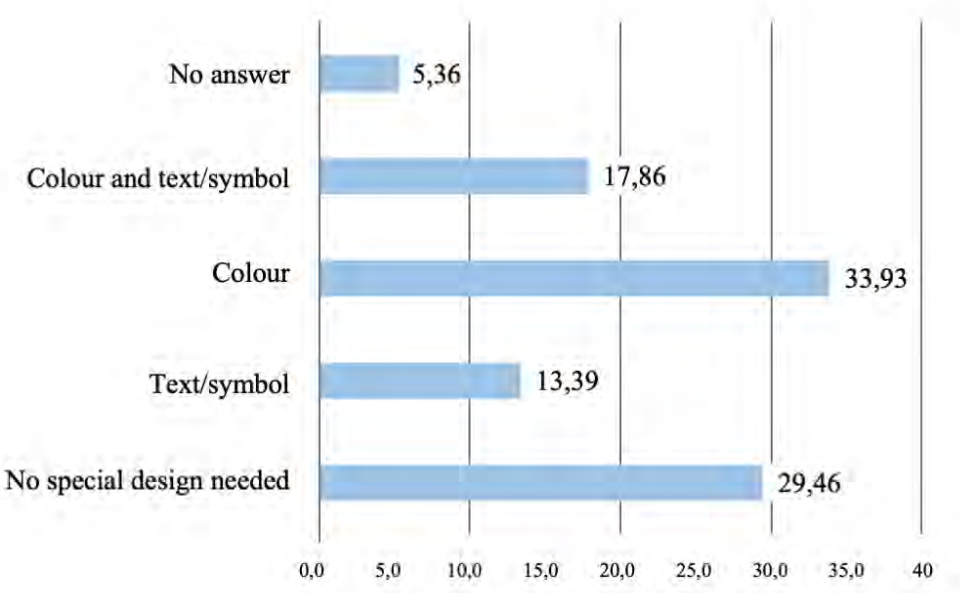


Figure 3 How should the Litfaßsäule 4.0 be designed? (in percent)

Conclusion and outlook

The prototype of the *Litfaßsäule 4.0* demonstrates how resilient crisis communication can be integrated in a sustainable manner by building on an existing and well-established infrastructure. The results of the on-site survey show high approval among citizens and indicate a need to improve the recognisability of the *Litfaßsäule 4.0* as a new crisis communication instrument when it is not in operation. The prototype is currently under discussion with a wide range of stakeholders to explore possibilities for improvement and bring it to practice. To further examine recognisability and public perception, a human-computer interaction study is planned.

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14. Resilience Of Local Authorities

Analysis of Intra- and Interorganizational Interdependencies in Municipal Crisis Management

Niklas Frings(1), Peter Windsheimer-Kolla(2), Nicolas Bock(3), Alexandra Schmitt(4)Sylvia Bach(5), Frank Fiedrich(6)

(1) University of Wuppertal, Institute for Public Safety and Emergency Management, frings@uni-wuppertal.de (2) Freie Universität Berlin, Disaster Research Unit, peter.windsheimer@fu-berlin.de (3) Freie Universität Berlin, Disaster Research Unit, nicolas.bock@fu-berlin.de (4) University of Wuppertal, Institute for Public Safety and Emergency Management, a.schmitt@uni-wuppertal.de (5) University of Wuppertal, Institute for Public Safety and Emergency Management, sbach@uni-wuppertal.de (6) University of Wuppertal, Institute for Public Safety and Emergency Management, fiedirch@uni-wuppertal.de

Abstract

This contribution introduces a novel combination of methodologies for analyzing interdependencies between critical infrastructures within the context of municipal crisis management in Germany. Recognizing the complexity of internal and external dependencies, the research employs a mixed-methods approach combining semi-quantitative surveys, graph theory modeling, and agent-based simulations. As part of a running project, this subproject aims to simulate failure and recovery scenarios to enhance resilience in municipal administrations. Initial findings and results will be presented at the upcoming conference.

Keywords: Critical Infrastructure Interdependencies; Municipal Crisis Management; Network Analysis; Resilience Modeling

Introduction

Germany's federal structure entails a division of responsibilities, with municipal authorities assuming a primary role in safeguarding the population, ensuring the provision of fundamental services, and functioning as the primary liaison between the state, population, and economy. These authorities are expected to retain the capacity to fulfill their functions effectively in standard operation mode as well as in situations during and after crises or catastrophes. In order to fulfill this range of tasks, municipal actors must collaborate not only across the different departments of their own bureaucratic organization, but also externally with a variety of other actors. This results in a complex network of internal and external dependencies, not least due to the extremely heterogeneous range of tasks.

In the contemporary era, characterized by the increase of advanced technical and organizational networking, the growing organizational complexity increases the difficulty of predicting challenges faced during crisis management. This claim is particularly important in the context of higher-order dependencies, i. e. when critical infrastructures do not have direct but indirect dependencies of the nth degree. In this context, there has been a surge in research activity focused on the utilization of modeling and simulation methodologies.

These approaches have been employed to identify and delineate dependencies between critical infrastructures, as well as to simulate the potential consequences of failure and the ensuing recovery processes (Sun et al. 2022). The present body of research examines either the interdependencies between critical infrastructures (CI) at the level of CI-sectors or the utilization of case studies in local settings. To the best of the author's knowledge, no studies have so far been conducted which take into account both internal and external processes, or which model municipal authorities where this challenge is encompassed in their framework conditions (Sun et al. 2022).
Due to this, we want to present a novel approach on data collection, modeling and simulating interdependencies between critical infrastructures with the special focus on the heterogeneous environment of municipal crisis management.

Methodology / Approach

In order to address the aforementioned gap and enable a comprehensive analysis of existing dependencies in the context of municipal crisis management, a methodology for conducting network analyses in municipal administrations is being developed as part of a currently running scientific project, which pursues a mixed methods approach.

The methodology employed in this study is based on a semi-quantitative process survey. The BSI 200-4 Standard (Bundesamt für Sicherheit in der Informationstechnik 2023) and ISO 22301 (Deutsche Norm DIN EN ISO 22301:2019) were used as the theoretical framework. Internal dependencies within the organization under consideration (in this case, the municipal administration) are first recorded and quantitatively modeled. Lauge et al. (2015) adopted a comparable approach, albeit in this instance, the dependencies between KRITIS were solely documented through expert interviews. Their work did not seek to undertake an analysis of internal dependencies, nor did it aspire to provide a comprehensive analysis of dependencies.

Following the approach of Rinaldi et al. (2001),the collected data is used to model physical, logical, IT and geographical dependencies using graph theory models. The model should be structured in such a way that both internal and external dependencies can be examined. In the third and final step, a simulation framework will be developed that will enable users to simulate and examine various failure and recovery scenarios for the modeled processes. This is based on agent-based simulations such as those by Mohebbi et al. (2025).

The validation of the methodology and the results is supported by qualitative interviews based on Mayring's methodology (Mayring 2002).

Findings / Results

The endeavour is currently in its initial phase. By the time of the conference, we will present the methodology as well as initial validation and empirical results.

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Disasters as critical moments. Towards a field-theoretical approach to the resilience of disaster management.

Sandra Maria Pichler
Disaster Competence Network Austria, Austria, sandra.pichler@dcna.at

Abstract

While the set of agents and institutions typically referred to as *disaster management (DM*) are the primary providers of disaster relief and prevention – thus, a key component of community resilience –, research on how disaster management itself is affected by disasters and subject to severe pressure remains scarce. This paper proposes a field-analytical framework to analyze how DM is put under pressure in disaster situations. It conceptualizes DM as a space of specialized practices – i.e., a social field – co-created by a heterogeneous set of agents and institutions. With the state bearing primary responsibility, DM is partly embedded in the bureaucratic state field, and public authorities are placed in a key position. Drawing on a case study of a mudslide disaster, the paper examines how structural dissonances emerge within the field, triggering adverse dynamics. By understanding the field as an ensemble of structural components, the proposed framework enables a nuanced and comprehensive understanding of the pressure exerted on the field of DM. Thereby, it delivers a blueprint for further analysis of resilience practices in the field, meaning how field agents mitigate pressure to maintain the field's functionality and structures.

Keywords: field analysis; disaster management, resilience

Introduction

Over the last decades, disaster scholars studied how disasters affect communities and various spheres of social action. Numerous studies examined the cornerstones of community resilience, and how the set of agents and institutional arrangements typically referred to as *disaster management (DM)* provides relief and prevention, thus, contributes to community resilience.

However, as argued in the proposed paper, disasters constitute "critical moments," (Bourdieu, 1988, p. 159), in which DM itself is put under severe pressure. Therefore, its ability to maintain its functionality and overall structure, i.e., the resilience of DM, becomes an additional challenge. Nevertheless, research on the resilience of DM as a relational configuration of a set of institutions and agents, and the practical dynamics, through which resilience is challenged and organized, remain scarce (Barton & Sutcliffe, 2023; Boin & van Eeten, 2013). Indeed, disasters have long been conceptualized as moments of "fundamental disruption" (Perry, 2018, p. 14) – e.g., of routines (e.g., Stallings, 1998), knowledge (e.g., Boin et al., 2009), or imbalances between needs and delivery by DM (e.g., Quarantelli, 1985). Also, some scholars examined how emergency organizations (French et al., 2021) or emergency management networks (Berthod et al., 2015; Son et al., 2020; Steen et al., 2022) address the challenges

associated with disasters, i.e., turn out to be resilient. Nevertheless – like for general resilience research, which was criticized for being built on a "rather weak empirical and theoretical basis" (Boin & van Eeten, 2013, p. 443) – there is still a lack of comprehensive analytical frameworks and detailed examination of how disaster dynamics spill over into the relational configuration considered *DM,* how disruptive dynamics unfold and interrelate, putting severe pressure on DM, and how this pressure is mitigated in order to maintain DM's overall functionality and structure. This paper contributes to that gap by approaching DM from a field-analytical perspective, and unfolds a nuanced understanding of how the *field of DM* is put under pressure at multiple points in disaster situations.

Theoretical Approach

The proposed paper suggests applying a field-analytical framework to DM inspired by Bourdieusian thinking for a differentiated and nuanced understanding of how DM is put under pressure at multiple points in disaster situations. It conceptualizes disaster management as a social field (hereafter called field of DM). With the state bearing primary responsibility, the field of DM is partly embedded in the bureaucratic state field (Bourdieu, 2014), with public authorities being placed in a key position, but spanned across a loosely coupled and partly fragmented network of heterogeneous agents and institutions, who co-create specialized practices and solutions to disaster-related problems. Drawing on a single case study of a mudslide disaster, it demonstrates, how the proposed framework enables a nuanced analysis of how disaster dynamics translate into the field and unfold pressure at multiple points. Moreover, it enriches the debate with a blueprint for further analyses of resilience in DM, and, thus, the most interesting puzzle, which is – according to Bourdieu – the ease of reproduction of a field's structure (Bourdieu, 2014)– even in its most challenging situations.

With this approach, it is in line with contributions, that acknowledge the potential of Bourdieusian theory (Uekusa et al., 2024) to understand the adverse dynamics in the field of disaster management, e.g., associated with unofficial responders (Merkes et al., 2024; Pichler, 2024), discursive struggles (Pfister, 2023), or individual resilience (Uekusa, 2017). However, to the authors' knowledge, none have applied Bourdieusian theory in a comprehensive manner to the field of DM and its resilience (problems).

Methodology

The proposed paper builds on theoretical reasoning and a single case study of a mudslide disaster. Closely following Bourdieu, theoretical and empirical reasoning go hand in hand, meaning neither to test a rigid theoretical framework but to take it as "thinking tools" (Bourdieu & Wacquant, 1992, p. 160), which only become useful when applied to encounter practical problems, nor to put the specific case in the foreground, but taking it as a vehicle to empirically enrich the field-theoretical framework, and illustrate its potential for a more nuanced understanding of how pressure is put on the field. To obtain multifaceted insights on both the practical field dynamics in the disaster situation (single case level) and the field structures, it follows the principle of data and method triangulation, conducting a document analysis of the administrative file of the disaster operation, and qualitative interviews with incident managers and agents involved in the OR. Data analysis follows qualitative text analysis (Kuckartz, 2014),

which can be applied to vast and heterogeneous data corpora, and allows a combination of deductive and inductive coding, which accounts for the theoretical richness and empirical openness required by the suggested approach.

Results

The paper demonstrates that a field-analytical framework enables a comprehensive and nuanced analysis of the diverse points, at which the field of DM is put under pressure in the wake of disasters. Drawing on previous theoretical contributions to the dynamics of change within Bourdieusian theory (Fowler, 2020) and potential lines of friction (Kropf, 2018) instead of structural homology (Bourdieu 2000), it models the field of DM as an ensemble of structural components. Drawing on the case study, it illuminates structural dissonances that occur in the field ensemble in the wake of disaters and unfold adverse dynamics, which put pressure on the field.

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Assessing and Enhancing Crisis Management in German Municipal Administrations

Alexandra Schmitt 1, Nicolas Bock 2, Peter Windsheimer-Kolla 3 1 Institute for Public Safety and Emergency Management, University of Wuppertal, Germany, a.schmitt@uni-wuppertal.de 2 Disaster Research Unit, Freie Universität Berlin, Germany, nicolas.bock@fu-berlin.de 3 Disaster Research Unit, Freie Universität Berlin, Germany, peter.windsheimer@fu-berlin.de

Abstract

A project investigates crisis preparedness in German municipal administrations, focusing on a rural district and a metropolitan city. Initial findings from literature reviews, a historical analysis, interviews, and workshops identify 57 crisis fitness indicators. The project aims—among other things—to develop a self-assessment tool to help municipalities evaluate and enhance their crisis readiness. Early results and planned future research will be presented and discussed.

Keywords: municipal crisis management; oganizational learning; knowledge management; prevention

Introduction

Municipal administrations, as the administrative level closest to the population and embedded within the federal system, play a central role in crisis management (CM)—a complex and multifaceted task, particularly in times of multiple or overlapping crises (Floeting, 2023; Schätzle & Trapp, 2025; Schütte et al., 2023). The project aims to support municipal administrations in Germany in assessing and improving their crisis preparedness. Project goals are the development and implementation of tools and recommendations for tackling these complex tasks and becoming more resilient. The following section presents the initial findings which will be further elaborated at and supplemented until the conference.

The Project

The research project is funded by a Federal Ministry. Coordinated by an Institute for Public Safety and Emergency, the project brings together academic and practice partners, a large city in North Rhine-Westphalia, and the district of Vorpommern-Rügen. The latter two represent our model municipalities. The project combines historical, legal, and social science approaches to develop a holistic understanding of CM, encompassing prevention, preparedness, response, and recovery.

One of the project's goals is to develop a freely accessible self-assessment tool (SET) that enables local authorities to evaluate their crisis fitness and identify areas for improvement. To this end, initial crisis fitness indicators (CFIs) have been identified, and a historical analysis of municipal CM has been completed. This contribution summarizes key findings to date and outlines the next steps for the continued identification of CFIs for the SET.

Crisis Fitness Indicators

Initial CFIs were identified through a comprehensive academic and practice-oriented literature review of scientific literature, relevant standards and legal principles. These findings were further elaborated upon by several workshops and guided interviews with administrative staff from the two model municipalities. Across all formats, the results confirmed the relevance of the 57 CFIs identified to date—e.g. a suitable knowledge management (Olfermann & Bhatti, 2022), resource registers (McManus et al., 2007), CM plans (DIN Deutsches Institut für Normung e. V., 2022), performing internal communication and public relations (Hustedt, 2019), regular joint training (Graf et al., 2024) and integration of CM into administrative education. Furthermore, further indicators were uncovered—e.g. the accessibility of relevant stakeholders (Kommunal Agentur NRW, 2020), and to view CM as a task for the administration as a whole. Each individual CFI is described in detail, including key questions for measuring it in the SET.

Historical Development of municipal CM

A further contribution towards a holistic understanding of communal CM is provided through the yet unpublished report on the historical development of municipal CM. It highlights recurring challenges in responsibilities, communication, and cross-organizational cooperation faced by communal actors during different crises scenarios across time. Examples for such scenarios include flooding events—like the North Sea flood of 1962 in Hamburg and the Elbe flood of 2002—, heatwaves, winter storms, the Chernobyl disaster as well as the war in Ukraine. Furthermore, the report outlines the legislative development of CM and civil defense in Germany and highlights past challenges in municipal CM and their responses, underlining the need for a multifaceted and comprehensive approach.

Knowledge Management as Exemplary CFI

Not least because of the demographic change and the impending loss of a large cohort from the labour market, knowledge management plays a crucial role in municipal CM (Joormann, 2017). Well-documented and accessible knowledge is a key component of effective CM across all phases of CM (Schulte et al., 2024). Therefore, this CFI assesses whether and how relevant information is collected, structured, and systematically recorded during crises, the preparation for and follow-up of crises. It also evaluates whether this knowledge is effectively shared within the administration—both horizontally across units and vertically across hierarchical levels. Additionally, it considers whether past crises or incidents are analyzed, documented, and used to derive concrete measures. Key questions of the SET address:

- Availability of central knowledge repositories (e.g., digital handbooks, wikis)
- Currency and quality of content
- Mechanisms for capturing and sharing tacit knowledge
- Organizational culture, including training and promotion of knowledge sharing.

Prospects

To capture the complex structures of CM in Germany, the next project stages include: categorizing CFIs by overarching themes as well identifying additional relevant aspects, conducting stakeholder analyses, compiling a legal register for municipal CM, and gathering civil society perspectives through a telephone-based population survey. In parallel, training and education formats for municipal CM are being developed; their requirements will be defined during the project in cooperation with the model municipalities.

By presenting these initial findings, this paper aims to highlight the potential of the project for strengthening municipal resilience and crisis preparedness and to provide a basis for further discussion at the conference.

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Institutional transformation under external pressure: (Re)constructing civil defence within a Swedish County Administrative Board

Gertrud Alirani, PhD[1] Erna Danielsson, Professor[2] Christine Große, Associate Professor[3] Sophie Kolmodin, Phd student[4] Pär M. Olausson, Associate Professor[5] Olof Oscarsson, PhD[6]

1 Risk and Crisis Research Center (RCR), Mid-Sweden University, Sweden, Gertrud.alirani@miun.se

2 Risk and Crisis Research Center (RCR), Mid-Sweden University, Sweden, erna.danielsson@miun.se

3 Department of Computer Science, Electical and Space Engineering, Luleå University of Technology, Christine.grosse@ltu.se

4 Risk and Crisis Research Center (RCR), Mid-Sweden University, Sweden, sophie.kolmodin@miun.se

5 Risk and Crisis Research Center (RCR), Mid-Sweden University, Sweden, par.olausson@miun.se

6 Risk and Crisis Research Center (RCR), Mid-Sweden University, Sweden, olof.oscarsson@miun.se

Since Russia's invasion of Ukraine, the European security architecture has undergone profound transformation. In Sweden, this altered geopolitical context has triggered extensive changes across national, regional, and local levels. Most notably, policy orientation has shifted from preventive measures targeting locally confined and specific crises towards a broader emphasis on resilience and *total defence (*MSB, 2025). This reorientation has become even more pronounced following Sweden's accession to NATO, signalling a fundamental recalibration of national security priorities.

Within the framework of Swedish total defence, the regional authorities—embodied by the County Administrative Boards (CAB)—are important actors, mandated to coordinate across a wide array of societal actors: from individual citizens to private enterprises, from municipalities to national agencies, and between civil and military defence structures. Such a mandate spans multiple policy domains and governance levels, demanding cross-sectoral collaboration and institutional adaptability.

At the same time, the CAB themselves must be organised to ensure institutional resilience and operational continuity in the face of crises, heightened alert, or, ultimately, armed conflict. As autonomous entities, they are not bound to a uniform organisational model; instead, each of Sweden's

21 CAB's must design an internal structure tailored to its specific circumstances and strategic considerations.

To explore how such institutional restructuring unfolds in practice, this article presents a case study of one CAB's approach to internal reorganisation in response to total defence requirements. Like several other CAB's, the selected case has opted to establish a distinct *wartime organisation*, separate from its everyday administrative structure. This configuration deliberately scales down the CAB's ordinarily broad mandate to the core functions required under conditions of armed conflict, thereby enabling more focused and resilient crisis governance.

Empirically, the analysis draws on interviews conducted in 2025 with managers at various hierarchical levels as well as with staff members responsible for security, total defence, and risk assessment. These interviews aimed at gaining deeper insight into how both managers and employees perceived the structure, feasibility, and internal reception of the organisational changes. In addition, the study explored how the CAB's crisis preparedness function—primarily concerned with preventive measures—might be reorganised and repositioned to effectively support the emerging demands placed upon Sweden's total defence architecture.

To interpret these findings, the study draws on institutional theory to better understand the underlying dynamics of organizational change. Specifically, it provides an illustrative example of how institutions evolve through the interplay between external pressures—such as NATO membership and the war in Europe—and internal interpretations and normative frameworks. The analysis is grounded in W. Richard Scott's (2014) institutional theory, which identifies three pillars that support institutions:

- Regulative pillar – formal rules, laws, and sanctions.
- Normative pillar – values, norms, and expectations.
- Cultural-cognitive pillar – shared beliefs and taken-for-granted understandings of reality.

The study demonstrates how the CAB is adapting its internal organization to meet new demands within the framework of total defence, particularly in light of Sweden's accession to NATO. It also highlights how external regulations and national security strategies influence internal organizational structures in diverse ways across the Board.

Building on this institutional lens, the study also uncovers a normative shift from a focus on preventive crisis management to a broader emphasis on resilience and total defence. This shift suggests a redefinition of what is considered the "appropriate" way to organize and prioritize in a new security policy context. However, the findings also indicate that this shift is not uniform across the organization; different parts of the Board interpret and implement these changes in varying ways.

This shift in priorities is further reflected in the CAB's decision to establish a total defence organization, which may be seen as institutionalizing new interpretations of what constitutes essential societal functions under heightened state of alert. For the leadership, this may involve developing a new understanding of the agency's role in a transformed security environment.

Scott's institutional theory thus provides a useful lens for understanding this case as an example of institutional change driven by the dynamic interaction between external pressures (e.g., NATO, geopolitical conflict) and internal meaning-making processes.

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Eroding Administrative Capacity: Understanding the Creeping Crisis in Public Administration

Paula Gnielinski (University of Potsdam), Philipp Gräfe (Ruhr-Universität Bochum), and Liz Marla Wehmeier (University of Potsdam)

Abstract

As public administrations are increasingly under pressure, with limited internal capacities, expanding policy demands, and the challenge of navigating overlapping external crises, they are less able to perform their tasks reliably and efficiently. This affects governments' overall performance and citizens' trust, fuelling criticism and calls for reform. Yet, while public and academic debates focus heavily on administrations' capacity to respond to current external crises, far less attention is paid to the internal incremental challenges that may gradually accumulate into a creeping crisis. This study asks whether decreasing administrative capacities constitute and are perceived as a creeping crisis, and how administrations respond. Based on expert interviews with 25 German public officials in leadership positions across four policy areas and different federal levels, the preliminary findings show that cross-cutting limited administrative capacities indeed display the dynamics of a creeping crisis and a perceived emerging threat to the functioning of public administrations. The study contributes to research on administrative capacity and crisis governance by demonstrating that creeping crisis can originate from within public administration itself and should be dealt with as such *[further to come]*.

Keywords: Administrative Capacity; Creeping Crisis; Public Administration; Legitimacy; Germany

Introduction

In recent years, public administrations have increasingly struggled to deal with external as well as internal pressures and disturbances. In many policy areas, cross-cutting implementation problems can be observed, with underlying issues ranging from a lack of resources to the complexity of policy and more. However, these problems do not manifest themselves as sudden crises but develop gradually without an immediate response (Boin et al., 2021).

So far, it is unclear whether and how public administrations react to issues that do not occur as exogenous shocks but develop incrementally and cumulatively – so-called creeping crises (Boin et al., 2021) – within the public sector. While much political and academic attention is paid to implementation deficits on the one hand, and public administrations' responses to external sudden crises on the other hand, little research has been done into whether implementation deficits might themselves constitute a creeping crisis; and if so, what organisational consequences follow from this.

Thus, the aim of this study is to understand in how far limited administrative capacity of public administrations can be considered as creeping crisis, whether administrations perceive it as such, and how they cope with limited administrative capacities under crisis conditions.

Theoretical background

In the political-administrative system, public administrations are responsible for implementing policy, thereby facing numerous challenges on a daily basis. Yet, when seemingly small issues in day-to-day operations go unnoticed or unaddressed, they can gradually accumulate and eventually impact administrations' capacity to act. While administrative capacity is typically defined in local government research as a municipality's overall ability to function based on local autonomy, stable financial revenues alongside functional responsibilities, intergovernmental relations, and territorial and political profiles (Kuhlmann et al., 2022), it can also be framed as the problem-solving capacity of the modern state (Wegrich & Lodge, 2014). Thereby, administrative capacity can be divided into four dimensions, namely analytical, regulatory, delivery, and coordination capacity (Wegrich & Lodge, 2014).

In this study, we explore how systematic deficiencies in administrations' ability to meet the expectations along those four dimensions can constitute a creeping crisis. A creeping crisis is conceptualised as a slow-burning crisis, incubating over extended periods and resurfacing intermittently, thereby constantly evolving over time and persisting indefinitely (Boin et al., 2020). The ambiguity surrounding the concept of creeping crises raises the question of when and how administrative capacity is collectively perceived and interpreted as a (creeping) crisis. Thus, this research examines administrative capacity in terms of four interlinked dynamics (Boin et al., 2021):

1. the emergence and gradual development of threat potential
2. the foreshadowing of the threat through precursor events
3. the shifting nature of threat attention
4. the partial or insufficient response to the threat

Methodology

The study aims to understand in how far cross-cutting limited administrative capacity of public administrations can be considered as creeping crisis, if administrations activate a "crisis mode", and how they (re)configure administrative capacities. For this purpose, it is based on semi-structured expert interviews with 25 public officials across different federal levels, including federal bodies as well as subnational (*Länder*) agencies and local government. For the selection of interview partners, we followed a purposive sampling approach, focusing on relevant actors from four different policy areas: job centres, road constructions, immission control approval procedures, and skilled labour immigration. Interviews were conducted between October 2024 and February 2025, either via video call or in person. The transcripts were analysed via qualitative content analysis, following an abductive approach using MAXQDA software.

Preliminary empirical findings

The preliminary findings show that limited administrative capacities indeed display the dynamics of a creeping crisis. The interviewees perceived a reduction in administrative

capacity. In particular, the analysis shows a relatively low delivery capacity across all policy areas, where public officials do not perceive themselves as able to provide their respective public services in the desired quality, quantity, and speed. As a consequence of lacking resources and other capacities, public administrations tend to focus on compulsory tasks while purposefully neglecting other facultative tasks left at the discretion of the respective organisation. Moreover, a lack of enforceability and a high complexity of legal regulations lead to substantial additional workload and, in some cases, unintended interpretations of the law by enforcement authorities.

Despite differences across the studied policy areas, there is a strong indication that public officials perceive an emerging threat to the functioning of their administrations that is being inadequately addressed, but only in social policy matters, a real administrative crisis perception emerged. However, the analysis did not show a shift to a genuine crisis mode in response to this threat in any of the administrations, which can be attributed to overshadowing urgent crises on one side and a limited scope for action on the other. Nonetheless, the preliminary findings reveal different coping mechanisms as strategic responses to addressing what we consider a creeping crisis originating from within public administration.

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Civil protection exercises as laboratory of governance

Jurgena Kamberaj[1], Simon Aebi[2] Dr. Myriam Dunn Cavelty[3]
1 Center for Security Studies-ETH-Zürich, Switzerland, jurgena.kamberaj@sipo.gess.ethz.ch
2 Center for Security Studies-ETH-Zürich, Switzerland, simon.aebi@sipo.gess.ethz.ch
3 Center for Security Studies-ETH-Zürich, Switzerland, dunn@sipo.gess.ethz.ch

Abstract

Local authorities increasingly face crises that are complex, cascading, and cross-border. Civil protection exercises provide structured environments to test capabilities and coordination, yet their strategic potential remains underused. Drawing on a study commissioned by the Swiss Federal Office for Civil Protection, this article analyses three exercises observed in 2024: an international European Union earthquake simulation, a national nuclear emergency exercise, and a regional drought tabletop exercise. The cases show that exercises can extend beyond operational training to support governance validation, diplomatic engagement, and policy innovation. However, their impact is constrained by weak feedback loops for institutional reform, limited involvement of political actors, and the absence of a strategic exercise doctrine. Embedding civil protection exercises more firmly into governance processes would enhance institutional resilience and better equip local authorities to manage interconnected risks.

Keywords: Civil protection; exercises; strategic; governance

Introduction

Local authorities stand at the frontline of crisis management. They are responsible not only for delivering essential services but also for ensuring continuity when disruptions occur. In this role, they form a core component of civil protection systems, which provide the backbone for managing emergencies and safeguarding populations (Niinistö, 2024). The effectiveness of these systems depends not only on operational readiness but also on adaptation, coordination, and foresight. In federal systems such as Switzerland, responsibilities are distributed across local, regional, and national levels, requiring strong vertical and horizontal coordination. This multi-level governance becomes even more critical in a risk landscape defined by cascading hazards, cross-border interdependencies, and polycrises, where international cooperation is indispensable (Eriksen et al., 2023).

Exercises are among the most effective instruments to prepare for these conditions. They provide structured environments to test capabilities, validate coordination mechanisms, and anticipate vulnerabilities. In civil protection, however, exercises are still mostly regarded as technical or operational drills. Unlike in the military domain, where their strategic value is well established, their potential to reinforce governance, enable diplomatic engagement, and foster policy innovation remains underexplored.

This article draws on a study commissioned by the Swiss Federal Office for Civil Protection. Its aim is twofold: first, to conceptualise how exercises can also generate strategic value in the domain of civil protection; and second, to illustrate this potential through three case studies placed at the international, national, and regional level. While grounded in the Swiss context,

the findings speak to broader debates and offer lessons relevant for local authorities in other federal and decentralised systems worldwide.

Methodology:

Our research employed a qualitative, multi-method approach combining three strands:

- Desk research: Review of international and Swiss policy frameworks, and related guidance on exercises.
- Field observations: Participation as observers in three exercises in 2024:
    - Magnitude: international, earthquake scenario, Germany.
    - General Emergency Exercise (GNU): national, nuclear accident scenario, Switzerland.
    - Tabletop "Drought": regional, slow-onset hazard, Switzerland.
- Expert interviews: Four semi-structured interviews with eight practitioners and officials from Switzerland, Germany, the EU, and Australia, involved in exercise design, implementation, or evaluation.

Key findings from case studies

The three case studies highlight how exercises can generate strategic value at different scales of governance:

1. Magnitude and diplomatic engagement

At the international scale, the Magnitude exercise underscored the diplomatic and integrative value of cross-border preparedness. Diplomatic engagement in this context refers to how participation in joint exercises strengthens trust, visibility, and alignment among states and institutions. For Switzerland, a neutral non-EU country, Magnitude was a test for operational readiness of its search and rescue teams and a signal of political intent to deepen cooperation with the EU Civil Protection Mechanism. The exercise showed that international formats connect not only systems but also people. Teams built trust in partner capabilities and overcame linguistic and cultural differences through standardised protocols. For public administrations and local authorities, this matters because trust and interoperability established internationally cascade down to local implementation, ensuring that municipal responders can integrate into multinational operations when required.

2. GNU and governance validation

At the national scale, GNU revealed how exercises formally organised with an operational focus can also function as instruments of governance validation. This means testing whether institutional arrangements, decision-making processes, and political responsibilities hold together under crisis conditions. Beyond nuclear power safety procedures, GNU assessed institutional performance under uncertainty, time pressure, and interdependences. The broadened participant base, including critical infrastructure operators, reflecting on a whole-of-society approach and enhanced coordination realism. Preparatory activities created space for analytical and political reflection, showing that strategic value emerges not only during the exercise itself but also in its design. Finally, the deliberate involvement of regional political

leaders linked operational response with political decision-making, exposing the interdependencies between levels of authority and between technical execution and governance.

3. Tabletop “Drought” and policy innovation

At the regional level, the drought tabletop exercise demonstrated how modestly resourced simulations can serve as laboratories for policy innovation. They create a safe space to test new coordination mechanisms and governance arrangements before they are needed in practice. By simulating regional drought task forces, the exercise moved a largely theoretical coordination mechanism into an applied decision environment. This process exposed unresolved questions of inter-regional cooperation, resource allocation, and communication responsibilities, which are distinctive governance challenges of slow-onset hazards. For local and regional authorities, the exercise demonstrated that effective drought management requires clarified roles, stronger vertical coordination with national actors, and improved collaboration across regions to sustain governance over long-duration crises.

Discussion

The three cases show that civil protection exercises can create value beyond operational training. At international, national, and regional levels, they validated governance, strengthened diplomatic ties, and opened space for policy experimentation. Yet, these potentials remain only partly realised.

The first limitation is a weak feedback loop between exercises and reform. Lessons are documented but often remain siloed within technical communities. Without mechanisms to embed findings in policy or organisational change, exercises risk reinforcing routines rather than driving adaptation.

Second, exercises in civil protection remain dominated by technical and operational framings. Strategic actors such as elected officials or senior administrators are typically observers rather than participants. Unlike the domain of crisis management, where political engagement is central, civil protection exercises often exclude decision-makers from active roles. This limits their ability to test governance under stress or build legitimacy for reforms.

Third, civil protection lacks a doctrine for strategic exercises. Military and security fields have long traditions of using simulations to stress-test governance or signal political intent. In civil protection, scenarios usually focus on procedures rather than decision-making. The absence of structured guidance constrains their role as instruments of institutional learning, leaving untapped potential for shaping policy and governance.

Conclusion

Exercises can be more than technical drills. They can validate governance, strengthen international trust, and enable innovation in how institutions prepare for emergencies. The case studies highlight both opportunities and limitations: exercises succeed in revealing systemic gaps but fall short in embedding lessons, integrating political actors, and shaping reform. To address these challenges, civil protection needs a clearer doctrine for strategic exercises and

stronger involvement of decision-makers. Embedding exercises into governance processes would enhance their value as tools of institutional resilience, supporting local authorities facing an increasingly complex and interconnected risk landscape.

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Enabling Resilient Decision-Making through Effective Information Management

Timm Wielgosch University of Wuppertal, Germany, wielgosch@uni-wuppertal.de

Abstract

Crisis management is a key element of a government's and a local authority's capacity to withstand crises and disasters. As a part of crisis management crisis teams play a crucial role by safeguarding the administration's ability to lead and restore desirable conditions. Within these interdisciplinary teams, decision-making represents a central process. The resilience and quality of this decision making depend heavily on effective information management.

Keywords: Crisis Management, Decision Making, Resilience, Information Management, Critical Infrastructure

Introduction

Crisis management is an essential component of a community's ability to cope with crises and disasters. It is becoming more important, especially given the increasing frequency and intensity of climate-related events (Bevacqua et al., 2019; Sillmann et al., 2019; Li et al., 2021; Calvin et al., 2023; Gißler et al., 2024) . Crisis Management Teams (CMT) play a special role as temporary mergers of different functions, serving as a leadership instrument to maximize the performance of the overall management system (Gißler, 2019; Heimann & Hofinger, 2022). One of the core processes of these structures is decision making (DM) (Gißler, 2024a). It is crucial that this ability is permanently guaranteed to ensure the state and administration's ability to act in a crisis. Consequently, municipal governments not only play an important role in crisis management but are also considered to be critical infrastructures themselves. In addition to operational commands, which direct operational-tactical units, administrative teams in particular play a central role, as they make administrative and organizational decisions. These teams are characterized by pronounced interorganizational collaboration, combining expertise from various disciplines. DM is subject to a wide range of influencing factors. Practical experience and research show that DM processes must be designed to remain robust in order to enable appropriate decisions (Gißler, 2024b, 2024c; Klein, 2025; Wittke, 2025). In this regard, information management plays a key role: Adequate information management can therefore be seen as a necessary prerequisite for strengthening DM processes in crisis management (Wolbers & Boersma, 2013; Adami, 2016; Grace et al., 2025).

The Role of Information Management

Information management plays a central role in CMTs: it provides decision makers with relevant data and supports communication between different organizations (Künzer et al., 2022; Queck & Gonner, 2022; Schilling, 2022). In general, information is indispensable for virtually every type of decision, whether routine, stereotypical, reflective or constructive (Pfister et al., 2017). At the same time, information itself influences which type of decision or tendency is applied. Furthermore, it is essential to understand the holistic concept of information management. Information management is not only a technical task but also a comprehensive management philosophy that includes the interface between humans and machines (Krcmar, 2015). In addition to the technical infrastructure, it includes the systematic organization, preparation, operation, and optimal utilization of available information and communication technologies. Of particular importance is the socio-technical perspective, which considers technical, organizational, and human factors alike. However, information management faces numerous challenges: these include dealing with an overload of information or information gaps, insufficient digitalization, and a lack of practical experience in handling modern technologies (Bharosa et al., 2010; Garrecht, 2014; Künzer et al., 2022). In addition, there is often a lack of expertise to transform information into knowledge through contextualization, a requirement achieving reliable situational awareness and well-founded decisions (Bellinger et al., 2004; Heimann, 2022; Jifa, 2013). From this, it can be concluded that decision makers need both professional and technical support to convert information into actionable knowledge and act proactively in dynamic situations.

Decision-making Processes in Crisis Management

The concept of a crisis is multifaceted due to its use in various contexts. In the context of civil protection, a crisis can be defined as a threatening situation that deviates from normal conditions and is linked to damage to protected assets or at least has the potential to cause such damage. As a result, urgent action is required (Bundesamt für Bevölkerungsschutz und Katastrophenhilfe, 2011; Krings et al., 2017). Crises can be understood as dynamic processes whose course is strongly influenced by the decisions made, as illustrated in Figure 1. The possible outcome of a crisis range from a “positive solution” to the restoration of the “status quo ante”, a “negative solution”, or, in the worst case, disaster or escalation into additional crises (Merten, 2013). In this context, CMTs structures serve as a supporting tool for decision makers with the aim of restoring “normal” conditions as quickly as possible and minimizing the impact of the crisis. It can therefore be concluded that DM is a central process of CMTs, which also reflects the prevailing view in scientific discourse (Gißler, 2019; Drews & Fiedrich, 2024).

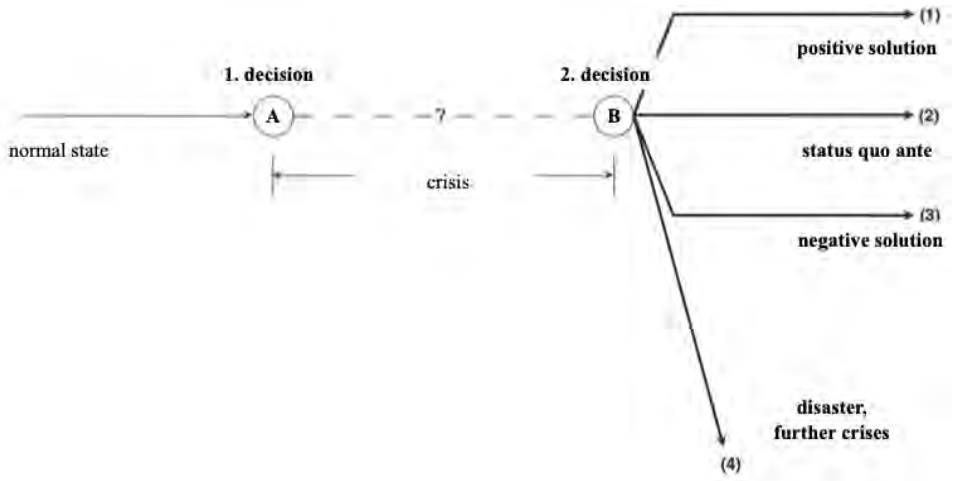


Figure 1. The structure of a crisis
Note. Adapted and translated (Merten, 2013, p.157)

Decisions, understood as the outcome of a selection process, differ significantly in crisis management from everyday DM situations. In a crisis, it is necessary to maintain a constant balance between time pressure and careful deliberation (Bédé, 2022). Based on the available information, problems and objectives are first identified and possible courses of action are developed. These alternatives are then compared, evaluated with the help of forecasts, and ultimately a decision is made. However, DM is often marked by uncertainities in the information available, contradictory data, and unclear impacts and feedback loops. Therefore, in practice, decisions can rarely be made with complete certainty. Usually, not all options, their consequences, or probabilities of occurrence are fully known, making it inevitable to choose a course under uncertainty (Klein, 2025). Figure 2 illustrates the tension between decisions making under uncertainty and the time dimension, which plays a central role in crises. The quality of information thus crucially shapes the initial conditions for DM.

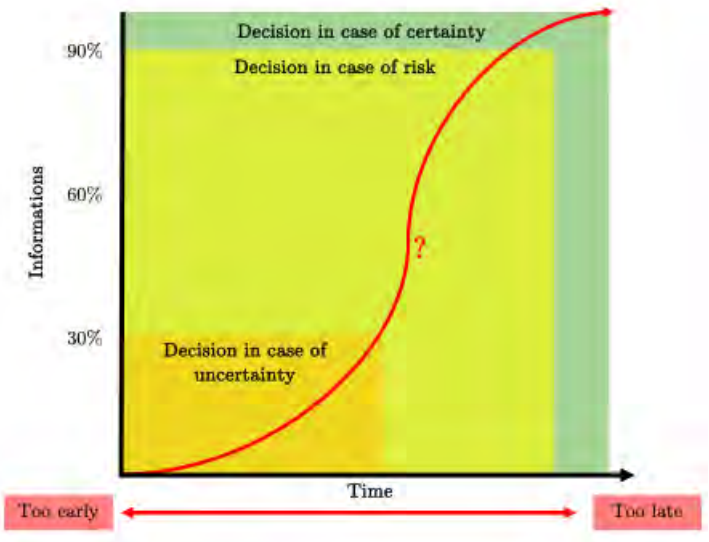


Figure 2. Decision status with different levels of information
Note. Adapted and translated (Thielmann, 2022, p.168)

At the same time, it should be noted that the terms data, information, and knowledge should not be used interchangeably. For data to become information and knowledge, it must be given meaning, collected systematically, and connected to existing knowledge (Bellinger et al., 2004; Jifa, 2013; Wiedemann et al., 2024). The review of the 2021 flood disaster in the Ahr Valley in Germany clearly shows that although the necessary information was available, it could not be transformed into actionable knowledge due to excessive demands or a lack of professional expertise (Gißler, 2024c, 2024b). As a result, it was not possible to effectively assess and develop alternative courses of action and measures. In conclusion, it should be emphasized that resilient information management is vital to effectively support the core process of DM.

Purpose

Building on the relevance of the topic outlined above, this contribution presents initial insights from the underlying research project. These insights are derived from a systematic literature review and a qualitative analysis of expert interviews and serve to indicate emerging requirements for information management and DM processes in CMT.

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Local Government Resilience: Lessons from Post-Disaster Recovery in Three U.S. States

Ali Nejat[1], Rodrigo Costa[2], Sara Hamideh[3], Ashley Ross[4]
1- Associate Professor, Department of Civil, Environmental, and Construction Engineering, Texas Tech University, Texas, USA - ali.nejat@ttu.edu
2- Assistant Professor, Department of Systems Design Engineering, University of Waterloo, Waterloo, Canada - rodrigo.costa@uwaterloo.ca
3- Associate Professor, The School of Marine and Atmospheric Sciences, Stony Brook University, New York, USA - sara.hamideh@stonybrook.edu
4- Associate Professor, Department of Marine and Coastal Environmental Science, Texas A&M University, Texas, USA - ashleydross@tamug.edu

The governance of disaster recovery has become increasingly complex in an era characterized by institutional, economic, and climatic challenges. For some communities, compounding challenges represents a persistent condition shaped by overlapping environmental risks and hazards, economic uncertainties, and shifting social dynamics. The burden of these complex and compounding challenges falls heavily on subnational governments facing dual challenges: maintaining critical infrastructures that are vulnerable to disruption and implementing large recovery programs after their communities face major disruptions. In this context, the administration of disaster recovery funds, particularly housing assistance, offers a revealing lens into how local governance systems manage disruption in practice. While significant federal resources are allocated to states and local jurisdictions in the United States following disasters, the ability of these funds to translate into tangible recovery outcomes depends heavily on the organizational capacities and priorities of subnational actors, among many other factors. Rarely have researchers examined how local government capacities and priorities interact with the external dynamics of federal and state governments, as well as broader socioeconomic systems, to shape recovery trajectories.

This research examines the administration of disaster housing recovery funds in the US, specifically Community Development Block Grant – Disaster Recovery (CDBG-DR), across the three most populous and disaster-prone U.S. states: Texas, Florida, and California. Drawing on our work conducted through the HUD Center for Capacity-building for Resilient Housing (CECREH) and a CAREER project funded by the National Science Foundation, we analyze how these local and states agencies navigate the complex processes of estimating, obligating, disbursing, and expending recovery funds in the aftermath of Hurricanes Harvey (2017, Texas), Irma and Ian (2017 and 2022, Florida), and the 2017 Wildfires and Mudflows (California).

We employ a mixed-methods approach that combines qualitative and quantitative data sources and analyses to explore the role of government capacity in disaster recovery management. Data drawn from semi-structured interviews with administrators of housing assistance programs (i.e., state agency officials, program managers, consultants, and local grantees). Interviews, focused on perceived challenges, decision-making logic, and adaptive strategies in administering CDBG-DR funds, are analyzed for emergent themes related to government capacity. On the quantitative side, we systematically analyzed financial trajectories of CDBG-DR funding allocations, obligations, disbursements, and expenditures, drawn from quarterly progress reports (QPRs) as well as State Action Plans (SAPs) and their amendments. For each case, we examined four key expenditure categories: housing reconstruction and rehabilitation, new housing construction, program administration costs, and reconstruction of public facilities over a multi-year recovery horizon. This analytical approach reveals patterns and cases of fund redirection and shifts in priorities, delays, and mismatches between obligated and expended amounts, as well as effective and innovative use of flexible funds thereby offering insights into the underlying capacity of subnational actors in disaster recovery. The mixed method analysis highlights the ways in which organizational capacity both enables and constrains recovery, producing distinct patterns within and across states.

Our findings underscore substantial variation across states in how obligated funds were managed, reflecting both differences in organizational capacity and broader governance approaches. In California, housing reconstruction funds expenditures illustrate the challenges of aligning obligation trajectories with expenditure capacity. Midway through the multi-year recovery period, obligated funds for housing reconstruction rose sharply, suggesting ambitious programmatic commitments. However, by the end of the period, expenditures fell significantly short, amounting to only about one-third of the obligated total. Specifically, the single-family housing reconstruction program funded by CDBG-DR was significantly undersubscribed, a pattern observed after other disasters as well. A critical factor was the lengthy and burdensome application process, which caused many homeowners and tenants to forego assistance in favor of handling repairs independently. The California Department of Housing and Community Development's (HCD) single-family program was delayed for years, with grant applications for survivors of the 2017 wildfires and mudflows not being released until early 2020. This outcome revealed a significant mismatch between the program's design and the urgent, "turbulent conditions" of household-level recovery.

In contrast, Florida demonstrated a more incremental, stepwise approach. Obligated housing reconstruction funds began at relatively high levels and increased gradually over the multi-year recovery period. Importantly, expenditure closely tracks obligations, converging by the end of the period. While obligated reconstruction funds increased over time and expenditure eventually tracked with obligations, this was not a seamless process. The state was forced to amend its action plan repeatedly, reallocating funds due to budget shortfalls and rising construction costs. Despite efforts, the recovery was hampered by significant delays, administrative burdens for homeowners, and low program completion rates for years after the storm.

Texas exhibited yet another trajectory. Following Hurricane Harvey, Texas took a rapid approach to its CDBG-DR housing recovery, with a large sum of funds obligated soon after the disaster to address urgent housing needs. The state maintained a high level of funding over the subsequent five years, and expenditure ultimately converged with the total allocated funds. This sustained commitment highlights the state's capacity to manage long-term recovery, yet the process was not without hurdles. While the funding was sustained, administrative and procedural delays, including issues with the managing entity (Texas General Land Office), affected the speed of program delivery, causing frustration and years of waiting for many residents to receive assistance. The state's approach demonstrates the benefits of a decisive, large-scale funding response for recovery stability but also underscores the risks of a rigid funding structure that may limit adaptability when local conditions and individual household needs evolve over a prolonged period.

Taken together, these findings highlight that delays and challenges in disaster recovery are not only a function of external crises but also of internal administrative capacity and accurate knowledge of community needs. The trajectories observed across California, Florida, and Texas demonstrate that even when federal funds are made available at scale, their effectiveness depends on the ability of subnational actors to align obligations with realistic implementation pathways. California’s case in particular illustrates that ambitious obligations can be hampered by delayed implementation and generate significant gaps, leaving resources underutilized and communities underserved. Florida’s case demonstrates the importance of incremental, flexible alignment between obligations and capacity, while Texas highlights the value of consistency but also the

limits of rigidity. Understanding these dynamics is critical for designing governance strategies that are both adaptive and equitable.

By framing disaster recovery governance through the lens of compounding challenges and capacity, this study contributes to advancing both theory and practice. For policymakers, the findings underscore the importance of coupling financial allocations with investments in organizational capacity and inter-organization collaboration to ensure that obligated funds can be effectively expended. For practitioners, they suggest the value of embedding flexibility in funding mechanisms, so that resources can be adjusted to meet evolving community needs and administrative realities. For researchers, the comparative lens highlights how different governance logics—rapid stabilization, incremental alignment, or ambitious commitments—produce divergent outcomes under compounding challenges and uncertain conditions.

Ultimately, our analysis shows that disaster recovery is not simply about the size of the allocation but about the capacity to convert commitments into results. Recognizing compounding challenges as a persistent governance condition, rather than a temporary disruption, shifts the focus toward designing recovery programs that are flexible, capacity-sensitive, and adaptive. Such approaches are essential not only for addressing immediate crises but also for building the long-term resilience of communities that will increasingly face compounding challenges in the years ahead.

Resilience at the Heart of Crisis Management: Evidence for Crisis Management Teams in Public Administration

Gesine Hofinger[1], Fynn Spilling[2]
[1]Akkon University, Germany, gesine.hofinger@akkon-hochschule.de
[2]Akkon University, Germany, fynn.spilling@akkon-hochschule.de

Abstract

We address the resilience of crisis management teams in public administration which are responsible for ensuring the citizens' safety in times of crisis. Drawing on resilience research findings, combined with evidence from public administration and civil protection research, we create a set of relevant factors for the resilience of those teams. Thereby we particularly focus on processes as well as on aspects of intra- and interorganizational coordination, using the SHELL model of Human Factors. We apply those factors in five dimensions and verify them empirically in a workshop and additional interviews with members of crisis management teams. Thus, this approach enhances the understanding of resilient crisis management teams and demonstrates the benefits of applying the SHELL model to public administration and crisis management.

Keywords: Resilience; Emergency Control Centers; Public Administration; Crisis Management Teams; Local Governance

Extended Abstract

In recent years, there has been an increasing number of crises, often occurring in rapid succession or triggering one another. This has led the term 'polycrisis' to gain popularity within academic discussions. It is characterized by the fact that crises no longer appear in isolation, but are instead caused by one another as a result of an increasingly globalized and interconnected world (Lawrence et al., 2024). While the modern state's primary function is providing protection for its citizens, the public sector is facing an increasing demand to ensure peoples' safety. Dealing with turbulence has become a permanent challenge for those responsible, bringing the spotlight to the affected entities in the public sector. Previous research has focused on crisis management in public administration in general (Boin & Lodge, 2016; Christensen et al., 2016; Tokakis et al., 2019), and the concept of resilience management as a proactive effort to enhance a system's resilience has become prevalent in many fields (Korang, 2025; Shekarian & Mellat Parast, 2021). Surprisingly, however, the question of how these entities maintain their ability to respond to crises has hardly been addressed. Research on crisis management and the resilience of public administration has rarely been connected (cf. Williams et al., 2017, p. 733) Therefore, we focus on the resilience at the heart of public administration crisis management itself, namely crisis management teams (CMT). We concentrate on CMTs of German local authorities ('Krisenstäbe' or 'Verwaltungsstäbe').

In our understanding, CMTs are teams that are activated in crisis situations to advise and support decision-makers. They are characterized by a division of responsibility and working within a predefined structure, which differs from ordinary administrative structures and they make use of specialized information flows (cf. Hofinger & Heimann, 2022, p. 4). The idea of CMT comes initially from the military and is also present in the civil protection literature, where the work of incident command teams, emergency services and law enforcement forces are studied. These CMTs are integrated into their specific organizational structure to ensure the execution of operational tasks. In contrast, the task of public administration CMTs is to satisfy the increased administrative requirements resulting from a crisis. Those teams can be activated either in addition to an operational CMT or independently (Gahlen, 2022). Recent examples on the local level can be found nationwide during the so-called 'refugee crisis' 2015 (Seibel et al., 2022) the COVID-19- pandemic (Thielsch et al., 2021) or during various local incidents.

Although the concept of resilience has spread from its origins into vast academic and public debates, it is not a one-size-fits-all solution and must be adapted to the respective context. Our goal is to identify the factors that enhance the resilience of public administration CMTs. To achieve this, we identified aspects from various fields of resilience research and combined them with findings from research on public administration and the operation of CMTs to create a set of relevant factors.

Through the lens of human factors research, we adapted the Human Factors model SHELL from aviation (Edwards, 1972 as cited in Hawkins, 2017, p. 20) to create a framework that provides resilience factors for administrative crisis management teams. The SHELL model contains five dimensions, enabling us to include relevant aspects systematically and consider the interfaces between them. 1) Software – including processes, rules, norms and all issues relating to how work is carried out. 2) Hardware – containing equipment, tools, furniture and other material resources as well as everything used for work. 3) Environment – including the physical and/or social aspects of the work atmosphere and considering the overall working conditions. 4) Liveware (I) – covering all aspects of the individual. This includes physiological, motivational and cognitive factors. 5) The final dimension, also described as Liveware (II), covers social interactions between individuals, including aspects of leadership and teamwork. Using this classification, factors that promote resilience of CMTs can be formulated for each dimension, which helps to bring the concept of resilience into an adaptable framework.

Having adapted the SHELL model to CMTs based on evidence from public administration and civil protection research, we presented the framework in a workshop involving various stakeholders working in coordination teams (both administrative and operational) and interviewed individuals responsible for administrative CMTs conducted as part our research project ReVerSy. Results show that the five dimensions of the model serve well as a framework for CMTs and stakeholders consider the model to be helpful for fostering resilience. But the framework also leads to a sharpening of the resilience concept as it combines advantages from different approaches. Especially processes of intra- and interorganizational coordination (e.g. with operational rescue forces) can be revealed and refines the understanding of a public administration entity with operational features. As a result, we also discuss questions related

to the conflicts between resilience factors (e.g. planning versus flexibility) and the practical application of resilience concepts within budgetary constraints.

The framework conceptualizes different approaches to resilience and can be a useful tool for users and resilience studies. Focusing on public administration, we combine crisis management and resilience research to shed light on resilience at the heart of crisis management. Additionally, the SHELL model of Human Factors is demonstrated to be a valuable instrument for multi-factor analysis in the context of humans working in complex environments.

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Resilience in the Making: Temporal Perspectives on Local Disaster and Civil Defence Management in Sweden

Sophie Kolmodin*, Olof Oscarsson **
*** Mid Sweden University, Risk- and Crisis Research Center (RCR)**
sophie.kolmodin@miun.se
**** Mid Sweden University, Risk- and Crisis Research Center (RCR)**
olof.oscarsson@miun.se

Research in Disaster management (DM) have long emphasized challenges encountered by DM professionals (Dynes, 1994), including the role of disaster planning (Perry & Lindell, 2003) , the role of material and financial resources in shaping DM (Kapucu et al., 2013) and the significance of collaboration and interorganizational networks in enabling effective coordination, information sharing, and joint problem-solving across institutional boundaries (Bodin & Nohrstedt, 2016).

Despite these valuable insights, we argue that one crucial dimension remains unexplored: temporality. By temporality we mean how time is understood, experienced, and enacted in DM practice. In this paper, we therefore, focus on how temporal assumptions shape the ways in which DM is conceptualised, negotiated, and transformed over time in local crisis governance. Our approach treats temporality not as a neutral backdrop against which crises unfold, but as an analytical lens for understanding how past events are reinterpreted, how present conditions are made sense of, and how futures are imagined in DM and civil defence contexts.

Temporal perspectives in disaster management

Research on disasters often adopts a linear conception of time (Kolmodin et al., 2019), framing time and disasters as a movement from “pre” to “during” and “post” phases (Abbott, 2016). This framing reflects conventional understandings of time as orderly, sequential, and measurable: work weeks, hours, and planning cycles divide and organise both professional practices and everyday life (Zerubavel, 2020). Within such a linear framing, disasters appear as discrete disruptions in otherwise stable systems, and DM consists of preparing for, responding to, and recovering from these disruptions. Even when the cycle is understood as repetitive—where the “post-disaster” phase sets the conditions for the next “pre-disaster” phase—the original event and its interpretations often remain fixed, rather than continuously re-evaluated in light of new developments.

Recent scholarship in organizational studies, however, challenges this linear view by emphasising temporality and processual ontology (Hernes, 2020). From this perspective, change rather than stability is the normal condition of social life (Abbott,

2016). Events are not final or closed but constantly in the making, interpreted and reinterpreted over time (Hernes, 2020). This processual view shifts attention from disasters as singular episodes to the ongoing practices through which meaning, responsibility, and action are constructed across past, present, and future horizons.

Empirical material and research context

Our analysis draws on two sets of empirical material from related but distinct research projects in Sweden.

The first dataset consists of nine interviews conducted in 2020 with individuals working in DM at the local level in four inland municipalities in northern Sweden. These interviews explored how local actors understood and organised DM in relation to both immediate hazards—such as extreme weather events—to broader efforts to build long-term resilience. The second dataset comprises ten interviews with local DM specialists and other actors responsible for the development and coordination of civil defence and total defence at local levels in a northern Swedish region. These interviews focus on how evolving security demands, including the re-establishment of total defence structures, reshape organisational roles, capacities, and collaborations across municipalities, county administrations, and regional authorities.

Together, these datasets allow us to analyse how ideas about DM are constructed, negotiated, and reconfigured across different local contexts in different temporalities. They also make it possible to trace connections between everyday DM practices and the shifting timeframes through which disasters are interpreted, re-interpreted as well as anticipated.

Temporality and local crisis governance

By combining processual perspectives with empirical analyses of local DM our study contributes to ongoing debates in two main ways. First, we show how temporal assumptions underpin local understandings of DM. For example, when DM is framed primarily around preparing for future events, this often draws on fixed interpretations of past events (“lessons learned”) and linear planning models. However, when time is understood as processual and open-ended, DM appears less as a state to be achieved and more as an ongoing negotiation shaped by uncertainty, shifting responsibilities, and evolving institutional arrangements.

Second, we demonstrate how temporality influences organisational practices. In our interviews, local actors described how changing security demands required not only new plans and capacities but also new ways of linking past experiences, present actions, and future scenarios. For instance, the re-emergence of total defence planning blurred boundaries between everyday DM, long-term risk reduction, and national security concerns.

Contribution and implications

We argue that temporality provides a useful analytical tool for understanding how DM is conceptualised and enacted in local crisis governance. Rather than treating disasters as isolated events, a temporal perspective highlights the processual nature of DM: how meanings, responsibilities, and actions are continuously made and remade across time. For research, this approach bridges debates on resilience, disaster management, and civil defence by showing how temporal assumptions shape both conceptual understandings and practical responses. For policy and practice, it underscores the importance of reflexivity: how local authorities interpret past experiences and imagine future scenarios directly influences organisational priorities, resource allocations, and collaborations in the present.

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Increasing resilience of state and public administration in Germany – sustainably and continuously

Maike Vollmer[1], Benjamin Lickert[2], Nils Krippner[3], Sorush Mirzaei[4], Fabian Kulms[5], Peter Mnich[6], Jan Seitz[7]
1 Fraunhofer Institute for Technological Trend Analysis INT, Germany, maike.vollmer@int.fraunhofer.de
2 Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach-Institute, EMI, Germany, benjamin.lickert@emi.fraunhofer.de
3 Federal Agency for Technical Relief, THW, Germany, nils.krippner@thw.de
4 Federal Office of Civil Protection and Disaster Assistance, Germany, sorush.mirzaei@bbk.bund.de
5 Fire Department Dortmund, Germany, fkulms@stadtdo.de
6 compleneo Consulting GmbH, Germany, mnich@compleneo-consulting.de
7 Technical University of Applied Sciences Wildau, Germany, jan.seitz@th-wildau.de

Abstract

The German research project RESKON addresses current and future challenges that public authorities face. It develops practice-oriented approaches for measuring and increasing resilience, both ad hoc and as part of a continuous improvement process. The results will be based on a heat-and-drought-scenario as well as a hybrid-crisis-scenario involving hybrid attacks and military deployments to NATO's eastern border. In addition, specific global trends are considered, which may essentially impact authorities' resilience.

Keywords: resilience; crisis management; public administration; megatrends

1. Introduction: How resilient are public authorities?

In a world shaped by global change, extreme weather, and hybrid threats, public authorities face increasing challenges. Initial analyses within the German research project RESKON (October 2024-September 2027) have identified key questions for a new, practice-oriented understanding of resilience in this context. Central issues include:

1. How can authorities not only respond to crises but also learn and adapt structurally over time?
2. What capabilities, structures, and cultures do they need to remain effective despite growing complexity and uncertainty, especially across federal levels?
3. How do specific scenarios like droughts or hybrid attacks affect their roles and resources?

Additionally, the importance of learning processes, as well as intra- and inter-organisational cooperation is highlighted.

2. Increasing resilience of public authorities

RESKON aims to measurably improve the resilience of public authorities, in particular focusing on organisations with security responsibilities and administrative authorities, thereby enabling more effective disaster prevention and management. In the context of RESKON, resilience is understood as a comprehensive ability that exists at both the individual and organisational levels to respond to disruptive events and gradual developments. It encompasses resistance and adaptability to stressors and disruptions, as well as the ability of individuals and organisations to prevent, prepare for and cope with incidents and recover from them as quickly as possible. Other key aspects include learning from past events to continuously improve resilience.

In the context of German public authorities, it should be noted that they operate within a tight framework of laws and guidelines (e.g. the division of powers between the federal government and the states) and other conditions that can have a positive or negative impact on their ability to act. In addition, cooperation between public authorities has so far been based on experience and the assumption of clear circumstances, such as a clear dichotomy between war and peace. However, the “next crisis” is increasingly unpredictable, and lines are blurred in the context of hybrid warfare and disinformation. Additionally, evolving legal requirements, as well as wide-ranging societal, technological, political, and climatic changes, make resilience a permanent challenge for public authorities. Ensuring and strengthening this resilience is an ongoing responsibility that must be addressed collectively by all stakeholders.

Against this background, RESKON is developing a ‘toolbox’ that supports public authorities in systematically measuring their resilience, identifying capability gaps and improving specific capabilities by implementing appropriate solutions. The toolbox will contain six modules that can be used as an integrated system or separately. These are:

1. A ‘resilience capability model’ for the qualitative assessment of existing and required resilience-enhancing capabilities;

2. A systematic procedure for ‘resilience quantification’ to quantitatively measure resilience performance;

3. A ‘methodology catalogue’ that collects suitable methods for increasing resilience;

4. A ‘cooperation concept’ for assessing and optimising cooperation between authorities;

5. A ‘continuous improvement process’ for the successful and sustainable integration and implementation of appropriate improvement measures; and

6. Transformation and training formats to support practical implementation and strengthen transfer into everyday administrative work.

In order to align the project results with current challenges and developments, two specific scenarios were formulated: a heat-and-drought-scenario and a hybrid-crisis-scenario involving hybrid attacks and military deployments to NATO's eastern border. These scenarios cover a broad spectrum of challenges. Plausible timelines of events were elaborated in detail and possible impacts, tasks and challenges for authorities were identified. These findings form the basis for further project work.

3. Megatrends and their impact on authorities' resilience

In addition to the effects and challenges posed by acute events, various global developments can have essential implications. To make the various global trends tangible, so-called megatrends are regularly described, for example by the Zukunftsinstitut, a German research and consulting company. The trends most relevant to the context of RESKON were identified and possible (positive and negative) impacts on public sector resilience were derived. In particular, the megatrends of *demographic change*, *connectivity*, *knowledge culture*, *urbanisation* and *security* were considered. Possible impacts include:

1. *Demographic change* may increase vulnerabilities, especially due to an ageing society, as well as labour shortage, which affects public authorities just as other organisations (Zukunftsinstitut 2025).
2. The megatrend *connectivity* highlights the dependence on functioning networks, including power supply, and the opportunities and challenges of artificial intelligence (Kompetenzteam Katastrophenschutz 2022; Zukunftsinstitut 2025).
3. Possible impacts of *knowledge culture* include an increasing relevance of fake news, and the need of employees with "future skills" in public authorities (Zukunftsinstitut 2025).
4. *Urbanisation* can challenge infrastructure (e.g. water management, food or fuel supply) (Koop and van Leeuwen 2017; Zukunftsinstitut 2025); and
5. the megatrend *security* stresses the need of resilience management in authorities as well as the relevance of involving citizens, especially for preparedness measures (Balbo 2024; Zukunftsinstitut 2025).

4. Outlook

The further development of the RESKON 'toolbox' will be guided by scenarios and megatrends, using scenario-specific data to inform analyses, tailor measures, and design context-sensitive cooperation models. The scenarios act as a 'resilience stress test' to assess the robustness of research findings.

At the same time, RESKON aims to create broadly applicable, low-threshold tools – such as the resilience capability model, quantification methods, and an expandable methodology catalogue – that support authorities in enhancing resilience across all contexts. Known and emerging challenges will be addressed through a continuous improvement process and forward-looking transformation and training concepts.

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Rethinking adaptive and robust disaster risk (self) governance mechanisms as a leverage for addressing complex trade-offs during disasters in developmental contexts: Insights from India and Indonesia

Mrudhula Koshya [a] & Annisa Triyantib [b]
a Department of Architecture and Planning, Norwegian University of Science and Technology, Trondheim, Norway , mrudhula.koshy@ntnu.no
b Copernicus Institute of Sustainable Development, Utrecht University, The Netherlands, a.triyanti@uu.nl

Abstract

This paper explores how existing self-governance mechanisms can be leveraged to navigate complex trade-offs during disasters in developmental contexts marked by chronic vulnerabilities, limited resources, and weak institutions. Using a south-south comparative lens, we explore trade-offs regarding systemic risk governance through two cases in the Global South: Unprecedented heavy monsoon floods in Wayanad, a peri-urban district in Kerala, India, and earthquakes and tsunamis in Palu, a coastal city in Sulawesi, Indonesia.

Keywords: Adaptive Governance; Disaster Risk Governance; compounding risks; Global South

Introduction

Effective disaster risk governance in developmental contexts requires adaptive, multilevel systems. This is especially crucial for addressing compounding and systemic risks that are reinforced by a combination of climate change and maladaptive manmade interventions. However, in many developmental contexts, despite progress toward decentralization and a push for localization (Author, 2022), governance mechanisms for large-scale adaptive interventions tends to favor a centralized model, with national and state actors dominating disaster planning and response. This top-heavy model often fails to address the complexity of modern disasters, which increasingly intersect across sectors and scales (Roelich & Giesekam, 2019). Crucially, under such top-down planning, marginalized and vulnerable communities who are most affected, as well as informal local actors with deep local knowledge, are frequently excluded from decision-making (Corburn, 2003). This results in an underutilization of local, adaptive decision-making and capacities that have often proven crucial in responses to unprecedented disasters, as shown by the contextual insights presented in this paper.

This paper explores how existing self-governance mechanisms can be leveraged to navigate trade-offs during disasters in developmental contexts marked by chronic vulnerabilities, limited resources, and weak institutions.

Accordingly, the paper addresses the following question:

How can existing (self-) governance mechanisms be used as a leverage for addressing complex trade-offs during disasters in developmental contexts with chronic vulnerabilities, scarce resources and weak institutional mechanisms?

Using a south-south comparative lens, we explore trade-offs regarding systemic risk governance through two cases: Wayanad, a peri-urban district in Kerala, India, and Palu, a coastal city in Sulawesi, Indonesia. We briefly present the two contexts below.

Contexts and Cases

Wayanad is a landlocked, hill district in the north of Kerala, a coastal province in India. In 2018, 12 out of 14 districts in Kerala experienced unprecedented monsoon flooding due to cloud burst, leading to widespread infrastructural destruction and loss of lives and livelihoods (IIA & CTP, 2018). Since the last known floods of this magnitude was in 1924, initially the floods were considered a rare event. However, the floods recurred in 2019, questioning this narrative and forcing decision-makers at the state, district and lower administrative levels to rethink traditional, reactive ways of disaster management. Wayanad, considered the least developed district in Kerala, has a fragile, mountainous landscape, vulnerable to flooding and consequent landslides. Wayanad's susceptibility to disaster consequences is also due to deforestation to make way for commercial agriculture, reclamation of wetlands and paddy fields for rampant real-estate development, less regard for building regulations for construction on steep slopes, and intensive quarrying of ecologically sensitive areas (Author, 2022), despite earlier studies that have warned against this (Gadgil et al., 2011).

Studies undertaken in the aftermath of the two floods have pointed to how informal local actors such as local NGOs and volunteers, formal village-level actors, and local elected representatives comprized the disaster response team through ad-hoc, incremental mechanisms (Author & XX, 2024). Formal state and district actors interviewed for this study in the aftermath of the two floods also acknowledged the important role of local actors in rescue, relief and recovery. In the years hence, disaster risk reduction and climate adaptation frameworks in Kerala (Government of Kerala (GoK), 2022) have accommodated localized capacities as a necessary part of refined adaptive governance. Crucial to note, however, is that Kerala is one of the few states in India with a well-developed decentralized governance system (Isaac & Heller, 2003), which was crucial for the immediate disaster relief. Existing social, political, and cultural nuances of societal and familial cooperation across religious, caste and community divides also enabled adaptive governance during the flood emergencies to some extent. Nevertheless, long-term sustainable development appears to be hindered by various planning, decision-making and governance challenges influenced by electoral cycles, existing political, social and economic power dynamics, weak building regulations, uncoordinated

zonal and sectoral spatial plans, and a lack of effective monitoring mechanisms to curb illicit building construction on fragile landscapes to name a few.

The second case is of Palu, the capital of Central Sulawesi Province in Indonesia, which is a vibrant coastal city marked by its multicultural population and dynamic development. Located along the Palu Koro Fault, the city faces persistent geological threats, including earthquakes and tsunamis. The 2018 Sulawesi disaster, a 7.4 magnitude earthquake followed by a tsunami and unprecedented soil liquefaction, was a stark reminder of Palu's vulnerability and underscored the urgent need for resilient urban planning and systemic risk governance. Despite its rich cultural tapestry, shaped by indigenous Kaili communities and decades of transmigration, Palu's history is deeply intertwined with disasters and social conflicts, many of which are preserved in local oral traditions and place names. However, disaster awareness remains uneven, with indigenous knowledge often overlooked by newer urban populations (Author et al., 2023).

Indonesia's broader disaster governance framework has struggled to address the complexity of risks facing cities like Palu. Although the establishment of the National Disaster Management Agency in 2008 marked a step forward, local integration of scientific data and multi-hazard assessments has been inadequate. Key vulnerabilities, such as liquefaction and cascading risks, were omitted from official planning documents, and limited resources, poor coordination, and superficial preparedness measures left communities exposed. Development projects, including Palu's waterfront initiative, prioritized economic growth over safety, ignoring well-documented geological hazards. When disaster struck, emergency response was disorganized, and recovery efforts focused narrowly on infrastructure, neglecting the needs of informal workers, displaced families, and vulnerable groups. The aftermath revealed deep governance gaps and a reliance on national intervention, highlighting the critical need for inclusive, culturally informed, and adaptive risk governance that empowers local communities and preserves intergenerational knowledge.

Commonalities among the two above-mentioned Global South contexts include a reliance on 5-year (zoning) plans, often influenced by political electoral cycles. Both regions, however, reveal the importance of empowering locally rooted actors—formal and informal—to organize, respond, and adapt using their own knowledge systems and lived experiences.

Conclusion

Our findings showcase the need to decolonize disaster knowledge and promote co-production of knowledge across temporal and spatial scales led by multiple, locally rooted formal and informal actors. Despite presenting insights that showcase the importance of locally rooted, self-organized, adaptive governance, we argue against a romanticization of community-based disaster risk reduction, wherein the burden of adaptation is undertaken by the affected, vulnerable communities (Fernando & Hilhorst, 2006; Kulsum et al., 2019). This is primarily because the complexity of compounding and cascading disasters needs diligent and well-thought-out interventions at different spatial, temporal and institutional scales. While

community-based approaches have immense potential to offer rapid, context-sensitive responses, it is necessary to integrate localized capacities with broader governance frameworks to address cascading risks.

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Investigating Risks in the Event Safety Process using Fault Tree Analysis

Felix Märtin (Stadt Freiburg, felix.maertin@freiburg.de)
Moritz Aberle (Stadt Freiburg, Moritz.Aberle@freiburg.de)
Béatrice Veselý (Stadt Freiburg, Béatrice.Veselý@freiburg.de)

Keywords: event safety, fault tree analysis, resilience, municipalities

1 Introduction

Large-scale events enrich public life but also pose risks requiring careful planning. In Germany, organizers document safety strategies, which local authorities audit and supervise (Sakschewski et al., 2019, pp. 71-81). This is referred to as the event safety process. According to the 'Swiss Cheese Model' (Reason, 1990), each step has weaknesses, but failures arise only when several align. Major disruptions indicate that the safety process has failed. A recent incident in Magdeburg, where barriers were bypassed and visitors harmed, highlighted inadequate placement and oversight. The inadequate placement of these access barriers, combined with a lack of oversight, has subsequently been identified as a major contributing fault.

Disaster risk management builds on learning from past incidents by tracing error sequences and root causes (United Nations Office for Disaster Risk Reduction [UNDRR], 2015, pp. 21). In light of recent disruptions at public events, this abstract aims to identify shortcomings within the processes of event safety management. We transfer an established methodology from engineering disciplines, the *Fault Tree Analysis* (FTA), to investigate the municipal safety process for large-scale events and public gatherings (Lee et al., 1985). This method allows us to investigate in our guiding research questions:

Which structural weaknesses and risks can be identified within municipal event safety pro- cesses when modelled through BPMN and analysed with FTA?

To what extent does focusing on process-internal risks, rather than external hazards, provide actionable insights for strengthening resilience in large-scale event management?

Our hypotheses are that our findings enable practitioners to identify critical steps within the process that disproportionately influence the overall safety of the event. We expect to create linkages between internal risks and actors within the event safety process, which supports process engineering by finding safety and security measures or actions at the origin.

2 Methodology

Our analysis targets flaws within the safety process itself rather than external hazards. For instance, establishing a perimeter may mitigate vehicular threats, but if barrier placement is not

double-checked—because site maps lack scale or accessibility—this constitutes a process fault. The same applies when responsibilities for mobile barriers, such as municipal trucks or police cars, remain unclear due to poor information flow among actors.

We built a BPMN model of event safety in Freiburg, based on interviews, observations, and guidelines. While it cannot capture every detail, it transparently displays activities and stakeholder roles(Chinosi & Trombetta, 2012).

Figure 1 illustrates the BPMN representation of the planning phase, from the submission of planning documents by the organizer to their dispatch by the Department of Public Order, review by local authorities, and final approval. This model forms the basis for fault tree analysis and the identification of weaknesses in municipal event safety processes.

Building on this model, we applied the FTA approach, originally developed to examine safety and reliability in a systems engineering context (Lee et al., 1985) to our process.

FTA was already used to analyze other municipal tasks, such as public utilities (Sadiq et al., 2008; Taheriyoun & Moradinejad, 2014) (Masalegooyan et al., 2022) and flood management (Piatyszek & Karagiannis, 2012).

Based on the BPMN model and identified risks, we developed a fault tree to map process activities, actor responsibilities, and hidden deficiencies. FTA starts with a single 'top event', defined as an undesired outcome of the process (e.g., an erroneous approval). The BPMN model does not contain this top event itself, but helps trace which activities could fail in ways that contribute to it. In the analysis, the activity preceding the top event is examined for possible faults; these are then combined through logical relations (AND/OR) to represent fault propagation (Edler et al., 2015, pp. 261).

In the next step, the preceding activity of the second-level cause is taken from the BPMN model and examined for potential sources of error. Any deviations, omissions, or incorrect executions of this activity are added as lower-level events in the fault tree.

Finally, critical paths were identified through the FTA. Causes and actions can be linked to specific actors and steps within the process. This iterative backward mapping continues until either the beginning of the BPMN process is reached or no further meaningful decomposition of activities is possible. The resulting tree thereby mirrors the process chain in reverse, with each branch directly anchored in a concrete BPMN activity. This ensures that the analysis remains grounded in the documented process structure and avoids introducing speculative error paths detached from the actual workflow.

By systematically linking FTA with BPMN artifacts, this approach facilitates the detection of structural weaknesses and the design of robust countermeasures for safety-critical processes and therefore supports our aim of combining risk engineering with internal process engineering.

3 Results

The following section describes our devised event safety process and presents our analysis of possible faults.

The fault tree mirrors the BPMN safety process and links failures to specific activities and actors. The top event is an erroneous approval decision, permitting an event despite unresolved safety issues.

The step before approval is the joint review meeting of municipal authorities. In the FTA, a fault arises if no comments are voiced during the discussion. This silence may result from time pressure, limited expertise, or reliance on others to intervene, highlighting weaknesses in interdepartmental communication.

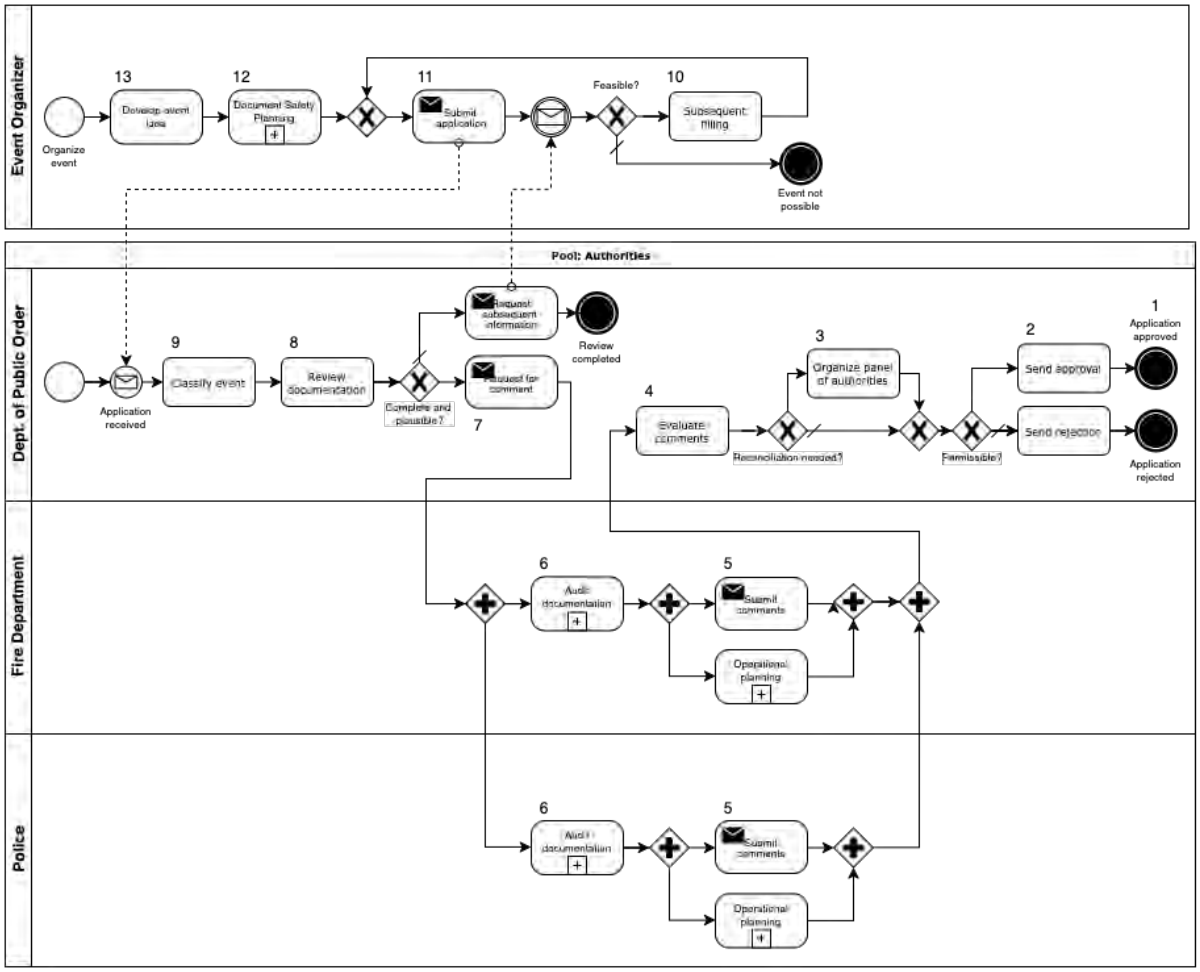


Figure 1: The event process during the planning phase using the *Business Process Modeling Notation*.

Further branches trace back to the fire department and police. In the BPMN they provide input to the Department of Public Order; in the fault tree, faults occur if feedback is incomplete or unrealistic, often due to staff shortages, limited expertise, or poor templates.

The organizer's submission and the authority's dispatch form the process start. In the FTA, faults occur if documents are incomplete, inaccurate, or not forwarded, due to lack of expertise, technical errors, or weak checking routines.

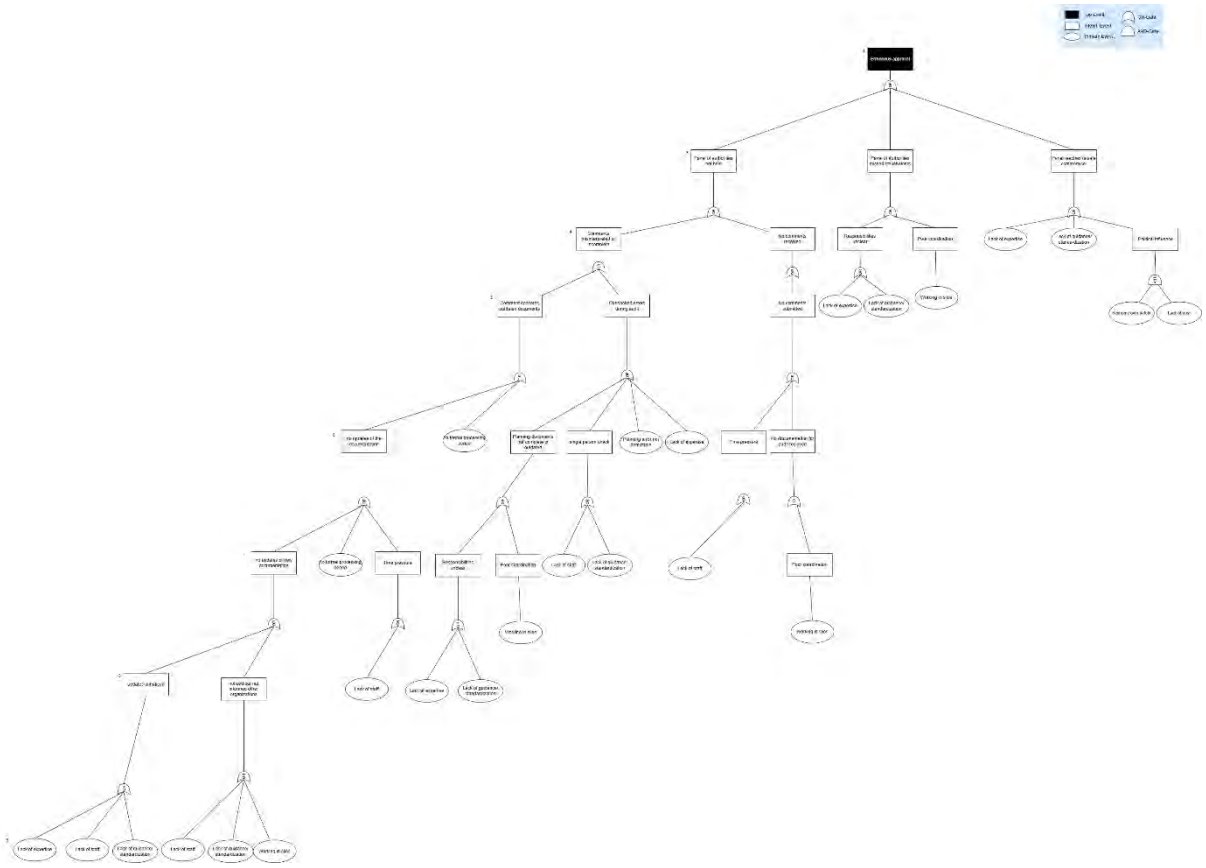


Figure 2: The fault tree after analyzing the event safety process. An exemplary critical path is highlighted.

Overall, the FTA shows that weaknesses stem from communication, verification, and coordi- nation steps. Each fault maps to a BPMN activity and actor, while root causes often lie outside the process in staffing, expertise, or politics.

4 Conclusion

Based on the identified fault tree, several weaknesses in the event safety process can be directly related to specific activities, actors, or artifacts within the BPMN model. Our results provide a systematic approach to investigate faults in the event safety process.

The process analysis reveals that points at which responsibilities are divided among multiple departments can serve as critical junctures, where procedural clarity may diminish. These points warrant further investigation to better understand their impact on process efficiency and reliability. One possible explanation for the absence of submitted comments from involved authorities is that the provided documentation may have been complete and adequate, thus requiring no additional input. Multiple potential fault sources have been identified throughout the municipal event safety process. While these do not suggest that the process is fundamen- tally flawed, they highlight areas where vulnerabilities exist. Branches of the fault tree that terminate at earlier stages nevertheless reveal the same fundamental flaws, such as incomplete documentation, insufficient expertise, or unclear responsibilities. This indicates that systemic weaknesses manifest repeatedly across different steps rather than being confined to a single stage. Importantly, many of these weaknesses, such as gaps in inter- departmental communica-

tion, the absence of standardized procedures, and staffing limitations, are addressable and can be mitigated through targeted interventions.

Our approach is limited as in practice, the process is even more dynamic than the BPMN suggests, as permanent changes and adjustments may occur throughout the planning phase. Such fluidity is difficult to represent in a static process model, but it increases the relevance of examining how deviations are handled in reality. Additionally, we only carried out our FTA up to the point where the organizer submits the initial application, focusing on the internal procedures of the administration.

This analysis is among the first to systematically identify weaknesses within the municipal event safety process. A logical next step would be to quantify the risks associated with each actor, weighting them according to likelihood and impact. This would allow for a more precise identification of the most critical leverage points in the process, providing decision-makers with actionable insights into which adjustments carry the highest potential to strengthen overall safety. Those findings could form the basis for actionable recommendations aimed at enhancing the process and reducing the risk of safety-related oversights in future events.

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KRISENFIT: Assessing and Enhancing Crisis Management in German Municipal Administrations

Alexandra Schmitt, Institute for Public Safety and Emergency Management, University of Wuppertal, a.schmitt@uni-wuppertal.de.
Nicolas Bock, Disaster Research Unit, Freie Universität Berlin, nicolas.bock@fu-berlin.de.
Peter Windsheimer-Kolla, Disaster Research Unit, Freie Universität Berlin, peter.windsheimer@fu-berlin.de.
Niklas Frings, Institute for Public Safety and Emergency Management, University of Wuppertal, frings@uni-wuppertal.de.

Abstract

The KRISENFIT project investigates crisis preparedness in German municipal administrations, focusing on a rural district and a metropolitan city. Initial findings from literature reviews, a historical analysis, interviews, and workshops identify 57 crisis fitness indicators. The project aims—among other things—to develop a self-assessment tool to help municipalities evaluate and enhance their crisis readiness. Early results and planned future research will be presented and discussed.

Keywords: municipal crisis management; organizational learning; knowledge management; prevention

Introduction

Municipal administrations, as the administrative level closest to the population and embedded within the federal system, play a central role in crisis management (CM)—a complex and multifaceted task, particularly in times of multiple or overlapping crises (Floeting, 2023; Schätzle & Trapp, 2025; Schütte et al., 2023). The KRISENFIT project aims to support municipal administrations in Germany in assessing and improving their crisis preparedness. Project goals are the development and implementation of tools and recommendations for tackling these complex tasks and becoming more resilient. The following section presents the initial findings.

The KRISENFIT Project

The research project KRISENFIT—„Krisenfitte Kommunalverwaltungen – Strategien und Instrumente zur Vorbereitung auf multiple Lagen" (09/2024–08/2027) is funded by the Federal Ministry of Research, Technology and Space. Coordinated by the Institute for Public Safety and Emergency Management at the University of Wuppertal, the project brings together academic and practice partners, namely the Disaster Research Unit at Freie Universität Berlin, the Fire and Rescue Institute of North Rhine-Westphalia, the University of Applied Sciences

for Police and Public Administration North Rhine-Westphalia, the City of Duisburg, and the district of Vorpommern-Rügen. The latter two represent our model municipalities. The project combines historical, legal, and social science approaches to develop a holistic understanding of CM, encompassing prevention, preparedness, response, and recovery.

One of the project's goals is to develop a freely accessible self-assessment tool (SET) that enables local authorities to evaluate their crisis fitness and identify areas for improvement. To this end, initial crisis fitness indicators (CFIs) have been identified, and a historical analysis of municipal CM has been completed. This contribution summarizes key findings to date and outlines the next steps for the continued identification of CFIs for the SET.

Crisis Fitness Indicators

Initial CFIs were identified through a comprehensive academic and practice-oriented literature review of scientific literature, relevant standards and legal principles. These findings were further elaborated upon by several workshops and guided interviews with administrative staff from the two model municipalities. Across all formats, the results confirmed the relevance of the 57 CFIs identified to date—e.g. a suitable knowledge management (Olfermann & Bhatti, 2022), resource registers (McManus et al., 2007), CM plans (DIN Deutsches Institut für Normung e. V., 2022), performing internal communication and public relations (Hustedt, 2019), regular joint training (Graf et al., 2024) and integration of CM into administrative education. Furthermore, further indicators were uncovered—e.g. the accessibility of relevant stakeholders (Kommunal Agentur NRW, 2020), and to view CM as a task for the administration as a whole. Each individual CFI is described in detail, including key questions for measuring it in the SET.

Historical Development of municipal CM

A further contribution towards a holistic understanding of communal CM is provided through the yet unpublished KRISENFIT-report on the historical development of municipal CM. It highlights recurring challenges in responsibilities, communication, and cross-organizational cooperation faced by communal actors during different crises scenarios across time. Examples for such scenarios include flooding events—like the North Sea flood of 1962 in Hamburg and the Elbe flood of 2002—, heatwaves, winter storms, the Chernobyl disaster as well as the war in Ukraine. Furthermore, the report outlines the legislative development of CM and civil defense in Germany and highlights past challenges in municipal CM and their responses, underlining the need for a multifaceted and comprehensive approach.

Knowledge Management as Exemplary CFI

Not least because of the demographic change and the impending departure of a large cohort from the labour market, knowledge management plays a crucial role in municipal CM (Joormann, 2017). Well-documented and accessible knowledge is a key component of effective CM across all its phases (Schulte et al., 2024). Therefore, this CFI assesses whether

and how relevant information is collected, structured, and systematically recorded during crises, the preparation for and follow-up of crises. It also evaluates whether this knowledge is effectively shared within the administration—both horizontally across units and vertically across hierarchical levels and systematically recorded as part of the preparation for, during and following-up on crises. The SET addresses the following key questions:

- Availability of central knowledge repositories (e.g., digital handbooks, wikis),
- Currency and quality of content,
- Mechanisms for capturing and sharing tacit knowledge,
- Organizational culture, including training and promotion of knowledge sharing,
- Communication capacities both within municipal administration and with external actors.

Prospects

To capture the complex structures of CM in Germany, the next project stages include: categorizing CFIs by overarching themes as well identifying additional relevant aspects, conducting stakeholder analyses, compiling a legal register for municipal CM, and gathering civil society perspectives through a telephone-based population survey. In parallel, training and education formats for municipal CM are being developed; their requirements will be defined during the project in cooperation with the model municipalities.

By presenting these initial findings, this paper aims to highlight the potential of KRISENFIT for strengthening municipal resilience and crisis preparedness and to provide a basis for further discussion at the conference.

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Simulative Resilience Quantification of Public Administrations and Organizations with Safety and Security Responsibilities

Benjamin Lickert(1), Mirjam Fehling-Kaschek(1), Nils Krippner(2), Maike Vollmer(3), Kai Fischer(1), Alexander Stolz(1)
1 Fraunhofer Ernst-Mach-Institut, EMI, Efringen-Kirchen, Germany
2 Bundesanstalt Technisches Hilfswerk, THW, Bonn, Germany
3 Fraunhofer-Institut für Naturwissenschaftlich-Technische Trendanalysen, INT, Euskirchen, Germany

Abstract

Quantifying the resilience of an organization of interest enables the evaluation and comparison of different system setups and levels of preparedness against natural hazards and man-made threats. This also holds for administrative authorities and organizations with safety and security responsibilities, where the adequate response to crises and disasters is of high importance for the society. This contribution introduces a simulative approach to derive such a resilience quantification based on practitioner's information. Exemplary simulation results are discussed to illustrate the approach.

Keywords: resilience quantification; simulation; crisis response; public authorities

Introduction

The resilience of contemporary societies is fundamentally influenced by the resilience of public organizations and authorities, such as fire departments or municipal administrations (Jungwirth et al. 2023). Recent developments exert significant adaptive pressure on these organizations, particularly with respect to their legal frameworks and organizational structures. These developments include the increasing frequency and severity of extreme weather events due to climate change and other global transformation processes. Additionally, political developments, causing the spread of hybrid threats, are problematic. The German national research project RESKON aims to improve administrative resilience, specifically within organizations with safety and security responsibilities and civil administrations. In this context, resilience is conceptualized as a multi-layered capability, manifested at both the individual and organizational levels, to respond to shocks, disruptive incidents, evolving environmental conditions, and gradual systemic changes. It includes the ability to absorb and adapt to stressors and disturbances, to proactively prevent and mitigate impacts, to manage critical situations efficiently, and to recover swiftly.

To appropriately address current challenges, two distinct and complementary hazard scenarios are investigated within the project:

1. The heat-and-drought-scenario considers challenges related to (drinking) water supply, heat impacts on vegetation and people, and heavy rainfall events.
2. The hybrid-crisis-scenario includes threats like sabotage, cyber-attacks and disinformation accompanying the challenges posed by a military deployment at the NATO eastern border during a period of political tension.

Against the background of these scenarios, authorities are examined regarding their related tasks and resources. Moreover, the resilience of these authorities in the face of the connected

challenges and threads is being analyzed. In addition, overarching global dynamics, such as demographic shifts and accelerating urbanization, were systematically identified and assessed regarding their implications for administrative resilience. These “megatrends” together with both scenarios are used to shape the development of the resilience quantification which will be examined more closely in the following.

Resilience quantification

Resilience quantifications are used to assess and evaluate the resilience of the system under study against disruptions and possible mitigation measures based on performance measures. To identify the relevant performance measures for public authorities, administrative structures and processes must first undergo a systematic, structured analysis. This involves categorizations such as classifying them into resilience dimensions (Bruneau et al. 2003) - technical, organizational, societal, and economic (TOSE) - as well as analyzing resilience characteristics, e.g., in terms of the 4 R’s (Bruneau et al. 2003) (Robustness, Rapidity, Resourcefulness and Redundancy). It is also important to understand the temporal dimension of resilience, i.e., which administration aspects are relevant when preparing for, preventing of, protecting against, responding to, recovering and learning from, and adapting to disruptive events (Thoma et al. 2016).

Figure 1 presents the overall concept to simulate and measure the resilience of authorities. An acquisition of critical authority characteristics builds here the basis of a resilience model. It allows to understand the investigated system and to develop a model for resilience quantification. The methodology presented in this paper starts with a tabular acquisition of the tasks, resources, workflows, communication channels, and inter- and intra-authority dependencies. This is done for the three authorities involved in RESKON: the German Federal Office of Civil Protection and Disaster Assistance (BBK) [1], the German Federal Agency for Technical Relief (THW) [2], and the Dortmund Fire Department [3]. The acquisition is done along the two scenarios since this facilitates the identification of the most important agency characteristics in crisis/disaster situations based on analyzing the specific scenario impacts and their consequences for the authority under study.

[1] https://www.bbk.bund.de/EN/Home/home_node.html
[2] https://www.thw.de/EN/homepage/homepage_node.html
[3] https://www.dortmund.de/themen/sicherheit-und-ordnung/berufsfeuerwehr/

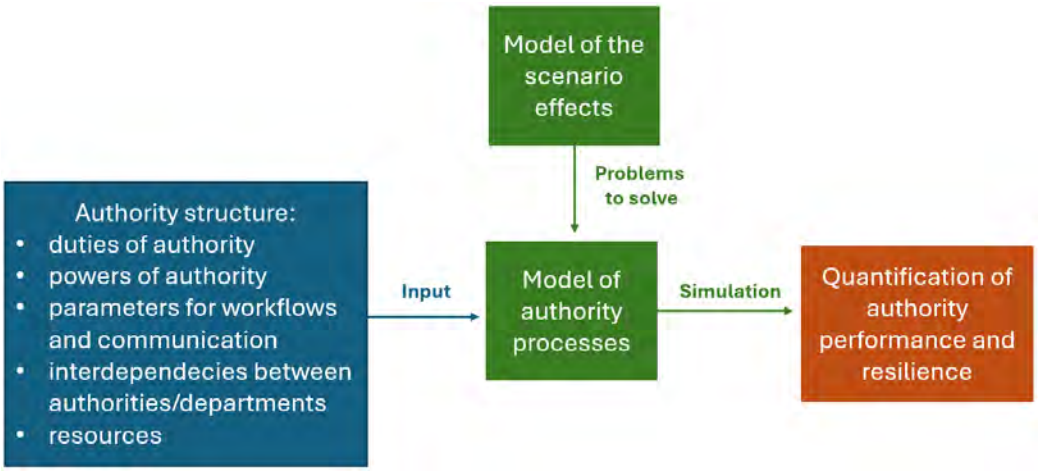


Figure 1: Concept of the resilience quantification of authorities. A model of the authority's processes is formulated (central box) and augmented with structural information (blue box). By receiving information of scenario effect from an auxiliary model (green box at the top), a time-resolved performance evolution can be calculated, allowing to quantify the resilience of the authority for the scenario considered.

To investigate simulatively how the model of the authority behaves under stress, additional input information for some events of interest, e.g., the RESKON-scenarios, is needed. Ideally, this information is provided by an auxiliary model that can be used to scale the intensity and progression of events. However, a simplified event schedule can also serve as dynamic input. In both cases, the authority processes model utilizes the provided dynamic disturbance information to simulate how the authority reacts to the scenario. During the simulation, it calculates performance indicators like reaction times or available resources for each timestep of the scenario. These performance indicators are then further processed to derive a quantitative assessment of resilience.

Example calculation

Figure 2 illustrates the simulation approach. An exemplary fire department is considered, which has one main duty: extinguishing fires. To fulfill this task, the department relies on resources such as fire-fighting vehicles, fire brigade personnel, personnel for coordination and receiving emergency calls, and communication equipment. Under standard operation conditions (Figure 2, top left), the fire department deals with the (rare) fire outbreaks without problems, as soon as an emergency call reports a fire, the response is triggered (Figure 2 bottom, blue curve). However, in a hybrid crisis scenario characterized by widespread sabotage causing a surge in fire outbreaks (Figure 2, top right), the fire department becomes overwhelmed and is no longer able to respond to all incidents immediately (Figure 2 bottom, red curve). While it is unrealistic to assume that the overload can be circumvented completely, resilient fire departments could possess reserves (like additional fire-fighting vehicles which can be manned by personnel called in on short notice) and react quickly and intelligently (for example by asking neighboring fire departments for assistance as fast as possible) such that the increase of the number of temporarily uncontrolled fires is reduced and normal operations, i.e., all fire outbreaks are treated immediately, is restored as fast as possible. This demonstrates the correlation between resilience and the performance curve shown in Figure 2, bottom.

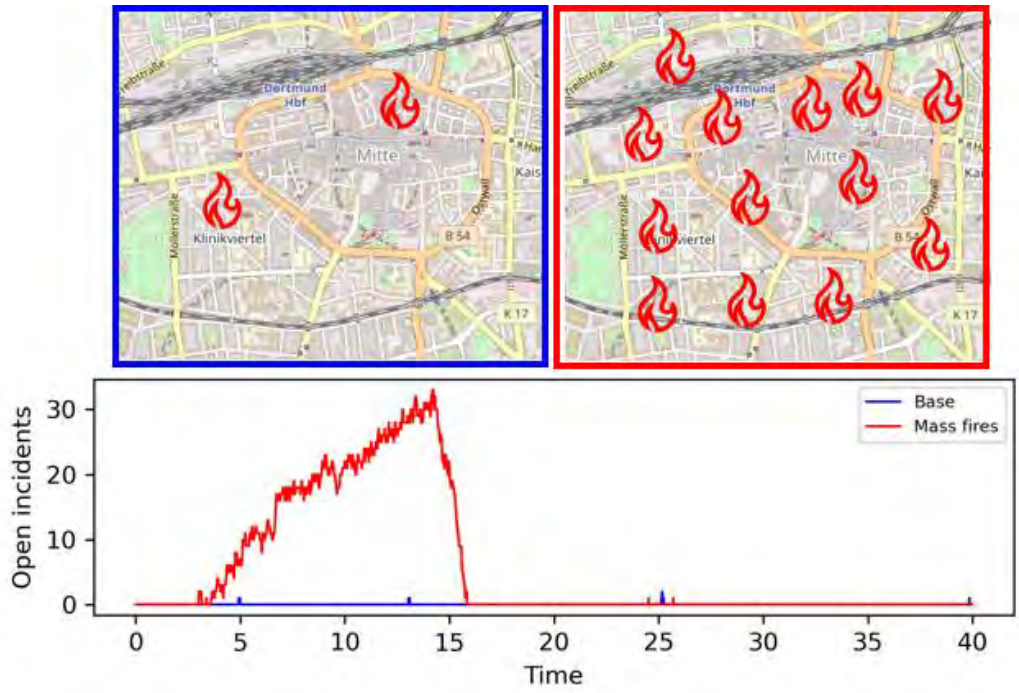


Figure 2: Visualization of the results of the simulation of authority processes. Inspected is an exemplary fire brigade which is sufficiently equipped to extinguish fires under normal circumstances (top left), allowing for immediate response to all fires (bottom, blue curve). Once heavy sabotage during a hybrid crisis causes a lot of fires at the same time (top right), the fire brigade gets overwhelmed, and several fires stay untreated for some time (bottom, red curve).

Outlook

In RESKON, to establish and verify the resilience quantification approach, the concept presented in the simplified example will be applied to the two scenarios, which have been comprehensively described including related challenges and tasks for authorities.

Acknowledgements

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Resilient neighborhoods – integration of resilience aspects into urban development plans in Ukrainian cities

Detlef Kurth, RPTU Kaiserslautern, Germany, detlef.kurth@ru.rptu.de
Anna Kuzyshyn, RPTU Kaiserslautern, Germany, anna.kuzyshyn@rptu.de
Poliksen Qorri-Dragaj, RPTU Kaiserslautern, Germany, poliksen.qorridragaj@ru.rptu.de

Abstract

European urban development is facing significant challenges due to climate change, demographic shifts, structural transformations and an increase in military conflicts. Urban resilience, defined as the capacity of urban systems to cope with shocks, adapt to changing conditions and transform towards sustainability, emerges as a central concept in addressing these challenges. Resilience should be integrated into urban planning as both a cross-cutting theme and a functional element of public services, anchored in the Sustainable Development Goals (SDGs), particularly SDG 11, to ensure continuity during disruptions. This study examines how resilience can be systematically integrated into urban development concepts, using insights from exchange programmes and international case studies to derive a catalogue of criteria for sustainable, resilience-oriented urban development.

Keywords: Urban resilience; urban regeneration; reconstruction; resilient neighborhoods

Facing multiple crisis

Urban development in European cities is facing profound challenges, including climate change, demographic shifts, structural transformations and an increase in military conflicts. Russia's full-scale invasion of Ukraine in 2022 made it particularly clear that climate policy, energy dependency, resilience strategies and security policy must be considered in the context of their interconnections, rather than in isolation. Refugee movements, cyberattacks and attacks on critical infrastructure have exposed the vulnerability of urban systems. Therefore, crises can no longer be regarded as singular, exceptional events, but must be understood as overlapping, persistent conditions for urban development.

Strategy of urban resilience

A key strategy in crisis management is urban resilience, defined as the ability of urban systems to cope with crises and disasters, adapt to changing conditions and transform in order to improve civil protection (UN-Habitat, 2025; Kurth, 2022). The dimensions of adaptability and transformability clarify that urban resilience is not merely about robustness, but also enables the development of new adaptation strategies through flexibility and the ability to learn (Greiving & Fleischhauer, 2022; Hafner & Miosga, 2019; Kegler, 2022).

The inclusion of resilience aspects in the Sustainable Development Goals (SDGs) of the 2030 Agenda emphasises the crucial role of cities and municipalities in ensuring the safety of their

residents. SDG 11 focuses on developing sustainable cities and municipalities, with member countries committing to making them 'inclusive, safe, resilient and sustainable' (United Nations, 2025). Resilience should therefore be integrated into urban development planning as both a cross-cutting issue and a complementary aspect of public services, to ensure that basic urban supply functions are maintained during disruptive events (Fekkak et al., 2016).

Urban resilience in neighborhood concepts

The concept of urban resilience is becoming increasingly important in the context of crisis and disaster management, particularly in Ukrainian cities. In the context of the ongoing Russian attack, strengthening urban resilience presents Ukrainian cities with particular challenges. Short-term solutions must be found to protect the population from acute and ongoing threats under rapidly changing conditions. At the same time, it is necessary to develop scenarios and strategies for medium- to long-term planning, taking into account the local impact of the war, as well as other global challenges and crises, such as ongoing climate change, increasing urbanisation and demographic shifts.

Learning from Ukrainian cities

Faced with enormous challenges, Ukraine has had to develop specific resilience strategies in a very short period of time, with a primary focus on civil protection and the safeguarding of critical infrastructure (Brenner, 2024; Dosch et al., 2022). Against this backdrop, this study explores how resilience aspects can be systematically incorporated into neighbourhood development concepts. The aim is to derive guidelines for the reconstruction of Ukrainian cities, enabling more sustainable and resilient development in view of the country's prospective EU integration, particularly in relation to the New Leipzig Charter of the EU.

Examples of initial approaches can be seen in the exchange and knowledge transfer programmes of the German Academic Exchange Service (DAAD), where existing urban renewal strategies are being supplemented with resilience approaches (TH Lübeck 2025). Additionally, international case studies provide comparative perspectives. Based on these, a catalogue of criteria will be developed to serve as a tool for neighbourhood development oriented towards resilience, combined with an integrated urban development concept.

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Resilience (re)producing urban organizing legacies: conceptualizing indetermination and structuration

Camilo Andres Benitez Avila, Delft University of Technology

Abstract

Environmental and social risks often materialize in cities (Whitehead, 2013), impacting the lives of nearly 55% of the global population in 2018. As the number is expected to rise by 80% by 2050, it comes as little surprise that cities are compelled to seize the resilience dividend (Zebrowski, 2020). A first wave of critical scholarship identified in such an imperative a disempowering ethics of vulnerability (Whitehead, 2013). Resilience defines the normative criterion by which people can succeed regardless of contingent shocks and chronic stresses (Chandler, 2013). Invoking resilience justifies the allocation of risk to the resilient individual, who is responsible for their own risk, thereby actualizing the legacy of neoliberal orders. Shifting risks from institutions to individuals increases the burden of adaptation for those already disadvantaged (Kaika, 2017).

A second wave of urban critical scholars notes that resilience is not reducible to a determinate (neoliberal) discursive order, but, on the contrary, operates upon an intrinsic logic of indeterminacy. Indeterminacy is foundational to Holling's concept of resilient systems, where the interconnection of all things leads to “qualitative unknowns” (Nelson, 2020). This particular understanding of uncertainty embraces the impossibility of fully grasping the world as complete, opening the possibility for creative emergence (Chandler et al., 2020). Responsibility allocation is, therefore, contingent on actors' ability to embrace the indeterminacy of qualitative unknowns and integrate new ways of thinking in urban resilience planning, governing processes, and practices, opening possibilities for new social relations (Grove et al., 2020).

This paper aims to make explicit the ontological framework used by second-wave resilience critical scholars to account for the structuration of existing urban orders. Firstly, we argue that the implicit ontological framework used to account for the process of structuration emerging from indeterminacy is grounded in a flat ontology of assemblages. “Resilience” characterizes the contemporary “urban risk regime” for many cities: the assemblage of governance, economic, and discursive dimensions providing precarious stability to the urban organizational field as part of a larger urban political economy (Wissman-Weber and Levy, 2018). This ontological horizon enables scholars to articulate diverse insights from diverse theories of urban organization (Table 1).

***Table 1**. Indeterminacy and urban risk regime assemblages.*

	Indeterminacy	**Resilience**	**Structuration**	**Relation to urban as a system**	**Social transformation/ reproduction**
Resilient focal organizations (Frigotto et al., 2022).	Environmental uncertainty impacts functionality (Material).	Maintaining the identity of a focal organization	Internal structuration for maintaining identity	Only single entities, not systems	Recovery to the status quo of focal organizations
Resilient economic regions (Magro et al., 2022)	Uncertainty as an economic crisis. (Material)	Renewal or reorientation of the regional system towards a growth path	Structuration of new organizing/institutional bricolage for growth path recovery	A single and uncontested value directing the system's evolution [economic growth]	Constrained by economic competitiveness as a systemic/normative imperative
Organization of risk (Hardy et al., 2020).	Uncertainty mediated by attaching risk meaning to objects (Discursive).	Reconfiguration of risk meanings that change [or maintain] the trajectory of the projected future.	Structuration solving prospective risk dilemma [that is subject to contingencies and reinterpretation of the risk cycle]	System identity is defined by the set of object-risk negotiated and discursively mediated	Contingent on the process by which new risk objects are defined and risk is translated.
Cultural Political Economy (Sum and Jessop, 2013)	Complexity is not fully grasped by structuration and semiosis, resulting in even greater complexity.	As construal that [as any other] aims to fix the crisis and eventually turn into common sense	As part of the construal that resonates with actors and diverse institutional levels	System identity is shaped by structuration and semiosis interplay	Contingent on the variation-selection-retention process

The assemblage framework of the urban risk regime provides an entry point to explain how not-yet-unrealized possibilities play a role in structuring institutions and organizational forms. In this context, resilience should be seen not only as a concept describing a capacity of a focal organization (Frigotto et al., 2022), an institutional regional system (Magro et al., 2022), or a risk discursive system (Hardy et al., 2020). Resilience operates as a construal that provides a more or less accurate diagnosis of the contemporary condition of urban life, while also resonating with specific interests and aligning with existing institutional and organizational frameworks. The resilience construal is subject to structural retention in social sites and institutional and organizational coherence across multiple levels.

Nevertheless, we further argue that the assembly framework obscures the structuration process, is problematic due to the conflation, on the one hand, of structure and agency, and, on the other hand, the cultural structural dimension with the material structural dimensions. Conflation that obscures the ontological status of what urban systems are about, their nature of structural predispositions, and the process by which those structural predispositions take form, and the

very chances to influence and transform them through collective action. Alternative, we introduce a process framework that aims to avoid conflations between agency, structure, and culture.

As an alternative, we explore a layered ontology for reconceptualizing the urban risk regime as situated within the larger process of structuration and semiosis of the urban political economy, interacting with wider socio-political systems (Sum and Jessop, 2013). The risk cycle process mediates the enactment of resilience construal in urban organizational forms (Hardy et al., 2020). First, prospective organizing grounds on the ruling imaginary where a construal articulates the object of social risk within the urban risk regime. Second, real-time organizing emerges from contingent risks, including those materializing the misfit between the ways of organizing risk translation and the material conditions impacting the intervention area. Third, the retrospective risk is enacted outside the temporary organizing level, predisposed by the level of discursive contradiction or synergy between (1) the gap between prospective and real-time risk organizing and (2) the hegemonic imaginary. Such predispositions are known as "ideational situational logic" (Archer, 1996), which, nevertheless, needs to be analytically differentiated from the "material situational logics" characterizing the levels of synergy or contradiction in capital accumulation regimes**.**

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Nested Agency and the Architecture of Human Resilience

Elena Lomeli Aguirre, Avans University of Applied Sciences, The Netherlands.

Abstract

In the context of interconnected and uncertain transitions, from climate disruption and systemic inequality to rising life dissatisfaction, static models of resilience are no longer sufficient. Contemporary approaches to resilience increasingly emphasise not only the capacity to withstand or recover from external shocks, but also the opportunity for deep social transformation. In this reshaping of resilience studies, the concept of agency becomes central. This paper argues that agency is an underexplored link in resilience theory.

This contribution articulates a theory of nested agency, unfolding from individual to collective to system. Drawing on insights from the Capability Approach, Transition Studies, Neurobiology and Phenomenology, it develops a relational, reflexive understanding of agency that reorients resilience systems from technical adaptation to normatively grounded transformation, where individuals and organisations reinterpret meaning, shift values, and reshape systems

Resilience is often treated as an external attribute of systems or communities, described through robustness, redundancy, or recovery speed. However, these characteristics do not emerge in isolation; they are shaped by the decisions, behaviours, and adaptive capacities of the people and organizations within those systems. In this sense, resilience is not merely a property of structures; it is a reflection of the agency exercised by individuals and collectives navigating complexity, uncertainty, and change.
Agency, in this context, is not a static trait but a dynamic, relational, and context-dependent substantive freedom to act that underpins how actors interpret, respond to, and ultimately reshape their environments. It unfolds across multiple, interconnected layers; from the personal to the organizational to the systemic. These layers are neither sequential nor hierarchical; rather, they form a system of mutual influence, where individual meaning-making and collective action recursively shape the evolution of socio-technical and environmental systems.

However, dominant approaches to resilience often overlook the reflective dimension of agency. Policy and design frameworks tend to rely on instrumental rationality, a mindset that treats actors as predictable, utility-maximizing entities who adapt through control, prediction, and optimisation. This framing reduces agency to rationalisation: the ability to optimise action within fixed goals and established structures.

This paper challenges that view by introducing a distinction between rationality and reasoning. While rationality is linear and control-oriented, reasoning is contextual, dynamic, and integrative. It enables individuals and collectives to navigate complexity with coherence and intentionality, aligning their actions with evolving values and social meaning. In this framework, reasoning is the internal logic of agency; the internal capacity that allows people to reflect, reframe, and act intentionally in uncertain and contested environments. Agency, thus, is understood not merely as the freedom to act, but as the capacity to act with intention and coherence, consider alternatives, align actions with evolving values, and pursue goals they have reason to value. Rather than treating reasoning as separate from agency, it is framed here as the internal conversion factor through which agency is exercised: the reflective process through which individuals and collectives examine values, consider alternatives, and make choices they have reason to value.

Crucially, this reflective capacity of agency is what enables resilience to become more than technical adaptation. It opens up the possibility for resilience not only to bounce back, but to bounce forward, not simply absorbing shocks, but responding in ways that challenge dominant assumptions and reconfigure relationships and systems. In this sense, resilience emerges not just from structural robustness, but from the depth and quality of agency exercised by those within the system.

A key element of this process is the role of mental models, the often-unconscious cognitive frameworks that shape how individuals make sense of the world and define what constitutes a "good life." When mental models are shaped by dominant social norms, commodified identities, or institutional pressure, they can constrain both agency and resilience by reinforcing adaptive preferences, where individuals reshape their aspirations to fit within unjust or stagnated systems.
However, when mental models become visible, reflexive, and open to transformation, they can function as powerful levers for change. Through reasoning, individuals and collectives can challenge inherited assumptions, realign actions with dynamic values, and develop new imaginaries for social and ecological life. In this sense, resilience is not simply about recovery or optimisation; it emerges through new ways of thinking and acting enabled by agency.

On this basis, this paper articulates a multi-level theory of transformation that connects personal development through agency to the emergence of adaptive systems resilience:

- At the individual level, agency begins with self-awareness and value clarity, enabling individuals to act from a sense of inner coherence.
- At the organizational level, this agency catalyses shifts in culture—creating space for participatory governance, ethical leadership, and deliberative innovation.
- At the systems level, individual and collective agency enable systems to bounce forward rather than merely recovering.

This progression aligns with the concept of leverage points in systems theory, with deep inner shifts (values, mental models, mindsets,) representing the most powerful levers for systemic change.

By anchoring resilience in the lived experience of agency, we move toward a model of development that is not only adaptive and dynamic but also conducive to living valuable lives.

Collective Agency, Resilience, Reason

Re-imaginaries of resilience: Feminist perspectives on politics of socio-cultural transformation

Aditi Natarajan[1], Juliana Gonçalves[2], Mehmet Ali Gasseloğlu[3]
1 Faculty of Architecture & Built Environment, Delft University of Technology, Netherlands, a.n.natarajan@tudelft.nl
2 Faculty of Architecture & Built Environment, Delft University of Technology, Netherlands, j.e.goncalves@tudelft.nl
3 Gebze Technical University, Kocaeli, Türkiye, m.gasseloglu@gtu.edu.tr

Abstract

The idea of 'resilience' has long been criticised due to its vague definition and diverse interpretations within various disciplines (Pendall, Foster, and Cowell, 2010). These diverse interpretations, while advantageous in terms of adaptations to suit local realities, also risk ambiguity on the part of planners and practitioners when preparing policies, action plans, and visions for resilience (Davoudi et al., 2012; Amirzadeh, Sobhaninia, and Sharifi, 2022). Such vagueness may also partially explain why the concept resonates so well in policy circles, where the goals and motivations of proponents are highly variable and politicised (Benıtez Avila, Gil-Clavel, and Copeland, 2025).

Specifically within engineering and socio-technical systems, earlier conceptualisations of resilience have sought to return to steady-state, equilibrium, or pre-existing conditions. More recent ones, in contrast, emphasise the need to make the system better in the future. However, how we interpret the 'state of normalcy' to return to or the 'state of betterment' to aim for is always a normative question within social systems (Davoudi et al., 2012). What follows are questions regarding whether the expected 'state of normalcy' is even a point worth returning to, what exactly is the 'state of betterment' aimed for, especially if it undermines aspirations of transformative change for populations who are supposed to become resilience, or worse pushes them into a regime of precarity, raising concerns of fairness and justice (Cutter, 2016).

Understandings of normalcy and betterment are not only rooted in sociocultural, political, and place-based terms but also arise from everyday embodied experiences, often cut along lines of class, race, gender, and caste. These encounters not only shape visions of the normal that we steer towards but also reveal that these visions are themselves rooted within structures of inequality and power. As a result, a return to a state of normalcy or betterment may keep people and entire population groups in conditions of inequality and even lead to maladaptation for some (Davoudi et al., 2012). Understanding different conceptions of normalcy and betterment requires tracing the overarching collective expectations of what resilience looks like and feels like to different populations – from here on referred to as 'resilience imaginaries'.

Imaginaries are understood as collective social expectations derived from negotiation between individuals and their material world, translating into a social fact, dictating the possibilities of our world (Appadurai 2008; Petek-Sargeant and Lane, 2021). They arise from our collective 'sense-making' abilities to form the social, about the material world and lay out the actors, spaces, materials, technologies, and narratives that shape the process of 'worldmaking' (Appadurai, 2008). Imaginaries are where collective action is staged and, therefore, drive the types of visions and norms that become embedded within resilience research and practice.

In this study, we investigate how resilience imaginaries shape how states of normalcy and betterment are defined in two illustrative cases and assess the consequent implications for justice and social transformation. Using a scoping literature review, we first identify dominant resilience imaginaries at play and use these imaginaries for selecting the case studies. Our unpacking of the case studies stems from the need to understand resilience imaginaries as embodied and lived. For this, we employ a feminist theoretical lens of 'weathering' to challenge the current manner in which resilience is imagined, overlooking structural inequalities that shape differentiated vulnerabilities and risks within engineering and socio-technical systems. Previous research has shown that such a lens helps to centre justice in planning and design processes (Natarajan et al., 2025).

Through weathering, we argue for the inseparability of bodily experiences of risks and vulnerabilities of social transformation as indistinguishable from the structural inequalities that bodies are situated within (Neimanis and Hamilton, 2018). Such an inquiry is necessary as both vulnerability and resilience are affected by inequalities (Amirzadeh, Sobhaninia, and Sharifi, 2022). By doing so, we foreground not only the importance of context and socio-cultural structures but also the agency of the practitioner that together shape structural inequalities and are crucial in influencing the resilience of socio-technical systems.

Keywords: imaginaries; structural inequalities, weathering

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Gendered resilience and road infrastructure: social structures, flood vulnerability and transformation: A case study from Sri Lanka

Ereesha De Silva[1]

1. Indo-Pacific Research Centre, Murdoch University, Australia, 35260302@student.murodch.edu.au

Abstract

Road infrastructure is widely celebrated for its role in advancing development, enhancing connectivity, and supporting disaster preparedness. Yet, its benefits are not equally distributed: women often bear disproportionate burdens due to entrenched sociocultural norms and systemic inequalities. In Sri Lanka, a country highly vulnerable to climate change-induced flooding that exemplifies challenges faced across developing regions, roads do more than connect; they also shape how communities, particularly women, experience vulnerability and resilience.

This paper presents a systematised review of scholarship on the intersection between roads, gender, and flood resilience, synthesising global, regional, and Sri Lankan literature. It employs a matrix approach to map these intersections, situating infrastructure as both a socio-technical and socio-cultural system. Drawing on feminist political ecology, underpinned by the concepts of social embeddedness and collective agency of road infrastructure development, this study interrogates how road development simultaneously enables mobility and exacerbates gendered vulnerability, while rarely integrating women's voices in planning and implementation.

The synthesis of early insights into the argument of gendered dimensions of road infrastructure outcomes posits that resilience must be understood as socially embedded and power-laden, with infrastructure projects both reflecting and reshaping existing inequalities. By centering women's lived realities in flood-prone Sri Lanka, this study contributes to rethinking resilience as a pathway for social transformation, offering conceptual and normative insights for gender-responsive infrastructure planning.

Keywords: gender; resilience; infrastructure; floods; Sri Lanka

Introduction

Road infrastructure symbolises modernity and drives socio-economic progress by linking communities and fostering development across cultural, social, economic, and environmental spheres. While roads are hailed for their potential to enhance mobility, economic opportunities, access to services, and disaster resilience, their benefits are often unevenly distributed, particularly across gender lines (Dankelman & Naidu, 2020). Outcomes of road infrastructure

impacts are deeply gendered. Women, especially in the Global South, increasingly bear the unacknowledged costs and disproportionate risks of infrastructure development, constrained by sociocultural norms and systemic inequalities (Domingue-Gonzalez et al., 2020; Legovini et al., 2022). The picture becomes more skewed when women in the Global South face mobility and access constraints during disasters such as floods.

Sri Lanka, a developing country in the South Asian sub-region, is highly vulnerable to the impacts of climate change-induced disasters such as floods (World Bank & Asian Development Bank, 2020). Inadequate road infrastructure becomes a barrier during floods, disproportionately affecting women's access to essential relief services, rescue operations, and welfare facilities. Women in flood-affected areas often experience unique challenges linked to mobility, caregiving roles, and safety, which shape their adaptive capacities (Pérez-Gañán et al., 2023). Understanding the intersection of gender dimensions in road infrastructure development in the context of climate-induced floods is important for resilience building and inclusive planning. Yet, it remains largely an underexplored field of inquiry (Chen, Lu, & Nanayakkara, 2023).

This paper addresses this gap by conjecturing how road infrastructure interacts with gendered social structures to shape resilience, not only as persistence or recovery but also as potential social transformation.

Conceptual Framework

Road infrastructure outcomes are inherently gendered (Foster et al., 2023). Women's experiences with roads are distinctly shaped by geographical, cultural, social, and economic factors that intersect with established gender roles and norms (Legovini et al., 2022). Despite these social dynamics, mainstream resilience and development literature continues to treat roads primarily as functional systems (Prud'homme, 2004). I argue that this mainstream thinking limits our understanding of how resilience is produced, for whom, and at what costs.

To address this gap, I propose a conceptual framework that integrates collective agency, socio-cultural embeddedness and feminist political ecology to reframe roads as extending beyond their role as socio-technical artefacts to function as a cultural, political, and gendered system, highlighting their deep social embeddedness. I contend that deliberative strategies such as collective agency and awareness during road planning and decision making enhance their critical role during disaster events such as floods, which themselves produce profoundly gendered outcomes (Kim, Park, & Kim, 2023). Grounded in the power relations (Domingue-Gonzalez et al., 2020) and intersectionality of gender and the multidimensional effects of road impacts during floods, I adopt feminist political ecology (Nightingale, 2006; Rocheleau, Thomas-Slayter, & Wangari, 2013) as the anchor for my conceptual framework.

The interconnections between these concepts are represented schematically in Figure 1. The diagram illustrates how feminist political ecology theory, with its emphasis on intersectionality and multidimensionality, informs both the socio-cultural embeddedness of infrastructure and the collective agency of communities. These dimensions converge and conceptualise roads as socio-technical as well as cultural systems. Together, they shape resilience trajectories and open pathways for transformative social justice. This approach allows resilience to be understood as a social transformation rather than merely as persistence or recovery. This

framework also guides the systematised thematic review of literature, concentrating on three domains: roads and gender, roads and environment, and gender and environment.

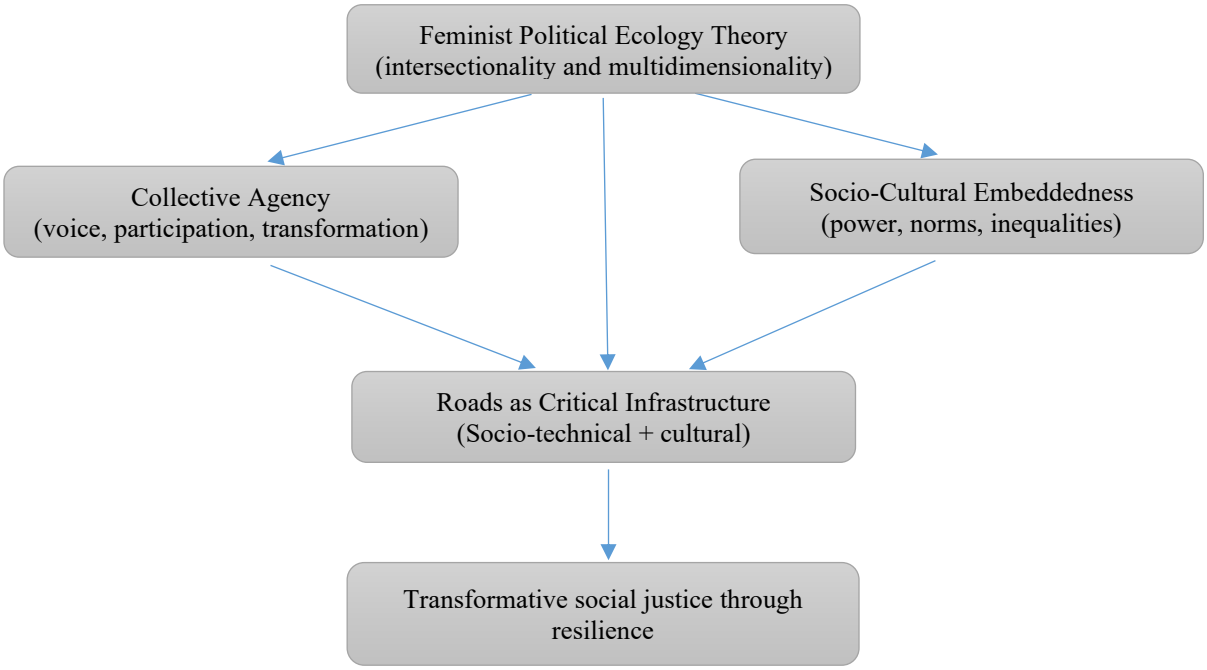


Figure 1. Conceptual framework linking feminist political ecology theory, socio-cultural embeddedness, and collective agency to roads as critical infrastructure and resilience outcomes.

Methodology

This paper employs a thematic review of literature across three intersecting domains: roads and gender, roads and environment, and gender and environment. The review analysed 202 articles from both academic sources and policy documents. Academic articles were sourced from Scopus, Web of Science, JSTOR, Emerald, and Google Scholar, while policy documents were from international development agencies and Sri Lankan government sources published between 2000 and 2024. The analysis examined how "resilience" is conceptualised in climate change-induced disaster literature, specifically assessing representations of gender and road infrastructure.

Searches combined keywords relating to roads, infrastructure, gender, women, feminist approaches, development, rural communities, mobility, transport, resilience, climate change-induced disasters, and floods. The review examined how each domain has been conceptualised, the extent to which socio-cultural embeddedness and collective agency have been addressed, and where feminist perspectives have been integrated or overlooked.

Findings and Synthesis

The literature review revealed three distinct patterns in scholarship on road infrastructure:

1. The dominant narrative of roads is of a technical-economic focus where roads have been portrayed primarily as engines for economic progress, emphasising connectivity and efficiency within a sociotechnical framework.
2. Studies examining social impacts consistently demonstrate disparities in road benefit distribution along gender lines, with women's access constrained by sociocultural norms.

3. The scholarship on roads remains fragmented. There was no single study that had integrated technical, environmental and social dimensions of roads, particularly in disaster contexts. This was evident in flood disaster studies in Sri Lanka, where they looked at how roads played a role in supporting or hindering women from effectively responding to floods.

Furthermore, the resilience scholarship on climate change-induced disasters, such as floods, highlights gendered vulnerabilities, but they are often argued through a narrower frame of persistence and recovery. For instance, the majority of the studies on disaster resilience document how women's coping strategies in disaster contexts are shaped by household responsibilities, limited mobility and social norms. But links to systemic questions of power, agency, or transformation are largely absent in such arguments. As a result, such studies take a reductionist approach concentrated on individual adaptations rather than collective capacity-building.

Synthesis of the literature reveals three critical limitations in current approaches.

1. Technocratic literature mainstreams roads as socio-technical systems rather than socio-cultural entities embedded in power relations.
2. Resilience takes a narrow frame of technocratic recovery rather than a transformative social process.
3. gender considerations remain tokenised in road infrastructure development, particularly in climate change-induced disaster contexts.

This fragmentation underscores the need for an integrated conceptual framework that repositions roads as cultural, political and gendered systems, where resilience emerges through socially embedded and transformative processes.

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Fairness as a Lever for Food System Resilience: Insights from West African Value Chains

Marilyne Chicoine[12], Joël Mongeon[1], Ebenezer Miezah Kwofie[1]
1- Sustainable Food Systems Engineering Lab (SASEL), Department of Bioresource Engineering, Faculty of Agricultural and Environmental Science, McGill University, Canada
marilyne.chicoine@mcgill.ca, joel.mongeon@mail.mcgill.ca, ebenezer.kwofie@mcgill.ca
2- McGill Center for the Convergence of Health and Economics, Department of Marketing, Desautels Faculty of Management, McGill University, Canada

Abstract:

Resilience scholarship has largely emphasized material and institutional factors enabling systems to withstand and adapt to shocks, while overlooking the role of fairness. This paper advances the argument that fairness—understood as distributive, procedural, informational, and interpersonal justice—is not only a normative expectation but also a functional driver of resilience. Drawing on 62 semi-structured interviews with stakeholders across cocoa, maize, groundnut, and palm oil value chains in Ghana and Nigeria, we show how local perceptions of fairness map onto distinct clusters of resilience: distributive fairness stabilizes economic and nutritional resilience; procedural fairness strengthens institutional legitimacy; informational fairness supports organizational adaptability; and interpersonal fairness sustains social cohesion. These findings highlight fairness as both the "glue" binding relationships of trust and legitimacy and the "fuel" energizing cooperation and transformation. By integrating fairness into resilience thinking, we contribute to the normative "social turn" in resilience research and underscore its practical relevance for designing more just and durable food systems.

Keywords: Resilience, Fairness, Food Systems, Value Chains

Introduction

Resilience has become a central lens for analyzing the capacity of systems to withstand shocks, adapt, and transform in the face of environmental, economic, and social pressures. In socio-technical and environmental systems research, resilience is often study in focusing on the material and organizational conditions that enable systems to persist and recover. Yet, an equally critical dimension remains underexplored: the role of fairness.

Fairness captures how individuals and groups perceive equity in outcomes, processes, information, and interpersonal treatment (Adams, 1965; Greenberg, 1990). While this framework has been widely applied in workplace and governance studies, its implications for resilience thinking have received little attention. Existing resilience research tends to emphasize distributive concerns, such as vulnerability and unequal exposure to risks, but has paid far less attention to procedural, informational, and interpersonal fairness (Meerow & Newell, 2019). This omission is problematic, as a growing body of work shows that perceptions of fairness influence trust, cooperation, and legitimacy, all essential for coordination and transformation in systems under stress (Coulthard, 2012; Eriksen et al., 2015).

Addressing this gap is crucial. If resilience is not value-neutral but inherently normative, involving judgments about what should be sustained, who benefits, and how transformation should occur (Cretney, 2014; Olsson et al., 2015), then fairness provides a vital lens to make these normative dimensions explicit. Investigating fairness in systems resilience offers not only an ethical justification but also a practical one: fairness may function as a driver of resilience by shaping the relationships, trust, and legitimacy on which adaptation and transformation depend.

This paper contributes to this emerging conversation by analyzing how fairness is conceptualized by stakeholders in West African agri-food value chains (cocoa, maize, groundnut, and palm oil) and how these perceptions intersect with established dimensions of resilience. Drawing on in-depth qualitative interviews, we examine whether classical categories of fairness resonate in these contexts and how they translate into resilience processes. In doing so, we argue that fairness is not only a normative concern but also a functional mechanism that binds food systems together and energizes their capacity to adapt and transform.

Conceptual Background

The concept of fairness has been widely studied in organizational and behavioral scholarship under the umbrella of organizational justice. Four classical dimensions have been established. Distributive fairness emphasizes equity in the allocation of outcomes and benefits, building on Adams (1965) equity theory. Procedural fairness focuses on the fairness of the processes by which decisions are made, including consistency, impartiality, and opportunities for voice (Thibaut & Walker, 1975). Informational fairness relates to the adequacy, clarity, and honesty of explanations given to stakeholders about decisions, while interpersonal fairness concerns the extent to which individuals are treated with dignity, and respect (Greenberg, 1990).

In parallel, the literature on resilience has expanded considerably, moving from ecological foundations (Holling, 1973) to socio-ecological and socio-technical applications (Folke, 2006; Walker et al., 2004). Resilience is now understood as the capacity of systems to anticipate, absorb, adapt, and transform in response to shocks and stresses, encompassing infrastructural, institutional, economic, social, and cultural domains (Béné et al., 2012; Folke et al., 2010). Increasingly, scholars emphasize that resilience is not value-neutral but deeply normative: it entails judgments about what should be sustained, who benefits, and what forms of transformation are desirable (Béné et al., 2016; Cretney, 2014; Meerow & Newell, 2019). This normative turn highlights the importance of equity, justice, and power relations in shaping resilience outcomes.

Methods

This study adopted a qualitative, exploratory, and inductive approach (Azungah, 2018) to gain a deep and contextualized understanding of stakeholders' perceptions, experiences, and priorities regarding fairness and resilience. The analysis is based on 62 semi-structured interviews conducted with farmers, aggregators, processors, retailers, NGOs, and institutional actors across four major value chains (cocoa, maize, groundnut, palm oil) in Ghana and Nigeria. Participants were asked to define fairness in their own terms, to reflect on its presence or absence in their value chain interactions, and to discuss how fairness could be a lever for resilience. Data was analyzed through NVivo 15 using an iterative thematic analysis approach, combining both inductive and deductive coding strategies to capture emergent themes while also structuring the analysis around predefined areas of interest (Mucchielli, 2006).

Results

Fairness as Distributive Justice: Stabilizing Economic and Nutritional Resilience

Most respondents equated fairness with the equitable distribution of benefits, resources, and outcomes, mirroring Adams (1965) distributive fairness. Farmers frequently emphasized proportionality between effort and reward, pointing to input allocation and price setting as core concerns. One farmer explained: "*What someone deserves is what should be given them…we*

should share it fairly, not cheating others" (C10F). Such concerns reveal distributive fairness as a cornerstone of economic resilience (Martin & Sunley, 2015; Sutton & Arku, 2022), where equitable returns are necessary to sustain livelihoods and prevent erosion of food security. Similarly, calls for "*equal rights and access to food for everybody*" (C16AG) align with the notion of nutritional resilience (McEvoy & McClure, 2024), ensuring that households maintain access to adequate diets during shocks.

Procedural Fairness: Legitimacy, Inclusion, and Institutional Resilience
Beyond outcomes, stakeholders stressed the importance of transparent and inclusive decision-making processes, echoing Thibaut and Walker (1975) framework of procedural fairness. Several respondents linked fairness to having a voice in governance: "*If the LBCs had listened to your opinions, would you consider that as fairness? – Yes*" (C4F). Others emphasized inclusion in price committees: "*We meet as a group […] to update us and tell us why they need to either increase or decrease the price*" (P1F). Such perceptions reinforce institutional resilience (Schneider et al., 2025), as participatory processes build trust, coordination, and legitimacy in governance systems (Ensor et al., 2015).

Informational Fairness: Transparency and Organizational Adaptability
Although less frequent, informational fairness, defined as adequate and honest communication (Greenberg, 1990), was considered vital by respondents. Farmers valued being informed, perceiving transparency as fairness in itself: "*They teach us for us to understand…so far it's transparent, especially with the regulation of prices*" (P1F). This highlights how organizational resilience (Vogus & Sutcliffe, 2007) can be enhanced through effective communication: clear explanations reduce uncertainty, foster acceptance of adaptive measures, and facilitate collective responses to shocks (Folke et al., 2010).

Interpersonal Fairness: Respect, Consideration, and Social Cohesion
Respondents also emphasized interpersonal treatment as a marker of fairness. This was often expressed through reciprocity and respect: "*Whatever you want others to do to you, you too should do to them*" (G6P-N). Another respondent explained: "*What I can actually define…is when all of us smile after a business transaction*" (P3P-N). Such narratives reflect Greenberg (1990) interpersonal fairness and show how social resilience (Adger, 2000; Cinner & Barnes, 2019) is built on dignity, respect, and trust within value chain relations. These relational aspects of fairness sustain social cohesion, a prerequisite for collective action in times of disruption.

Discussion
These results illustrate how fairness map directly onto different clusters of resilience. Distributive fairness contributes to economic and nutritional resilience by stabilizing incomes and diets; procedural fairness strengthens institutional resilience by enhancing legitimacy and participation; informational fairness supports organizational resilience by reducing uncertainty; and interpersonal fairness sustains social resilience by fostering trust and cohesion. Together, these findings demonstrate that fairness is not merely a normative expectation but a functional driver of resilience, shaping the ability of food systems to absorb, adapt, and transform under stress.

This resonates with calls to address the normative dimensions of resilience (Cretney, 2014; Olsson et al., 2015). Resilience scholarship increasingly acknowledges that resilience is never neutral: it implies choices about what should be sustained, who benefits, and at what cost. Meerow and

Newell (2019) heuristic about resilience for whom, what, when, where, and why, is especially relevant here.

For whom? Respondents consistently emphasized that fairness means all actors, but especially farmers, should benefit proportionally. This positions fairness as a corrective to power asymmetries in value chains. *For what?* Fairness was defined not only in terms of profit but also in terms of dignity, respect, and legitimate participation, broadening what resilience seeks to sustain. *When?* Stakeholders insisted that fairness must be present not only in moments of crisis but in everyday transactions. This underscores that resilience is built cumulatively, not only during shocks. *Where?* Localized experiences of unfairness reveal how resilience is shaped by context-specific practices and institutions. *Why?* Fairness was justified as well as normatively. This dual rationale highlights fairness as both a moral value and a mechanism of stability. By articulating resilience through fairness, actors in West African food systems effectively bridge normative and functional perspectives. Fairness becomes the principle that ensures resilience is not only about persistence and recovery, but also about justice and transformation. In this sense, fairness operationalizes the "social turn" in resilience studies, connecting system adaptability with equity, legitimacy, and cohesion.

Conclusion

This study demonstrates that fairness is both a normative expectation and a practical mechanism for strengthening resilience in systems. By examining stakeholders lived experiences across West African value chains, we show that fairness map directly onto distinct clusters of resilience. Taken together, these findings position fairness as both the glue and the fuel of resilience. Fairness is the glue that binds actors together in relationships of trust, reciprocity, and legitimacy, preventing fragmentation when systems are under stress. At the same time, fairness is the fuel that motivates cooperation, enables participation, and fosters innovation, thus energizing the adaptive and transformative capacities of systems. Without fairness, resilience risks reinforcing existing inequalities and power asymmetries. With fairness, resilience can evolve into a pathway for justice and collective flourishing. Recognizing and operationalizing fairness in its multiple dimensions therefore provides a critical entry point for designing systems that are not only more robust in the face of shocks but can also be sustainable in the long term.

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Scrutinizing the Global Learning Crisis: A Cartography of Literature Through a Critical Realist Pedagogy of Crisis (PoC-CR) Framework

Juan David Parra

Extended Abstract

While 'crisis' has become a recurrent theme in comparative education (Ahmed 2023), reports from the past decade by influential international organizations have increasingly framed the crisis in learning as both an economic and a moral crisis. The emphasis here is on how poor quality in educational services results in missed opportunities to promote employment, fight against poverty, foster democratic governance, and advance peace and security, among other economic and social goals (Elfert and Ydesen 2023; UNICEF 2017; World Bank 2017).

Despite the calls for action to reverse the so-called Global Learning Crisis (GLC), scholars working from political economy perspectives have raised concerns over the limitations of existing empirical and theoretical frameworks in helping to unravel the roots of, and therefore to illuminate potential solutions to, the persistent learning deficit (Clarke 2022; Hickey and Hossain 2019; Paglayan 2024; Pritchett 2019). One relevant case in point is Lant Prichett's pessimistic assertion, as Research Director of the RISE (Research on Improving Systems of Education) program, that "nearly everything that is known about education reforms—everything that donors are bringing in as solutions—won't work" (Khalid 2020). This view aligns with a recent critique put forward by a former senior specialist at the World Bank and the Global Partnership for Education, who argues that the widespread misuse of different research tools such as large-scale surveys and randomized controlled trials to guide the design and implementation of education interventions has hindered the accumulation of relevant knowledge. Given this situation, she contends, "the educational ecosystem in a [typical] country, which includes numerous institutions at the micro and meso levels interacting and working together to make a school system function, is a black box" (Clarke 2022, 11).

Our (proposed) presentation engages with this debate by framing it as a problemátique of a Pedagogy of Crisis (PoC)—namely, the reflection, in both policy-making and academic settings, on how to encourage the "learning in and from crises and drawing lessons for future crises" (Jessop 2018, 64). We draw more specifically on Knio's (2018) proposal for a PoC framework, which is grounded in the philosophy of Critical Realism—hence the PoC-CR—and which, according to the author, provides the pillars for a "promising methodology to disentangle the complex and interwoven dimensions of crisis" (p. 43). We see this as directly relevant for resilience debates, since the PoC-CR helps to theorize how socio-technical and educational systems are embedded within wider sociocultural and political structures, and how crises can both reinforce and transform those structures.

As we further elaborate in the presentation, this potential for unpacking and distinguishing between symptoms, mediators, and causal forces behind crises draws on the PoC-CR's explicit commitment to a stratified conception (or ontology) of social reality. From this perspective, events in the world (like poor learning) exist in a different domain of reality from the one that explains their occurrence. That is the case because events in the world are emergent phenomena—that is, they are more than the sum of their parts—arising from the interplay between pre-existing material and ideational mechanisms and their activation by human agency in specific temporal and geographical contexts. This allows us to

capture how resilience in education systems is conditioned by structural inequalities and power relations embedded in broader sociocultural contexts. A logical implication of this philosophical position is that different lessons can be drawn depending on the ontological level at which a crisis is explored. Consequently, a comprehensive theory of phenomena such as the GLC must account for the connections and manifestations of crisis across different levels of the reality in which education systems operate.

Following this, we argue that operationalizing a PoC framework enables a critical reading of various theoretical approaches to the GLC, as put forward by different scholars and practitioners, to construct a cartography that provides readers with heuristics and theoretical elements to navigate these divergent explanations. This also contributes to resilience debates by clarifying how different conceptualisations of crisis reflect contrasting views of social transformation—whether resilience is framed as persistence, recovery, or as a pathway to structural change. We contend that understanding how these theories position themselves vis-à-vis education policy debates is a necessary step toward identifying more promising methodological pathways for scrutinizing the dynamics and challenges of education systems across scales and levels of analysis. Particular attention is paid to how different types of social relations associated with the emergence of, and the responses to, crises (e.g., at the individual, organizational, institutional, or sociopolitical levels) are introduced across the literature. Each level is analytically significant, as all entail "distinctive forms of embeddedness and kinds of emergent properties that can serve as the basis for interpreting crisis symptoms based on direct experience or capacities for collective reflection (...) and as the basis for learning through and from crisis, based on critical self-reflection of different kinds of actors in different settings" (Knio and Jessop 2018, 5).

Our findings identify three dominant strands in the literature published since the release of the World Bank's emblematic 2018 World Development Report, which reenergized debates on the GLC (Ginsburg et al. 2018). The first strand conceptualizes crises as critical junctures, or external ruptures in the normal functioning of global education governance. A second, more constructivist, approach focuses on how crisis discourses are manufactured, thereby problematising their supposed objectivity and foregrounding the interests of specific agents in advancing particular political agendas. Finally, a third strand adopts a more historical-materialist perspective, interpreting crises as manifestations of systemic failure and internal contradictions within capitalism. In line with the conference's focus, our discussion highlights how these perspectives shed light on the resilience of educational systems to shocks and stresses, but also on their role in reproducing or transforming sociocultural structures.

Finally, an overarching conclusion of our analysis is that, despite their contributions, none of the analysed perspectives comprehensively addresses all levels of reality, nor the emergent interactions across levels. From our ontological standpoint, this analytical limitation suggests that the literature would benefit from more ontologically grounded explanations that can enhance its explanatory power with respect to the GLC. We conclude by suggesting methodological principles that can inform future research into resilience and education policy, emphasizing the need to theorize responsibility arrangements and transformation trajectories in societies exposed to the persistent "shock" of learning crises.

Keywords: crisis, education systems, resilience, learning,

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Engineering Responsibility and the Ethics of Structural Change: A Macro-Object Perspective on Resilience

Diana Adela Martin, Centre for Engineering Education, University College London, The UK, diana.martin@ucl.ac.uk

Resilience thinking has undergone a conceptual shift over the last two decades. Once narrowly framed in ecological and systems-theoretical terms focused on recovery, persistence, or adaptation, resilience is now increasingly viewed through a socio-technical and political lens (Taysom & Crilly, 2017; Humbert & Joseph, 2019). This normative reorientation raises several ethical questions for engineers: What social structures are being preserved? What inequalities are being reinforced? And what forms of transformation are needed? This means that our understanding of the responsibilities engineers have needs to be expanded to account for the societal and political dimensions of resilience.

This paper contributes to this conversation by introducing a novel framework for understanding macro-object responsibilities in engineering ethics. Drawing from recent work in engineering ethics and the philosophy of technology, I argue that engineering responsibility must be reconceptualized to address not only individual decision-making (microethics), but also systemic responsibilities directed toward external institutions, socio-political structures, and technological regimes. These macro-object responsibilities are especially relevant in resilience contexts where shocks and stresses (e.g., climate change, infrastructural failure, algorithmic harms) are not only technical challenges but expressions of deeper structural injustice.

The concept of responsibility itself is notoriously multifaceted, encompassing notions of moral duty, legal liability, causal attribution, and professional accountability. In this work, I propose a relational understanding of responsibility, aligned with Smith, Gardoni, and Murphy's (2014) view that ethical responsibilities are those expected of engineers *qua* engineers, namely as actors embedded within systems of power and influence. I employ a analytical matrix that distinguishes responsibility along two axes: Micro vs. Macro (individual vs. collective/systemic scale) and Subject vs. Object (internally grounded vs. externally oriented). The resulting matrix includes Micro-Subject (e.g., focused on personal characteristics and actions), Micro-Object (e.g. focused on engineers as employees), macro-subject (e.g., collective mission of the profession), and macro-object responsibilities. The

latter refer to collective obligations that address the systems, laws, institutions and industries, in which engineering is practiced.

This paper focuses specifically on the macro-object quadrant, where responsibilities are not just about acting ethically *within* a system but working to transform that system when it is misaligned with justice, sustainability, or the public good. Macro-Object responsibilities invite engineers to engage politically, structurally, and normatively with the broader social conditions in which engineering operates. This reframing aligns closely with emerging concerns in resilience discourse, which increasingly ask how resilience planning can address, not reproduce, structural racism, climate injustice, and economic inequality.

The resilience literature has yet to fully develop a theory of responsibility that can handle these complexities. While the concept of resilience has evolved to include social and institutional dimensions, it still lacks a robust ethical framework for evaluating how responsibilities are distributed and enacted across system actors. Responsibility is often implied through ideas like stakeholder engagement, participation, or inclusive governance, but not clearly theorized in terms of who *ought* to act, *on what basis*, and *toward what ends*. This limits our ability to distinguish between individual and collective resilience efforts.

This connects to one of the core questions posed by the conference call: *What responsibility arrangements or frameworks are best suited for desirable transformation in societies exposed to shocks and stresses?* I argue that macro-object responsibility offers one such framework. It distributes ethical agency across collectives, emphasizes the need for structural reflexivity, and supports institutional reform as a condition for just resilience. The articulation of macro-object responsibilities can support the normative underpinnings of resilience strategies. By placing structural transformation at the heart of engineering ethics, this framework contributes to the emerging paradigm of resilience as transformation toward more equitable, inclusive, and democratic futures.

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Distilling Resilience

Marcin Korecki, TU Delft, the Netherlands, mkorecki@tudelft.nl

Abstract

Resilience is a widely popular concept with broad applications. However, its generality is also its limitation. We present a criticism of the concept and argue for distinguishing between epistemic and normative resilience.

Keywords: Normative Resilience; Epistemic Resilience; Limits of Resilience

Introduction

Resilience is taking academia by storm. From health, through ecology, to social sciences, the concept of resilience has established itself across disciplines. Beyond academia the term has been spreading with similar rapidity, as institutions, especially public ones, race to protect its stakeholders from the increasingly unstable future. Its propensity for connecting disparate fields stems from its generality but this very generality is also one of its most significant limitations. On a surface level one may apply resilience to any system whatsoever to denote its ability to maintain its function in the face of disruptions (Walker, 2020). However, the general applicability of the term might perhaps occlude some of its complexities. The mental resilience of an individual discussed in medicine is not the same resilience spoken of by urban scientists. Indeed, while highly general, resilience, is a concept with context-dependency. So the more specific meaning of resilience is dependent on the system it is applied to. In particular it is linked to the particular function of the system (which is supposed to be maintained if the system is resilient) and the conditions for its stability. But regardless of its widespread appeal resilience has also come under criticism.

Critique

First and foremost, resilience, being context-dependent, cannot be considered to be always positive. In fact, if we consider a system whose functioning is negative (e.g. a totalitarian dictatorship) then making such a system resilient also has negative connotations. This argument applies beyond social systems and has also been raised in the context of health Fisher and Jones (2024); Saulnier and Topp (2024). Moreover, limits of resilience in social context have also been discussed at length Béné et al. (2014). In certain contexts resilience may also be seen as masking vulnerability rather than addressing it (Mahdiani and Ungar, 2021). It is also interesting to juxtapose resilience against the field of AI value alignment, which strives to ensure AI is aligned with humanity. As a last resort value alignment designs often involve an off-switch that enables a human to turn off an AI that has gone rouge. Thus, from a human perspective making AI too resilient (e.g. such that it cannot be turned off easily) could be seen as dangerous.

In addition to that, resilience poses a risk for systems to get stuck in a dead-end, non-functional paradigm. Indeed, certain crises may be seen as indicators of the inherent ineffectiveness of the systems, which should be replaced by another system rather than rigidly resisting change. Thus, perhaps resilience should be enhanced with the concept of graceful degradation — bad systems should deteriorate gracefully to be replaced by good systems.

Distillation

Given the above criticism it appears useful to distinguish between two types of resilience: the epistemic one and the normative (engineering) one. The former refers to the epistemic concept that has no normative dimension. It is purely descriptive and can be used to neutrally assess if a given system meets certain conditions that are defined as resilience. The normative resilience, on the other hand, is when a given system is purposefully designed to meet certain resilience conditions. In this case the concept is no longer neutral and carries with it a normative dimension. Thus, when resilience is used purely descriptively it may avoid much of the trappings elaborated on above. However, when it becomes an aim to be engineered, then, depending on the context it might be good or bad and the above critique needs to be taken into consideration.

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The Ethics of 'Rotterdam Resilience'

Katharina Bauer, Thijs Heijmeskamp

Abstract

The municipality of Rotterdam adapted a strategy of resilience in order to adapt to climate change and guide societal transformation. As a result resilience has been adopted by many actors, each with different understandings of resilience and with different normative considerations attached to the notion of resilience. Through the use of a mixture of interviews, literature studies, and variations of Socratic Dialogue with different stakeholders we aimed to uncover normative assumptions that were attached to the different conceptions of resilience. Secondly, we have used the relationship between these commitment and the crisis that put pressure on them to inform an account of moral resilience.

Keywords: moral resilience; normative commitments; vulnerability; climate change adaptation strategies; social initiatives.

Introduction

In order to facilitate the transformation of Rotterdam into a city that can adapt itself to the effects of climate change, the Rotterdam municipality adopted a 'Resilience Strategy' in 2016 which was continued in the 'Resilient Rotterdam Strategy 2022 – 2027'. Yet, the resilience strategy of the city also encompasses social and economic dimensions, recognizing crises in biodiversity, soil pollution, health, inequality and a cybercrisis. The concept "resilience" was originally used to describe the amount of disturbance a material can sustain without breaking. It describes "the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks" (Walker et al. 2004, 5). At the same time resilience has proven to be a productive notion in scientific inquiry, ranging from disciplines like psychology to ecological management. This wide adoption of resilience amongst different actors and its application to a diverse body of subjects has led to a wide range of subtle difference in understanding of what I means to be resilient. This also comes with different normative implications and challenges. We examine some of these implications and challenges within the context of the city of Rotterdam. We use these insights to inform what it means to be morally resilient.

Rotterdam resilience

Both in academic and policy use there a many different notions of resilience in use. As a result resilience is cashed out in different conceptualizations within the context of the municipality of Rotterdam. How do these different strategies and initiatives relate to each other and what is specific about "Rotterdam Resilience"? While at a municipal level resilience is often conceptualized in terms of systems and infrastructure, at the level of neighborhoods we find resilience in terms of strengthened social networks. We argue that this means that resilience

should be considered an essentially contested concept. An essentially contested concept is a notion that although it has agreed upon means of how it is phrased, yet they can always be disputed on their proper use in such a way that the dispute cannot be settled by appeals to empirical evidence, linguistic usage, or the canons of logic alone (Gallie, 1956; Gray, 1977).

Normativity and moral resilience

Within the strategy ecosystem of Rotterdam the theoretical tension between different understandings of resilience come to the foreground. That is resilience as material resistance, resilience as a psychological capacity, resilience a system property. Furthermore, it has been well argued that resilience is an inherently normative concept (e.g., Cañizares et al, 2021). We argue that from the above examinations two interesting lines of inquiry follow. First, how different assumptions and normative commitments are attached to resilience in different contexts. In exploring these normative assumptions, we have focused on the neighborhoods of Bospolder-Tussendijken and IJsselmonde. The first because of the extensive resilience oriented program "Veerkrachtig BoTu" that has run for quite some years now and the latter because of the relative absence of similar overarching programs. Through the use of a mixture of interviews, literature studies, and variations of Socratic Dialogue with different stakeholders we aimed to uncover normative assumptions that were attached to the different conceptions of resilience. As any notion of resilience assumes some crisis that cannot be (fully) avoided, Rotterdam is an interesting case study because of it historical connection to struggle as is capture in its motto: "Sterker door Strijd" (Stronger through Struggle). This captures the socially transformative potentiality that resilience can have. Yet also areas of tension appear between social participation and institutions, top-down policies and bottom-up initiatives, bringing to the foreground themes of vulnerability and power imbalances (Pele et al. 2023).

Second, within the crises that requires resilience, how can individuals and groups maintain or acquire normative agency? The crises that require resilience and our adaptation to those crises often challenge our normative frameworks (Bauer & Hermann 2022). Crisis bring with them moral uncertainty and complexity. The question of societal transformation is therefore a deeply ethical and political question. We argue that systemic crises, such as climate change, require a moral resilience – a dimension that is underdeveloped in current resilience strategies and policies. When the pedagogues Oser and Reichenbach (2005) originally introduced the term 'moral resilience', they defined it as the capacity for moral judgment and agency under pressure - under real life conditions of conflict and complexity. Their understanding of moral resilience is closely connected to moral courage and resistance. One of the first examples they discuss is civil disobedience. We would like to reactivate this connection between moral resilience and resistance and overcome risks of a resilience discourse that might foster passivity and depolitization (Evans & Reid 2014).

A philosophical understanding of moral resilience

Currently, moral resilience is mainly discussed in the field of nursing ethics, as the capacity of caregivers to cope with moral distress (Rushton 2018, Lachman 2016, Lützén & Ewalds Kvist 2013). We can build on Rushton's analysis of moral resilience and on her Moral Resilience

Scale which is already rather differentiated and grounded in a broad review of the existing literature (Young & Rushton 2017). Rushton defines moral resilience as the capacity to sustain or restore moral integrity. Her approach is based primarily on the presupposition that individuals need "moral wholeness" (2018, 13) and congruency with their "values, character, conscience and commitment to do what we are best" (16). We will put more emphasis on the ability to integrate self-determined transformations of one's moral outlook into a coherent self-understanding that is still open to change. Furthermore, we belief that self-respect and hope of being able to contribute to efficient moral agency and change for the better are also decisive for moral resilience. While Rushton draws primarily on theories of psychological resilience and an understanding of moral resilience as the capacity of coping with moral distress, we will be looking more closely at philosophical theories of competent moral agency to deepen the philosophical understanding of moral resilience.

By combining these two lines of inquiry we hope to gain a grasp on wat Rotterdam Resilience means in its many actualizations and identify which competencies and support do individuals or communities need to develop "moral resilience" – as a capacity of dealing with experiences of normative destabilization and confusion in order to be capable of agency that is adequately responsive to complex moral challenges.

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From Canal to Commons: Participatory Revitalization and Social Innovation for Community Resilience in Bangkok's Samsen Corridor

Pechladda Pechpakdee[1] Tipsukon Chuangthong [2]
1 Faculty of Architecture, Urban Design, and Creative Arts, Mahasarakham University, Thailand, Pechladda.p@msu.ac.th
2 Department of City Planning and Urban Development, Bangkok Metropolitan Administration, Thailand, Tipsukonch@gmail.com

Abstract

The Samsen Canal, once a historic drainage waterway linking royal heritage, religious sites, and civic institutions, has long been marginalized in Bangkok's modern urban planning. This paper explores the first phase of its revitalization as a process of cultural reclamation and resilient transformation. By reconnecting the canal with mass transportation networks and neighborhood life, the initiative reimagines it as a shared urban common. Through co-creation, the project mobilizes partnerships between local communities, the Bangkok Metropolitan Administration (BMA), the private sector, educational institutions, and international actors , including the Netherlands Embassy's PIB program.

Key to overcoming fragmentation, silo-based governance has been a robust multi-channel engagement process. This includes cross-department communication within BMA, participatory meetings in both general and site-specific formats, active use of social media, and collaboration
with influencers as civic moderators. The inclusive process welcomes all ages, genders, religious communities, and learning institutions, fostering a shared sense of ownership. Youth and educational institutions play a long-term role in sustaining the canal through citizen science, curricular integration, and living lab engagement, nurturing emotional and intellectual bonds with the waterway.

This case demonstrates how revitalizing a historic canal through inclusive design, storytelling, and cross-sectoral governance can transform it into a platform for resilience, mobility, and social innovation in a complex urban environment.

Keywords: *urban commons; canal revitalization; co-creation; participatory planning; sustainable transport*

1. Introduction

The Samsen Canal, a historic urban waterway that once played a central role in Bangkok's transport, cultural, and civic life, has gradually deteriorated into a neglected drainage line. As it runs through some of the city's most sensitive inner-royal precincts, its revitalization requires more than landscape design demands coordinated action across ecological, social, and institutional systems.

In this project, I serve two interlinked roles: as a lecturer in urban design and development, and as a practitioner leading the project as a project manager. I have worked closely with the Bangkok Metropolitan Administration (BMA), particularly the team from the Department of City Planning and Urban Development, from inception through to implementation. The BMA's strong commitment is reflected in the project's guiding principle: *The revitalization of Samsen Canal's landscape through a participatory process.*

The initiative emerged through a strategic partnership between the Bangkok Metropolitan Administration (BMA) and a dedicated urban design and planning consultancy. The Samsen Canal runs through Bangkok's inner-royal precinct, a highly sensitive area. This location is subject to strict regulations and holds deep cultural significance. To address the complexity, the project assembled a diverse range of experts. These included specialists in wastewater treatment, stormwater management, public transit, and heritage conservation. Their combined knowledge was crucial to solving both technical and social challenges along the canal. The canal's degradation directly undermined its cultural integrity and blocked opportunities for enhanced hydrological connectivity and mobility.

Drawing on insights from Pechpakdee (2024), this paper highlights that "mobility infrastructure emerges as the most significant challenge for urban tourism and development in Bangkok" (p. 60), the project integrated transportation planning into its core vision. This included revitalizing heritage wooden boats as floating museums, combined with the introduction of electric water buses synchronized with MRT and BTS systems. Water taxis and yacht piers were also proposed to link Samsen Canal into the broader Chao Phraya River tourism network, thereby facilitating both local transit and high-value tourism.

By explicitly linking mobility improvements with heritage and ecological restoration, the plan addresses Pechpakdee's identified need for "primary attractions, secondary support facilities and additional elements for convenient mobility" to elevate Bangkok's appeal as a resilient, tourism-sensitive urban corridor (p. 62). In doing so, the initiative transforms the canal from a neglected drainage channel into a multimodal, living urban commons where transit, culture, and sustainability converge.

Planning and engagement processes combined mass public participation with targeted stakeholder consultations. Many challenges, such as interagency coordination and data silos, were overcome through B2B dialogues, co-creation workshops, and iterative consensus building. The Samsen Canal project thus exemplifies how participatory planning and governance innovation can reimagine a forgotten canal as a civic common that serves mobility, heritage, and resilience.

This project aligns with the global resilience discourse, which calls for multifunctional urban blue-green infrastructure and collaborative governance (Ahern, 2011; Brown et al., 2009). It also demonstrates how cross-sectoral design, when rooted in local culture and supported by institutional will, can reclaim a canal as a civic common for climate-adaptive, inclusive, and connected urban living.

2. Practical Approach and Methods

The development of the Samsen Canal revitalization plan was carried out through a staged, cross-sectoral, and interdisciplinary process. The consulting team, comprising professionals from academic sectors, collaborated closely with BMA's Department of City Planning and other technical departments, including environmental engineers, urban planners, sanitation and hydraulic engineers, as well as specialists in urban heritage and architecture. Public hospitals, religious institutions, community leaders, the Crown Property Bureau, police, business operators, and residents along the canal corridor also played critical roles.

Table 1 The process of participation and co-creation

Timeframe	Key Activities	Stakeholders Involved
Apr-2025	The first general assembly is held to introduce the project, establish the vision, and identify the core challenges.	BMA, consultancy team, community leaders, general public
May-2025	Five district-based workshops conducted; spatial plans presented and refined with community feedback.	BMA district offices, local communities, urban designers, planners

May-June 2025	Over 20 bilateral meetings with BMA, agencies, and communities; PIB (NL Embassy) provided advisory input.	BMA departments, specific agencies, community groups, NL Embassy (PIB)
Jun-2025	Four pilot areas selected using triangulation and Delphi methods; co-design sessions launched.	Academic advisors, BMA planners, local residents, and co-design teams
June-July 2025	Technical problem-solving phase: land rights, wastewater, stormwater, seasonal flows, heritage-sensitive design.	BMA engineers, academic experts, heritage specialists, utility managers
Aug-2025	The second general assembly convened to present the revised master plan, incorporating stakeholder feedback.	All stakeholders from previous phases, community representatives
Nov-2025	Final designs were released publicly and shared via social media for broad validation and awareness.	BMA communications team, public audiences, social media influencers

Overcoming Structural Barriers in Canal Revitalization: Challenges and Responses

Fragmented Governance and Coordination Gaps

One of the central challenges of revitalizing Samsen Canal lies in overcoming fragmented governance within the Bangkok Metropolitan Administration (BMA) and across external agencies. Siloed communication and disjointed mandates often impede integrated planning. To address this, the project initiated structured internal-external dialogues, using bilateral meetings and stakeholder workshops to bridge planning silos.

Critical Wastewater Constraints

A foundational limitation is Bangkok's centralized sewage system, which does not yet separate greywater from blackwater. As a result, over 90% of untreated wastewater continues to discharge into the canal. To mitigate this, the project proposed decentralized, green infrastructure along the canal—integrating hidden piping systems with ecological walkways. This approach challenges traditional engineering norms and requires sustained institutional support.

Navigability and Heritage-Sensitive Design

Canal navigation introduces further complexity. Water levels must remain stable to accommodate transport, yet must not disrupt the royal precinct's environmental integrity. With guidance from Dutch experts, solutions such as low-impact propulsion and silent boat docks were developed. These innovations, while promising, require tight regulation and sensitive spatial integration.

Public Concerns and Social Cohesion

Local resistance, especially regarding privacy and safety near new walkways, posed additional hurdles. These concerns were addressed through participatory design, landscape buffers, and surveillance systems. Still, trust-building in high-density areas remains a long-term challenge.

Funding and Land Tenure Barriers

Constraints also stem from diverse land ownership along the canal and BMA's annual budget cycle, which limits long-term project continuity. The team responded by cultivating public-private partnerships, artistic collaborations, and phased co-creation strategies.

Conclusion

Despite systemic barriers, this initiative offers a model for culturally grounded, technically adaptive, and collaboratively governed urban revitalization. Success hinges on aligning institutional flexibility with inclusive and resilient design.

Acknowledgements We acknowledge the collaborative input of BMA, Netherlands Embassy (PIB), City Plan Profession Co.Ltd., and the Samsen community participants.

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Resilience Assessment with Behavioral Markers in Healthcare

Thomas Mühlbradt

Abstract

This paper investigates the use of behavioral markers from Crew Resource Management (CRM) as indicators for resilience assessment in healthcare. A field study was conducted in three hospital departments and one emergency rescue service in Germany (N = 284 addressed staff) using a 16-item online questionnaire. Respondents were able to meaningfully evaluate team behaviors, and qualitative remarks confirmed item comprehension. A confirmatory factor analysis supported a four-factor model with adequate fit but limited convergent validity. The results suggest CRM markers provide a feasible basis for resilience assessment, though further refinement of the factor structure is needed.

Keywords: Resilience Assessment; Behavioral Markers; Crew Resource Management; Healthcare

Systemic Resilience and Resilience Assessment

Systemic resilience is defined in resilience engineering as the ability of a system to sustain required operations by adjusting before, during, or after disturbances (Hollnagel, Woods & Leveson, 2006). Four abilities—to monitor, respond, anticipate, and learn—form the basis of resilient behavior, though they are not directly observable (Hollnagel, 2018). Indicators are therefore needed for resilience assessment. Hollnagel's Resilience Assessment Grid (RAG) provides a conceptual framework but leaves indicator development to users. Alternatives propose transferring ready-made indicator sets to specific sectors (e.g., Rodríguez et al., 2020; Safi et al., 2024). Both strategies face limitations: self-developed sets are resource-intensive and error-prone, while transferred sets may lack acceptance and contextual fit.

Crew Resource Management and Behavioral Markers

Crew Resource Management (CRM) originated in aviation as a structured approach to improving team performance in critical and high-risk situations (Kanki, Helmreich & Anca, 2010). Its central focus lies on systematic team training to enhance communication, leadership, decision-making, and coordination under pressure. In this context, the concept of behavioral markers emerged—observable indicators of effective or ineffective team behaviors that allow performance in simulated or real scenarios to be assessed and improved. Building on this idea, Rall and Gaba proposed a comprehensive list of behavioral markers that capture the essential dimensions of CRM in clinical and other high-stakes domains (Rall et al., 2010). The items were subsequently translated into German as "CRM-Leitlinien" (CRM guidelines) thereby providing a practical framework for training and evaluating teams in healthcare and beyond (Rall & Langewand, 2022).

The responsiveness of teams in crisis situations can be understood as an expression of systemic resilience. Consequently, it should be possible to derive generally applicable indicators for

resilience assessment from the CRM guidelines. This approach is particularly compelling since the validity of these indicators can be considered well established, and they already enjoy a significant degree of recognition within healthcare (see also WHO, 2021, p.23).
On a deeper theoretical level, there is a connection to resilience engineering. If the four abilities mentioned above are potentials for resilient behaviour, behavioral markers should in turn be able to indicate the presence of resilience potentials.

A Field Study

Healthcare is a field that is strongly affected by complexity (Mühlbradt, Speer & Schröder, 2023) with consequences for patient safety. Woods & Cook (2001, S. 91) even postulate: „… the enemy of safety is … complexity" (Woods & Cook, 2001, p. 91). If one assumes that resilient systems are poised to cope with complexity (Mühlbradt & Unger, 2024). Increasing knowledge and awareness of the degree of resilience of existing systems in healthcare should contribute to patient safety.
We conducted a field study with a self-selected sample to test whether staff in healthcare would be able to assess the resilience of their team in an online-questionnaire. The study took place in three hospital departments and one regional emergency rescue service in Germany. The participating hospital departments were Anesthesiology and intensive care (two) and Central emergency (one). In total, 284 staff members were addressed.
The questionnaire started with demographic questions about job group, department and personal CRM-experience. It then proceeded to 16 questions concerning observable behaviors in one´s teamwork, accompanied by short explanations for each item. Answers were to be given on a Likert scale. After each item, an option for open remarks was provided.
The survey started in December 2023 and ended in March 2024. Participation rates lay between 44% and 78% with dropout rates (questionnaire visited but no answering) between 8.7 and 25%.

Results

The assumption that the items operationalize the resilience potentials is plausible, but it cannot be verified directly, since the CRM guidelines show no explicit reference to resilience engineering and are not structured according to the four potentials. Therefore, for the evaluation of the responses, the assignments were established through a rating.

Figure 1 shows boxplots of aggregated resilience potentials for hospital department 3.

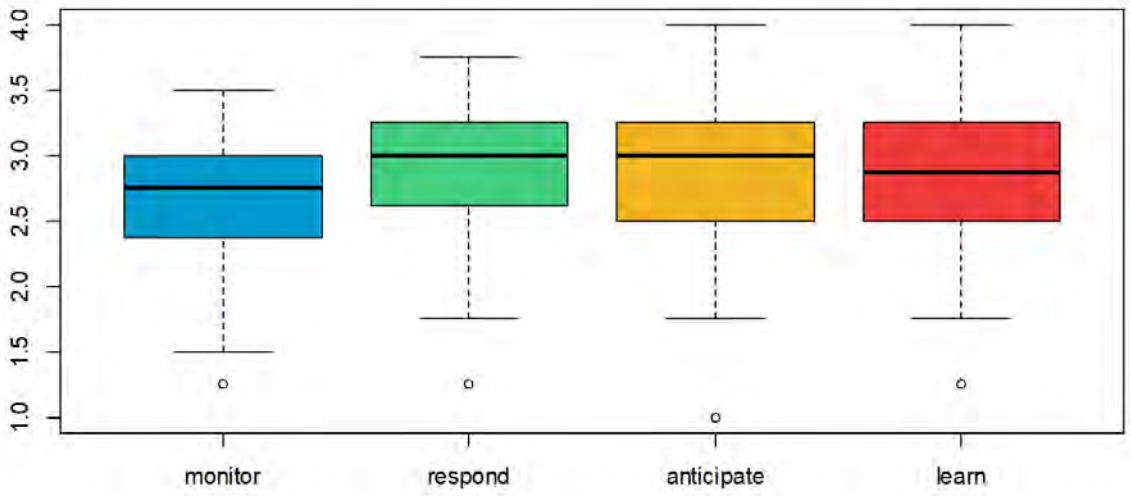


Figure 1. Aggregated Resilience Potentials (hospital department 3)

The results become more differentiated when analyzed at the level of individual items and separated by job groups. Figure 2 shows boxplots for the indicator "request for help" by job group, also in hospital department 3. Red dots indicate the group mean.

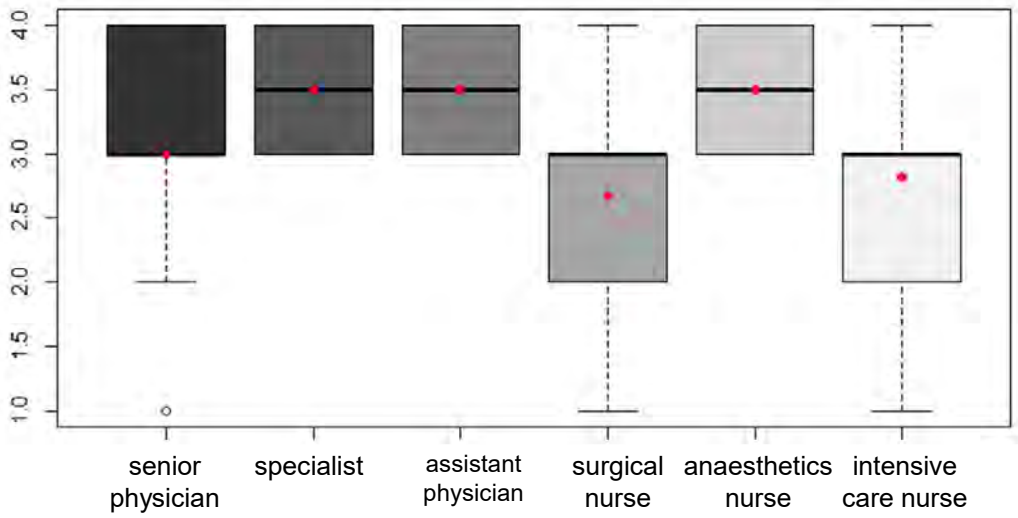


Figure 2. Single indicator "request for help" by job group (hospital department 3)

In addition to the quantitative results, the qualitative comments are also of interest. Table 1 gives an overview about the number of free remarks by item and organization.

Table 1. Number of free remarks by item and organization

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	∑
Hospital Dep. 1	0	1	1	2	3	0	3	0	1	1	1	1	1	0	0	0	15
Rescue Service	8	6	7	9	5	4	5	1	7	5	8	3	8	3	1	9	89
Hospital Dep. 2	7	5	6	5	6	1	4	4	3	5	7	4	4	6	5	5	77
Hospital Dep. 3	7	3	2	2	2	1	4	2	0	2	3	2	2	3	2	4	41
∑	22	15	16	18	16	6	16	7	11	13	19	10	15	12	8	18	222

The content analysis of the open-ended comments indicated that respondents understood the items, as their statements could be logically and consistently assigned to the intended categories. Here also, like in many other surveys, bad is stronger than good, i.e. negative remarks are dominant. Most remarks concern work environment, checklists and memory aids, leadership and knowledge transfer.

Finally, a confirmatory factor analysis (CFA) for four factors was conducted. The standardized factor loadings were generally acceptable, and the overall model fit indices indicated an adequate fit to the data. Convergent validity values ranged between .41 and .48, suggesting that the items accounted for less than half of the variance expected for their respective factors. Thus, while the model structure itself appeared sound, the item–factor relationships were not optimal.

Discussion

The results indicate that the chosen approach is feasible in principle. This suggests the potential for an instrument for resilience assessment that could overcome the shortcomings of previous methodologies. However, the factor structure of the items requires further examination.

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Desilience: When resilience interventions create further risks

Milad Zamanifar, Planetary Resilience Institute, Germany, milad@planetary-resilience.org

Abstract

This article critically examines the status quo of global resilience investments, identifying pathways and mechanisms through which resilience solutions become counterproductive. We introduce the concept of "desilience" as a condition in which an intervention initially intended to build resilience otherwise leads to a net loss of systemic resilience. This concept synthesizes and extends prior work on maladaptation by emphasizing systemic pathways, cross-scale feedbacks, ecological pressure, and transformation opportunity loss. We present a typology of desilience drivers and propose an impact assessment approach for de-risking resilience interventions.

Keywords: Resilience; Risk; Maladaptation; Disaster; Desilience

1) The Case for Desilience

Resilience interventions (e.g., climate action, disaster risk reduction, biodiversity protection, social equality, or waste and pollution control) are recognized as crucial frontiers of humankind's effort for a habitable planet. A vast global collective effort (involving an estimated US\$2 trillion in annual capital) is made to maintain and restore the physical biosphere and governing social dynamics that sustain life.

However, despite this massive funding, the return on investment is far from sufficient. The UN Midterm Review of the Sendai Framework notes an inadequate progress toward risk reduction targets amid rising disaster losses and damages, and increasingly systemic cascading failures (UNDRR, 2023*)*. In ecological resilience, worsening conditions become increasingly apparent as the planet approaches critical tipping points and significant biospheric dysbiosis, manifested by the climate crisis, massive biodiversity losses, and ecosystem collapses (Caesar et al., 2024; WWF and ZSL, 2024; IPBES, 2019).

Current investment in resilience is inadequate. Yet, effectiveness—not only adequacy—remains a problem: The failure of global resilience investments is not always due to a lack of funding or intention. For example, the World Bank reports that nearly half of the projects evaluated failed to achieve sustainable outcomes, with malinvestment costing $40–60B annually (World Bank IEG, 2022). IPCC AR6 WGII (2022) report evidence that climate actions inadvertently increase vulnerabilities, create lock-ins, or worsen inequities (IPCC, 2022—SPM; AR6 WGII). Similarly, 50% of DRR projects are likely to fail in reducing long-term risks due to persistent shortcomings in risk governance, results frameworks, and project design quality (OECD, 2024; OECD, 2020), while most are significantly carbon-intensive. Moreover, 92% of climate finance bypasses consultation with local actors (Oxfam, 2023), and

less than 10% of climate finance reaches the local actors, despite strong evidence that locally led resilience building improves effectiveness and equity (IIED, 2017; IFRC, 2023).

In sum, the gap in resilience investment goes beyond the adequacy of funding. Inaction, delayed action, maladaptation in design and implementation, misconceived or misformulated problem, siloed solutions, and short-termism all erode resilience and can introduce new risks—sometimes from the very interventions that were meant to enhance resilience (IPCC, 2022; UNEP, 2023; Reckien et al., 2023; Zamanifar et al., 2023). This failure mode is termed "Desilience". Desilience occurs when disaster risk reduction becomes disaster risk creation, when climate adaptation proves maladaptive, when sustainable development increases consumption or inequality, or when resilience measures exacerbate social injustice, ecotoxicity, and waste. Desilience is therefore a condition in which an intervention — initially intended to build resilience — otherwise leads to a net loss of systemic resilience across temporal, spatial, and sectoral scales. This concept synthesizes and extends prior work on maladaptation by emphasizing systemic pathways, cross-scale feedback, and planetary-level tensions, as well as covering system transformation opportunity loss. For example, although maladaptation itself falls under the category of desilience, successful adaptation might yield a net negative outcome for resilience transformation, too. Additionally, desilience shifts the focus from categorizing sector-specific temporally and spatially limited negative outcomes of climate action-related investment to a wider scope and for diagnosing the underlying pathways and drivers of systemwide resilience loss across scales and levels.

2) Characteristics of Desilience

We argue that desilience emerges from two core challenges in resilience programming: (a) a sensitive dependence on context, level, and scale, and (b) a sensitive dependence on how a problem and its system boundaries are defined. These challenges facilitate desilience through three major drivers, classified by error type and knowledge gap (Table 1).

Table 1: *Desilience drivers, categories, and examples, excluding the existing power dissymmetry and lack of resources*

Desilience drivers	Category of error and Gap in knowledge	Examples
1) **Conceptual ambiguity of what systemic resilience is and lack of sector-specific, actionable definitions benchmarking, and assessment methodologies**	- Ontological and epistemological errors - Gap in declarative knowledge	▪ Terminological polysemy, confusion on resilience definition, redundant terms ▪ Focus on static resilience of asset instead of dynamic resilience of system ▪ Misconception and flawed framing of the true problem thus error of the third kind ▪ Discursive hegemony (e.g., western vulnerability discourse, neocolonialism in social resilience) ▪ Resilience designs and sustainable transitions only for privileged groups ▪ Emission centric resilience and carbon tunnel vision, $7 billion fossil fuel annual funding ▪ Infrastructure-centered resilience for communities

		▪ Adaptation by resuming the convenient status quo as opposed to paradigm shift and transformation
2) **Dysfunctional organizational culture, poor governance, and axiological errors in resilience building**	- Axiological error - Gap in conditional knowledge	▪ Failed NGO-led research model ▪ The quality of design and implementation of resilience solutions ▪ Phantom Aid phenomenon: Aid sent but never reaches recipients ▪ Short-termism in policies and strategies ▪ Siloed resilience solutions that are limited to their sectors ▪ Perverse incentives (e.g., corruption, funding models, rewarded visible outcome) ▪ Gender exclusive resilience design, community exclusion, not locally led, designed and implemented solutions ▪ Existing monitoring and evaluation systems, procurement mechanism, and project management regimes ▪ Tendency to transfer resilience accountability in systems (resilience leak)
3) **Methodological errors in applied research, modelling and system boundaries**	- Epistemological and praxeological errors - Gap in procedural knowledge	▪ Indicator-based prioritization and evaluation scoring systems ▪ Contextual disparity of the problem and the designed solution ▪ Colorful maps with information loss ▪ Oversimplified hazard and exposure modeling and universal fragility curves ▪ Western-biased risk studies and discourse ▪ Failure to conduct, understand and make use of uncertainty analysis ▪ Limited system representation in modeling consequences and impact ▪ Kitchen Sink Fallacy: Overwhelmed model with decision parameters and model variables for the sake of inclusivity ▪ Overcompensation of actionability according to the local context with loss of specificity or depth of resilience design ▪ Absence of cross-sectoral and cross-generational cascade impact models due to limited computational capacity

3) De-Risking Resilience Projects

Desilience is preventable. To de-risk projects, we propose a systemic risk assessment approach tailored for resilience interventions. Current evaluations often prioritize short-term, sector-bound outputs over long-term, system-wide resilience outcomes. Therefore, we argue for a standardized evaluation framework that identifies a project's impact chain and potential cascading systemic risks. This facilitates determining the holistic net benefit of interventions in terms of their capacity to protect the biophysical and social system’s resilience and thereby helps to maximize the Planetary Resilience Return on Investment (PRROI) for any intervention (e.g., policy, strategy, or investment in projects and products).

As shown in Figure 1, the proposed planetary resilience impact system is a systemic risk assessment framework of project impacts. This evaluation mechanism captures the recursive relationships among impact elements, including transformational opportunity loss, human and social risk, anthropogenic throughput pressure, and ecosphere disruption, in addition to the positive feedback loops among them. Each impact element represents a “pathway” consisting of a set of proxy measures that form a chain of interactions, allowing for the assessment of both

micro- and macro-level impacts. This approach yields a scenario tree of cascade risks along the four pathways as well as the integrated synergistic dynamics (syndynamics) due to emergent cascades of one or many of the impact elements.

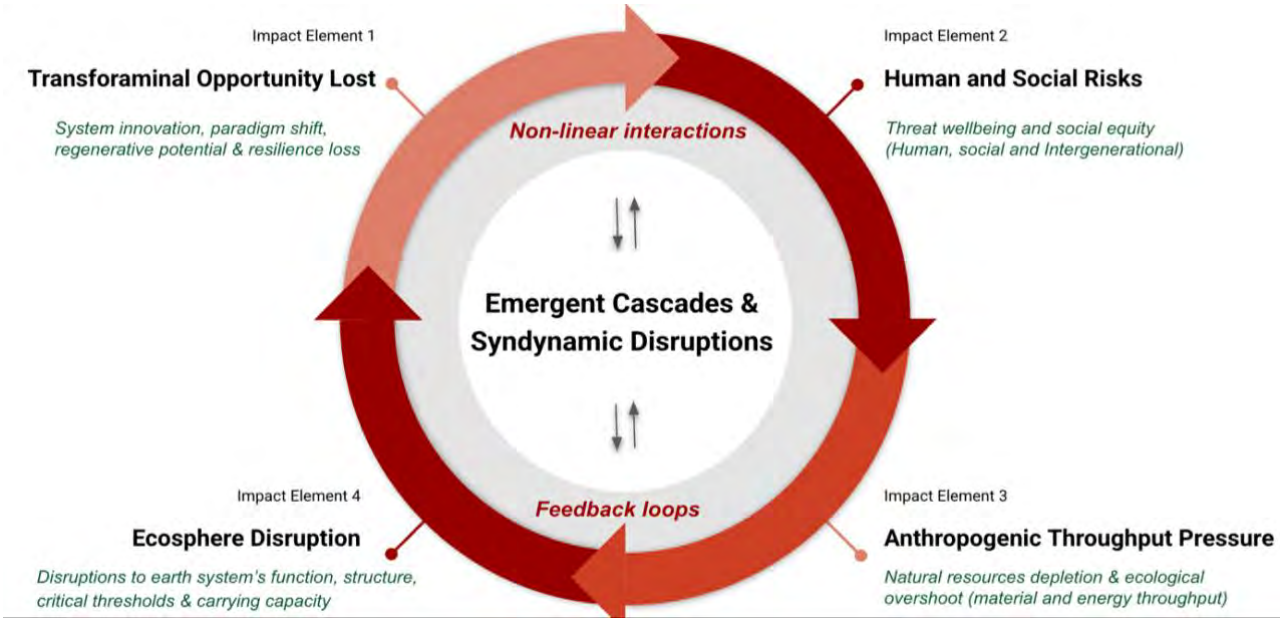


Fig.1. Impact system and four impact elements involved in planetary resilience evaluation

The impact system captures the systemic, long-term, integrated socioecological response to an intervention. It is a set of institutional, technical, human, social, and ecological capacities and pathways that are created, preserved, lost, or disrupted, either in the present or in the future, from the implementation of a resilience intervention.

The framework proposed allows for just and risk-informed development, adaptation, and preparedness, meaning every intervention (infrastructure built, adaptation projects, environmental programs, resilience investment) enhances long-term system-wide resilience for all, across generations, and does not exacerbate risk and inequality.

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Bridging Resilient Systems and Education: A Multi-Year Case Study on Fostering Resilience Thinking in Engineering

Ann-Kristin Winkens, RWTH Aachen University
ann-kristin.winkens@rwth-aachen.de

Abstract

Resilience thinking is essential for engineers to design adaptive socio-technical systems, yet it is rarely addressed in engineering curricula. This contribution presents a multi-year case study (2022–2025) of a master's-level elective course combining problem- and case-based learning with structured reflection. Mixed-methods evaluation (pre-post surveys, reflective diaries) shows substantial perceived gains in applying, analyzing, and evaluating resilience, alongside improvements in interpersonal skills such as communication and coping with crisis. Qualitative insights indicate a shift toward resilience thinking, greater acceptance of complexity and uncertainty, and recognition of resilience as vital for engineering practice. The course offers a transferable framework for integrating resilience thinking into engineering education across disciplines.

Keywords: Resilience Thinking; Engineering Education; Socio-Technical Systems; Capacity Building

Introduction and Course Design

Global challenges such as climate change and the increasing frequency of extreme events require engineers not only to design technical sound infrastructure but also to develop resilient socio-technical systems that can adapt to sudden crises in the face of increasing uncertainty and complexity. However, engineering curricula often do not systematically build competencies which are relevant to design resilient systems, such as anticipatory thinking, systems thinking, and the ability to learn from failure (e.g., Helmrich & Chester, 2020; Scharte, 2019; Winkens & Leicht-Scholten, 2023). This contribution presents a multi-year case study (2022–2025) of the master's-level elective course *Resilience and Socio-Technical Systems*, offered to environmental, civil and industrial engineering students at a large technical University in Germany. The course is designed to address that educational gap through a holistic, problem- and case-based learning approach (for more details see Winkens et al., 2024). The one-semester course combines different activities related to active learning with structured reflection to foster competencies directly linked to designing resilient systems. Intended learning outcomes include defining resilience across different conceptual frameworks, comparing interdisciplinary discourses on resilience, applying resilience-oriented approaches to practice-based decisions, analyzing and evaluating scenarios and crisis management strategies for resilience potential, and reflecting on the implications of resilience thinking for both local/global crises and students' future professional practice as engineers. The course

content addresses topics such as system behavior and assessment approaches, differences between resilience and traditional risk management, resilience in engineering education and practice, urban resilience, and the concept of resilience thinking as a way to deal with change and uncertainty.

Each semester, about 20 students work in groups of 4–5 on self-chosen real-world (past) crises, define system boundaries (i.e., asking "resilience of what to what") and propose resilience-enhancing solutions. The chosen cases span diverse contexts, from extreme weather events and floods (e.g., German Flood 2021, Hurricane Katrina 2005) to technological and infrastructural disruptions (e.g., Ever Given Suez Canal blockage, Love Parade Disaster) and large-scale disasters such as wildfires and dam failures. Choosing their own cases challenges students to reach consensus within their teams but also allows them to explore resilience across different types of systems and contexts. However, as the past four years have shown, most groups chose water-related cases, reflecting the primary focus of their study backgrounds.

Course Evaluation and Findings

A mixed-methods evaluation combines pre-post self-assessment surveys with qualitative reflective diaries to capture competency development and learning processes.

Across all cohorts from 2022 to 2025, the pre-post self-assessment results for resilience-related content and methodological competencies (R1–R8) show a consistent and substantial increase in agreement levels after course completion (Figure 1). Foundational knowledge and understanding (R1–R4) started at moderate to high agreement levels (e.g., R2: 43% in 2022, 78% in 2023) and reached >80% post-course in all years. More complex skills (R5–R8) were less pronounced before the course (mostly <20%; in some years 0%) but showed the largest gains, with post-course agreement rates reaching 100% in most cohorts. This pattern indicates that the course is particularly effective in advancing students' perceived ability to apply, analyze, and evaluate resilience in practical contexts. The consistently high post-course scores across multiple cohorts point towards similar competency development, while year-to-year variation likely reflects differences in student composition and chosen case studies.

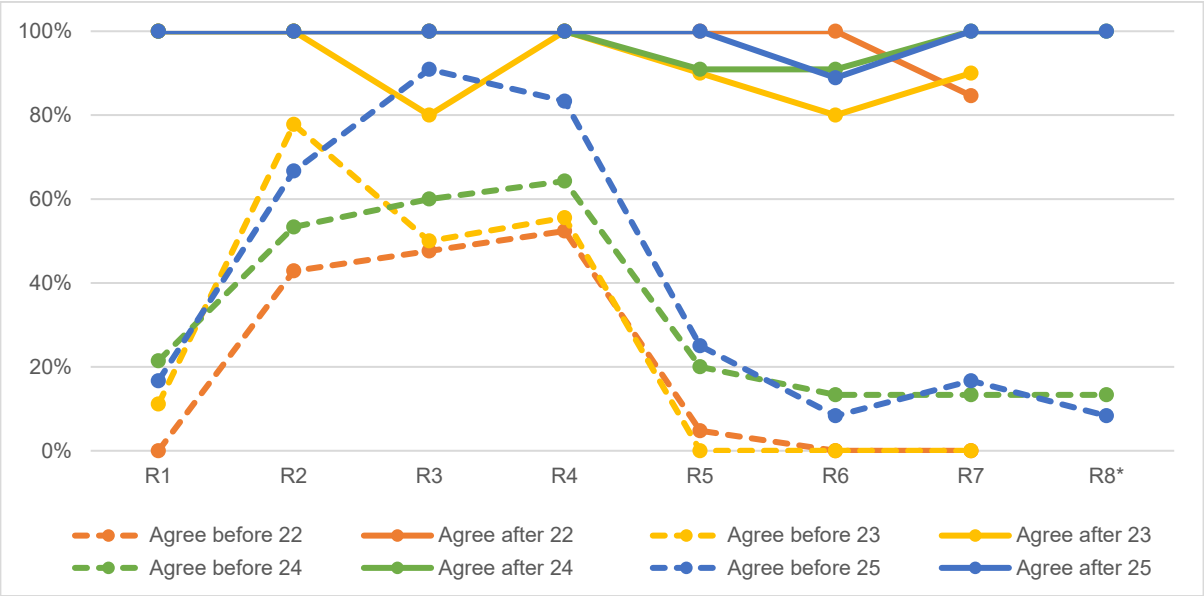


Figure 1: Cumulative percentage of students' agreement on perceived competency development (R1–R8) before and after the course across cohorts 2022–2025 (n=21/13, 18/10, 15/11, 12/9). R1: know scientific discourses; R2: explain resilience; R3: understand relevance for global crises; R4: understand relevance for engineering work; R5: apply resilience; R6: analyze resilience in scenarios; R7: evaluate crisis management for resilience; R8: develop resilience-promoting solutions (item included in 2024).*

In addition to subject-related competency development, post-course results also indicate perceived improvements in selected interpersonal competencies such as presentation skills, conflict resolution and the ability to cope with sudden crises. Notably, students consistently rate themselves as to be more resilient after the course than before, even though the course primarily focuses on the resilience of systems rather than on personal resilience.

Qualitative insights from reflective diaries and end-of-course feedback discussions complement the quantitative results by providing a richer understanding of students' learning processes. In general, the insights reveal shifts from a risk management mindset toward resilience thinking, a deeper acceptance of complexity and uncertainty, and a stronger sense of professional responsibility. However, students point out recurring challenges, such as selecting a suitable case, defining system boundaries in response to the "resilience of what to what" question, managing time and coordination within groups, engaging with entirely new topics and teaching formats, assessing resilience, and critically interrogating scientific literature. Students also struggled with developing a nuanced understanding of resilience: "*I have realized that the topic of resilience is much more complex than I had initially assumed.*" (student's quotes denoted by italics), distinguishing it from risk management, and identifying appropriate assessment criteria. Despite these challenges, above all, students recognize the critical importance of resilience for engineering practice and the lack thereof in their prior studies: "*It is also the responsibility of engineers to consider not only the technical and known components of a system, but also the uncertainties and unknown components. Resilience is therefore not only about minimizing and controlling risks, but also about being prepared for the unknown, or adapting flexibly and adaptively to a disaster/crisis*." They reported increased ability to structure arguments, think critically and creatively, and accept complexity and uncertainty as

inherent features of real-world problems: "*Realizing that the solution to complex problems is not to keep doing the same things over and over again, to revert to previous states, and then hope for the best, is something that will help me both in my professional and personal life. Oh, and: you can never know everything.*" Analyzing past crises reinforced the value of learning from failure as key for designing resilient systems (Foley et al., 2022; Pearson et al., 2018).

Implications

The insights of the course highlight that systematically integrating resilience thinking into engineering education not only helps to develop the technical and methodological competencies needed to design adaptive, resilient systems, but also fosters interpersonal skills and mindsets essential for resilience practice. The course provides a transferable framework that can be adapted to different engineering disciplines and educational contexts, thereby bridging the gap between resilience research and the preparation of future engineers. Embedding such approaches more broadly into curricula is key to cultivating the human resources required to address the complex, uncertain challenges faced by built and lived systems worldwide.

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Inclination Effects of Timber Foundation Piles in Urban Quay Walls: A Finite Element Study on the Marnixkade Case in The Netherlands

van Vliet, N.A. Delft University of Technology, The Netherlands, nielsvanvliet@tudelft.nl

Abstract

Amsterdam's historic urban quay walls are deteriorating due to the lifespan exceeding 100 years and the increased loading. Traditionally founded on vertical timber piles, later adaptations introduced inclined piles, while more recent designs have switched to concrete or steel foundations. With sustainability becoming a priority, timber as a construction material is re-attracting interest, supported by new experimental insights into its mechanical properties. Two design solutions are studied with a masonry wall on a timber kesp (transversal beam) on straight (Type 1) and inclined (Type 2) timber piles. This study investigates the influence of pile inclination on quay wall performance through a Finite Element case study of the Marnixkade, using soil data from Cone Penetration Tests (CPTs) taken at a nearby location of the Bullebak bridge. Thereby, it aims to find the optimum angle of the foundation piles. Numerical analyses were carried out in PLAXIS 2D with staged construction and automated parametric variation of pile inclination. Results show that inclining compression piles from 0° to 16° significantly reduce pile displacements, bending moments, axial forces, and unity checks of the piles (47.7% reduction) for Type 1 quay walls. For Type 2 quay walls, the optimum angle appears to be at 21°. Governing unity checks decrease for the same pile dimensions, indicating improved structural design and efficiency. These findings suggest that pile inclination may provide a viable means to increase safety of foundation piles in quay walls. However, for Type 2 quay walls, this effect is very limited as compared to the current historically applied inclination of 14°, as a further reduction of the unity check of only 5.1% is achieved when increasing this angle to 21°. The results demonstrate that in the design of quay walls, the structural potential of the inclination angles of the foundation piles to reduce bending demand, optimise material use, and potentially increase service life across all foundation types, should be considered.

Keywords: Urban quay walls; Pile inclination; Foundation optimization; Timber piles; PLAXIS 2D

Introduction

In Amsterdam, quay walls are used as retaining structure to prevent the soil from collapsing into the water along the canals. Originally, Type 1 quay walls (Figure 1) were constructed with vertical timber piles and no inclination, thereby posing a risk to lateral failure of the foundation piles (Hemel, 2023). In later Type 2 designs, inclined piles were introduced to shift load-bearing from bending to axial capacity of the piles and thereby improve the safety of the structure. In current practice, fearing degradation of timber, piles are again applied straight, using strong but environmentally impactful materials such as concrete and steel, and the structural benefits of pile inclination are no longer exploited. This study aims to find how much

reintroducing pile inclination can reduce bending moments, normal forces, and deformations, while accounting for timber pile degradation (Pagella, 2025) and practical construction limits.

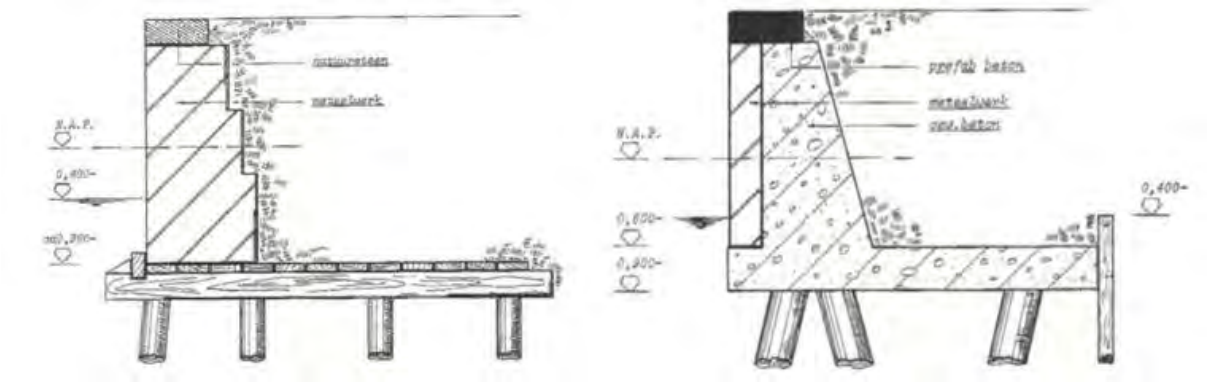


Figure 1 – 'Historic quay wall configurations most often seen in Amsterdam: Type 1 (left) and Type 2 (right)' (Ingenieursbureau van Amsterdam, 2023)

Methodology

A staged-construction finite-element model was built in PLAXIS 2D, using a medium mesh size of approximately 0.4 m by 0.4 m for the soil, the model consisting in total out of 2441 elements, which have been defined according to the PLAXIS Scientific Manual (Bentley, 2024), and inclination angles were varied parametrically using Python scripting. Governing pile forces and unity checks were computed according to Eurocode 5.

For Type 1 walls only compression piles were analyzed from an angle of 0° to an angle of 16.03°, whereas Type 2 walls included both compression and tension piles. Compression-pile angles ranged from 5.71° to 28.85°, and tension-pile angles from 5.71° to 18.11°, with limits set by building-interference constraints and a minimum practical inclination of 1H:10V. Timber-pile degradation was incorporated by reducing the moment of inertia to exclude the soft-shell (Pagella, 2025). Stresses were determined, and soil displacements were checked against a 50 mm serviceability limit.

Results for each simulation were compared with a baseline of vertical piles for Type 1 and a historic 14.04° inclination for Type 2, enabling evaluation of changes in ULS and SLS performance relative to current practice.

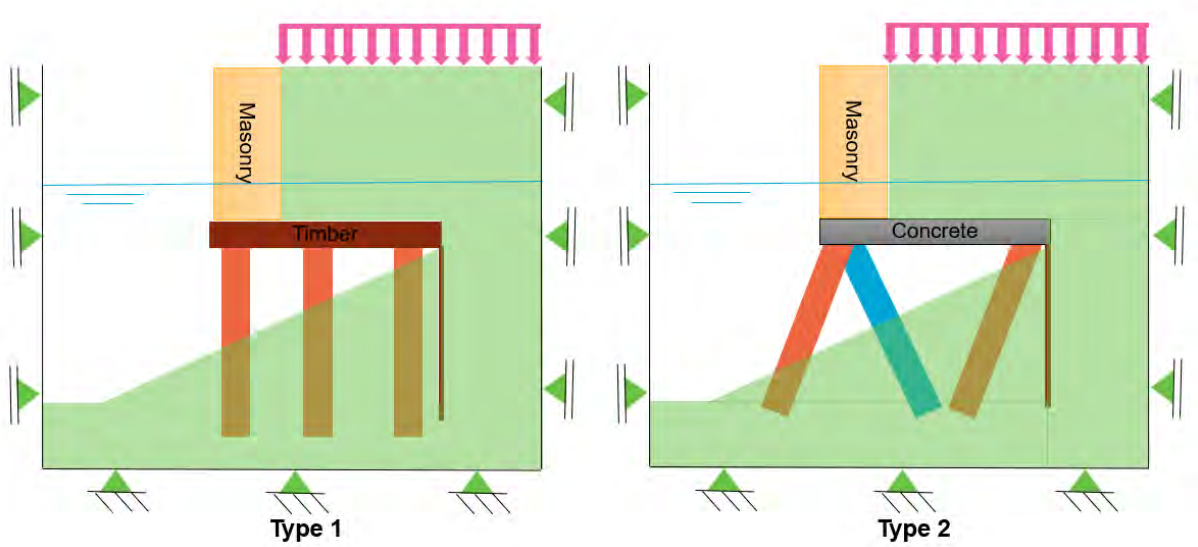


Figure 2 - Schematization of both Type 1 (left) and Type 2 geometry (right) in PLAXIS 2D, not according to scale. The soil consists out of multiple soft clay layers with a stiffer tidal sand layer between NAP-6 m and NAP-8.5m and stiff first sand layer between NAP-12.7m NAP and NAP-15.5m, in which the tip of the piles is located. Loading of 10 kN/m is applied on the land side of the quay wall at NAP+0.58m. The water level is at NAP-0.4m Note that the compression piles are indicated in red and the tension piles in blue for both geometries. The piles are modelled as embedded beams and have an out of plane spacing of 1 m.

Results

Increasing pile inclination reduces bending moments, normal forces, and horizontal displacements for both Type 1 and Type 2 quay walls. The load transfer progressively shifts from lateral resistance to axial capacity as inclination increases, resulting in lower structural demand and smaller unity checks. Type 2 walls consistently perform better than Type 1 due to the additional stiffness from the concrete slab and the presence of tension piles.

Type 1

Table 1 shows that increasing inclination from 0° to α = 16.03° reduces maximum bending moments by 49.7%, while normal forces increase by 48.2% relative to the base case, because the load path transitions from bending-dominated to axial compression-dominated behavior as the pile is rotated. Horizontal soil displacements reduce by 91% at α = 16.03°, but beyond this

angle the model becomes unstable at 19.24° due to the soil collapsing. From Figure 3 it is observed that this effect is more pronounced for the third pile.

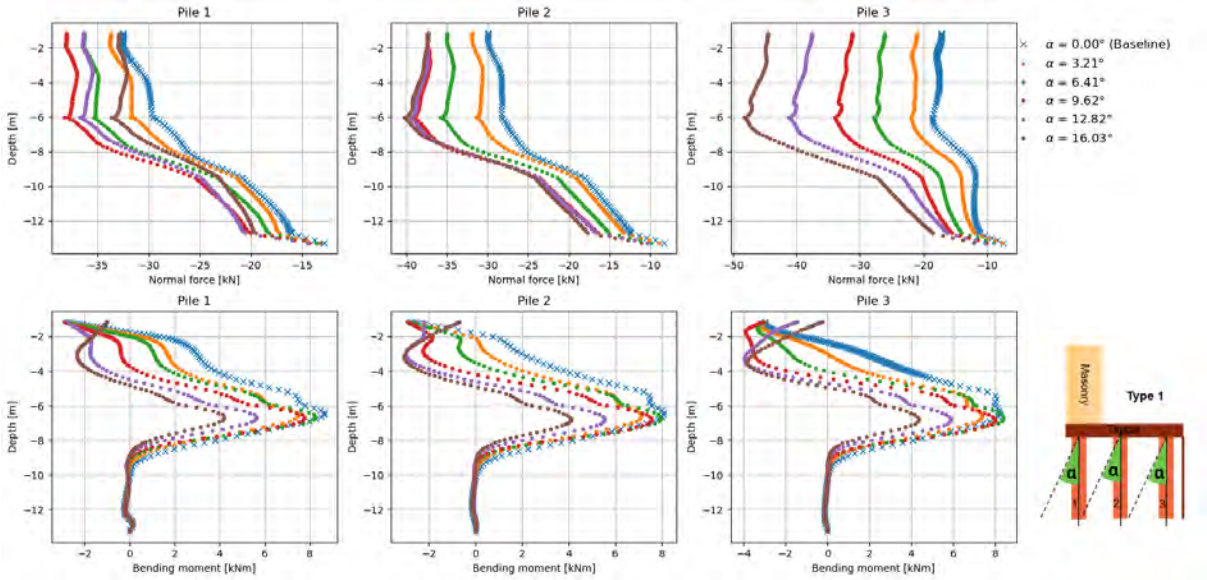


Figure 3 - Normal forces and bending moments in the piles of Type 1 geometry for different inclination angles (α)

Table 1 - Type 1 ULS checks piles and relative differences compared to baseline (highlighted in grey)

ULS checks piles						Relative difference ULS piles compared to 0° angle					
Angle	N	M	UC compression	UC bending	UC combined	Angle	N	M	UC compression	UC bending	UC combined
[°]	*[kN]*	*[kNm]*	*[-]*	*[-]*	*[-]*	*[°]*	*[kN]*	*[kNm]*	*[-]*	*[-]*	*[-]*
0.00	-32.59	8.63	0.13	1.48	1.49	0.00	0.0%	0.0%	0.0%	0.0%	0.0%
3.21	-33.82	7.48	0.14	1.28	1.29	3.21	3.8%	-13.3%	3.8%	-13.3%	-13.0%
6.41	-36.41	8.39	0.15	1.44	1.45	6.41	11.7%	-2.7%	11.7%	-2.7%	-2.8%
9.62	-39.42	8.00	0.16	1.37	1.39	9.62	21.0%	-7.3%	21.0%	-7.3%	-6.9%
12.82	-41.25	5.88	0.17	1.01	1.03	12.82	26.6%	-31.8%	26.6%	-31.8%	-30.7%
16.03	-48.31	4.34	0.20	0.74	0.78	16.03	48.2%	-49.7%	48.2%	-49.7%	-47.7%

Although unity checks decrease with inclination (ULS UC reduced from 1.49 to 0.78), the values remain large for all simulations. This is caused by the reduced section modulus from timber degradation. A larger decrease of displacements was observed (SLS UC reduced from 1.11 to 0.10).

Type 2

For Type 2 walls, which include a concrete slab and both compression (α) and tension (β) piles, the effects of inclination are different per pile. Increasing α from 14.06° (baseline) to 21.14° Results in a 5.1% reduction in the governing unity check. From both Figure 4 and Table 2 it is observed that this 21.14° is the optimum angle in terms of minimal unity check. A higher angle is preferred, as 5.71° (minimum of this parametric study) yields worse results than a 28.85° (maximum of this study) angle.

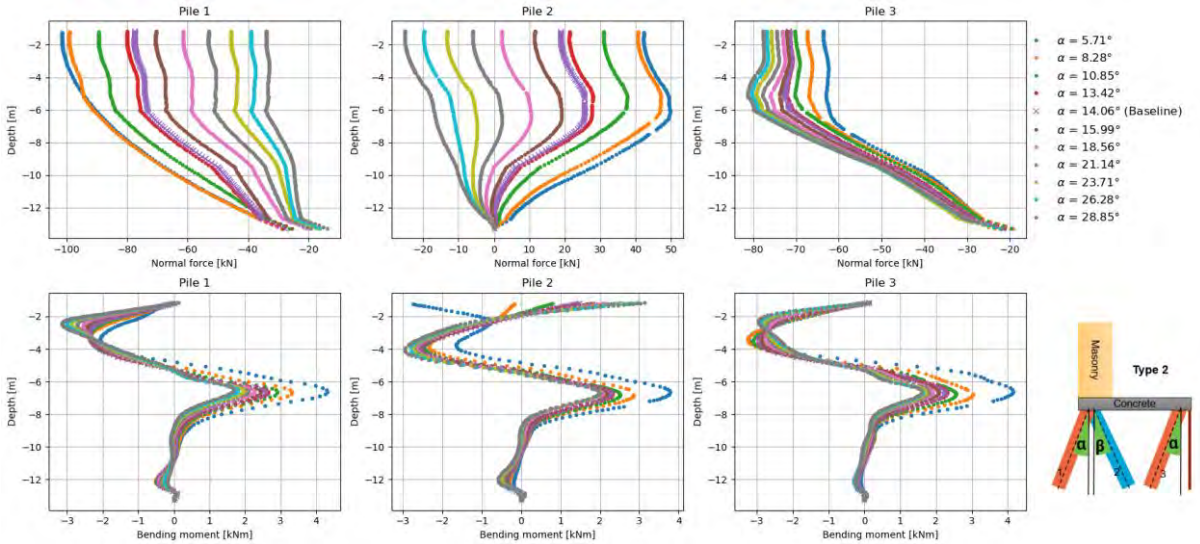


Figure 4 - Normal forces and bending moments in the compression piles of Type 2 geometry for different inclination angles (α) under a fixed angle in the tension pile (β)

Table 2 - Type 2 ULS checks piles and relative differences compared to baseline (highlighted in grey)

ULS checks piles						Relative difference ULS piles compared to baseline					
Angle	N	M	UC compression	UC bending	UC combined	Angle	N	M	UC compression	UC bending	UC combined
[°]	*[kN]*	*[kNm]*	*[-]*	*[-]*	*[-]*	*[°]*	*[kN]*	*[kNm]*	*[-]*	*[-]*	*[-]*
5.71	-101.56	4.30	0.41	0.74	0.86	5.71	30.9%	66.5%	30.9%	46.0%	46.5%
8.28	-99.19	3.32	0.40	0.57	0.70	8.28	27.8%	28.3%	27.8%	12.5%	18.2%
10.85	-89.48	2.91	0.36	0.53	0.61	10.85	15.3%	12.5%	15.3%	5.2%	3.6%
13.42	-80.00	2.65	0.33	0.51	0.59	13.42	3.1%	2.3%	3.1%	0.9%	0.6%
14.04	-77.61	2.58	0.32	0.50	0.59	14.04	0.0%	0.0%	0.0%	0.0%	0.0%
15.99	-73.79	2.44	0.30	0.49	0.58	15.99	-4.9%	-5.5%	-4.9%	-2.8%	-2.2%
18.56	-76.01	2.26	0.31	0.47	0.56	18.56	-2.1%	-12.6%	-2.1%	-6.5%	-5.0%
21.14	-77.78	2.52	0.32	0.47	0.56	21.14	0.2%	-2.5%	0.2%	-7.2%	-5.1%
23.71	-79.29	2.78	0.32	0.49	0.58	23.71	2.2%	7.6%	2.2%	-2.4%	-2.3%
26.28	-80.32	2.95	0.33	0.52	0.59	26.28	3.5%	14.2%	3.5%	2.2%	0.3%
28.85	-81.28	3.13	0.33	0.54	0.61	28.85	4.7%	20.9%	4.7%	6.7%	2.9%

Conclusion

This study examined how the inclination of timber foundation piles affects the structural performance of historic Amsterdam quay walls, using a model in PLAXIS 2D**.** Results show that increasing pile inclination shifts the load path from bending to axial action, reducing bending moments, soil displacements, and unity checks across timber-founded quay walls.

Overall, the performance for bending-dominated Type 1 walls is significantly improved by designing inclined piles, while offering only minor gains for the inherently stiffer Type 2 configuration, reinforcing its relevance as a design parameter in timber-founded quay walls.

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Autonomous Road Vehicles at Disasters: Threat or Solution?

Julian Schindler, Gerald Temme
German Aerospace Center (DLR), Germany, julian.schindler@dlr.de
German Aerospace Center (DLR), Germany, gerald.temme@dlr.de

Abstract

Autonomous (SAE Level 4, L4) vehicles must be able to handle all possible situations within their Operational Design Domain (ODD). In regular traffic, this includes the correct interaction with emergency services. While there have been several reported incidents related to wrong interaction of autonomous vehicles with emergency services in the beginning, first L4 brands now validated that their vehicles behave according to best practice emergency response guidelines. Nevertheless, these validations focus on isolated emergency situations only. When it comes to large-scale emergency situations, disasters or (cyber-) attacks, these solutions are insufficient. In such cases, autonomous vehicles on the one hand can aggravate the situation, e.g. when several of them are failing to operate (correctly) at the same time. On the other hand, autonomous vehicles can serve as helping instrument for emergency services, when they are applied properly. This paper provides a comprehensive overview of potential hazards and anticipated benefits of autonomous vehicles. It also presents first possible recommendations for an advantageous application.

Keywords: autonomous road vehicles; large-scale emergency situations; remote operation

Introduction

Autonomous road vehicles (Level-4 according to SAE J3016 (SAE International, 2021)) start to become reality, all over the world.
The vehicles perform quite good in relation to safety and service quality, issues have been reported related to rescue operations in the beginning of the deployment phase (Mitchel, 2023). Countermeasures have been developed, but only focusing on single/local events.
Impact of autonomous driving in case of large-scale events has not yet been sufficiently addressed in research.
The DLR-internal project RESITEK addresses this topic, investigating different kinds of disasters and the interplay of autonomous road vehicles, airborne surveillance systems and emergency services.

Autonomous vehicles in rescue situations

Several issues have already been identified, dealing with the correct response of autonomous vehicles to rescue services. According to (The Margulies Communications Group, 2025), a 2023 report of San Francisco police revealed that autonomous vehicles are:

- Blocking entrances to fire stations
- Obstructing emergency vehicles in transit

- Making contact or near misses with personnel or equipment
- Disrupting active police operations
- Displaying unpredictable operations near a response zone

In the aftermath, the Society of Automotive Engineers' (SAE) released best practice guidelines for First Responder Interactions with Fleet-Managed Automated Driving System-Dedicated Vehicles (ADS-DV) (SAE International, 2024), which include the following areas of actions:

- Stabilization and extrication,
- Securing a scene involving an ADS-DV,
- Traffic direction and control,
- Traffic stop or checkpoint,
- Interacting with ADS-DVs in traffic,
- ADS emergency assistance,
- Unattended ADS-DV (Not in a parking spot)

Waymo is the first company which has been certified to be in-line with the requirements (The Waymo Team, 2024). The company also created Waymo's Emergency Response Guide (Waymo LLC, 2024) which explains in detail e.g. how vehicles can be stopped, deactivated and secured.

Research is also investigating how specific emergency situations should be handled. Possible solutions include the cooperative creation of corridors for emergency vehicles (DLR, 2024) on highways or in situations where traffic is stuck, or the coordinated blocking of roads by autonomous vehicles to allow safe and fast landing of rescue helicopters (May, Bargmann, & Fehr, 2020).

From isolated incidents to large-scale emergencies

While several solutions exist to handle isolated incidents, there is a lack of insights related to large-scale emergency situations, where large areas and several vehicles are impacted, sometimes suddenly and without warning. Predicted threats are:

- ODD limitations: The shutdown of communication channels (due to e.g. hardware failures or cyber-attacks) as well as heavy rain/snow/fog/smoke, or destroyed infrastructure (e.g. through earthquakes) can lead to (sudden) stops of several autonomous vehicles at their current position, resulting in blocked roads, traffic jams and even accidents.
- Limited availability of remote operation centers: In case of unpredicted events the vehicles are forced to come to safe stop while at the same time contacting technical supervision or remote operation centers. Several requests at the same time will overload the centers (due to limited personnel).

- Break-down of communication infrastructure: Several requests for technical supervision at the same time will most likely cause communication bottle-necks, esp. as communication may already be used extensively by affected people and should be available for rescue services.

Solutions & Impact:

- Use of Remote Assistance: It is important to allow remote control of vehicles with low bandwidth requirements, such as acknowledgements of maneuvers suggested by the ADS-DV based on abstracted data instead of high-resolution video streams and remote driving.
- Handling of multiple vehicles at a time, evacuation of entire fleets from impacted areas, also in coordination of fleet operation and emergency operations centers to achieve coordinated removal of vehicles from an area
- ODD degradation: Controlled override of ODD limitations in order to achieve higher-level objectives, e.g. allow to drive slowly on sidewalks to prevent person damage, or higher resilience in case of disasters (needs to be done carefully)
- Advanced resilient decision-making and vehicle control, so that road vehicles are able to pass also difficult terrains in case of disasters.

Such solutions possibly require changes of the entire service architecture and should be considered also in testing and validation.

Autonomous vehicles being part of the solution

Besides being a potential threat at large-scale emergencies, autonomous vehicles can also drastically improve their handling.

Specialized autonomous rescue vehicles, such as autonomous ambulances, fire trucks, police vehicles, disaster response vehicles can be used for specific search and rescue tasks (Karpushin, 2024).

Autonomous fleet vehicles or privately owned autonomous road vehicles can be beneficial when integrated into emergency services, specifically as they can offer services without the need of endangering the general public or rescue personnel. Possible scenarios (among others) are:

- Self-evacuation
- Evacuation of people
- Transport of required personnel or equipment to emergency sites
- Using the vehicle as communication relay (to extend communication range)
- Using the vehicle as moving speaker
- Using vehicle sensors for situation awareness by sending sensor data to emergency operations centers

- Using vehicle sensors for search and rescue missions, e.g. to detect missing or injured people

Implementation and Discussion

In RESITEK, workshops with rescue organizations have been performed to understand future requirements and to discuss the above possible future scenarios as well as the foreseen impact. Furthermore, the project prototypically sets up demonstrators to better visualize the threat and the potential of autonomous vehicles. This includes setting up of emergency scenarios in simulation linked to real remote operation workstations, as well as implementation in real-world autonomous test vehicles.

First feedback of the emergency organizations includes:

- Rescue forces in Germany could hardly imagine a future with autonomous vehicles.
- Nevertheless, the topic seems to be highly relevant when explained (and when providing already available feedback of the US)

Conclusion

Although autonomous vehicles are basically able to react to single emergency situations in a correct way, it is important to start investigation of the possible threat, but also the potential of the new technology at large-scale disasters. In RESITEK, the possible scenarios are analyzed and discussed with rescue organizations. As the large-scale deployment of autonomous vehicles seems imminent (European Commission, 2025), it is important to insist on resilience requirements of such systems from the very beginning, in standardization, architecture and from a legal perspective.

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Rethinking Resilience in Interdependent Urban Infrastructures

Rhea Srivastava [1], Manu Sasidharan [2], Prof. Carmine Galasso [3]
1 2 3 Department of Civil, Environmental and Geomatic Engineering, University College London, London, United Kingdom
1 Rhea.srivastava.24@ucl.ac.uk
2 Manu.sasidharan@ucl.ac.uk
3 c.galasso@ucl.ac.uk

Abstract

Resilience has emerged as a central concept across fields such as disaster risk reduction, infrastructure management, and climate adaptation. Much of the academic literature to date, however, continues to conceptualise resilience as the ability of systems to return to a prior state of equilibrium following a disruption. Although foundational, this perspective is based on the idea that return to pre-event conditions is both attainable and desirable. This assumption is being increasingly challenged in the case of cities with highly interdependent infrastructure. Urban infrastructures like transport, energy, water, and communications networks form complex systems-of-systems, that interact physically, geographically, institutionally and socially. Treating infrastructure systems in isolation, therefore, risks overlooking emergent behaviours and limits the capacity to anticipate broader, system-wide vulnerabilities. Multi-hazard and recurrent shocks compound these challenges, highlighting the need to move beyond equilibrium-based, short-term resilience. This study conducts a narrative literature review with thematic analysis applied to selected literature, focussing on three themes: the definition and operationalisation of resilience, how interdependencies and cascading failures are addressed in infrastructure systems, and if approaches can extend beyond equilibrium-based recovery. The analysis argues that resilience should be reconceptualised not just as a return to normalcy, but as the ability to "bounce forward," enabling infrastructures to adapt, learn, and possibly transform in response to shocks.

Keywords: Urban resilience, Infrastructure interdependencies, Critical infrastructure

enhancing climate resilience in European cities: insights from the Covenant of Mayors initiative

Valentina Palermo [1], Aldo Treville[1], Giulia Melica[1], Paulo Barbosa [2]
1 European Commission - Joint Research Centre, Ispra
2 European Commission - Joint Research Centre, Sevilla

Abstract

The Covenant of Mayors (CoM) initiative has been instrumental in promoting sustainable energy and climate action in European cities. This study provides an overview of the CoM initiative and the approach of local authorities to climate adaptation. We analyze the reported climate hazards, vulnerabilities, and adaptation actions by CoM cities, highlighting the most frequent hazards and vulnerable groups and sectors. The study shows the importance of integrating climate change adaptation into urban planning policies and practice and of ongoing support and guidance to enhance city resilience.

Keywords: Covenant of Mayors; Adaptation; Risk and vulnerability assessment

Introduction

The European Union (EU) has set ambitious targets to reduce greenhouse gas emissions and become climate neutral by 2050. The Covenant of Mayors (CoM) initiative, launched in 2008, is a key instrument in promoting climate action in European municipalities. The initiative has evolved over the years, integrating in 2015 the adaptation pillar and setting a more ambitious mitigation target in line with the EU headline target of 40% GHG emission reduction by 2030 and becoming, in 2017, an international global alliance of cities committed to fighting climate change, the Global Covenant of Mayors for Climate and Energy (GCoM).

The CoM initiative has been successful in mobilizing cities to act on climate change. As of 2023, over 9000 cities in the EU have signed the CoM, representing more than 200 million citizens. The initiative provides a common framework and guidelines for local authorities to develop and implement sustainable energy and climate action plans (SECAP) aimed at advancing the resilience of their territories and reducing greenhouse gas emissions. The Joint Research Centre (JRC) of the European Commission (EC) provides scientific, methodological and technical support to the EU CoM initiative to ensure its coherence with EU climate and energy policies as well as its scientific credibility. Every year the JRC conducts an assessment of the Covenant of Mayors status to track the overall progress of the initiative on the basis of action plans and monitoring reports.

In addition, the JRC regularly publishes datasets of submitted SECAPs and monitoring reports as open data, after extracting and harnessing the reference GCoM datasets from the full set of raw submissions (Franco et al., 2023, 2024).

This study provides an overview of key adaptation results from the latest assessment of the initiative (Melica et al., 2024) focusing on local authorities from EU-27.

Methodology and results

The analysis is based on adaptation-related data from SECAPs reported by cities in the EU-27 through one of the official CoM platforms: CDP-ICLEI Track and MyCovenant (Baldi et al., 2023). We examine the most frequent climate hazards and vulnerable sectors, as well as the adaptation actions taken to address these hazards.

The SECAPs focus on actions at local level, addressing activities and sectors within the influence of the municipality covering climate change mitigation, adaptation (climate resilience) and (since 2025) energy poverty. For adaptation, the SECAP starts from the assessment of climate risks and vulnerabilities within the territory (RVA), to define at least one adaptation goal and a set of actions to increase the resilience of the local authority sectors and vulnerable groups. The RVA describes sectors, areas and population groups that are likely to be most vulnerable to climate change in the territory covered. Vulnerable sectors (e.g. buildings, transport, energy, water, waste, land use planning, environment & biodiversity, agriculture & forestry…) as well as intensity and frequency of hazards can vary considerably within urban perimeters, from one municipality to another, and from urban areas to more rural areas. This is why gaining a deep understanding of the hazards and vulnerabilities of territories for which the municipality is responsible is of paramount importance to plan actions that protect vulnerable groups and enhance resilience (Davide et al., 2025). The RVA consists of several tables outlining the main climate hazards, indicating their current probability and impact, the expected changes in intensity and frequency, and the relevant timeframe, along with the associated vulnerable sectors and population groups. Our analysis assesses most frequent hazards, vulnerable sectors and groups and related climate actions to map risks and evaluate the progress of local climate action. The RVA process combines scientific data with local knowledge, and risk can be assessed both qualitatively and quantitatively. (IPCC, 2014). Municipalities can, hence, flexibly develop their RVA according to their specific needs, resources, and level of expertise, making it a reliable and suitable source for informing subsequent planning, decision-making, and implementation steps (Palermo et al., 2025).

Following the data cleaning process, the total number of signatories in the EU-27 with a submitted SECAP at the cut-off date of 31st March 2023 is 6893, covering about 183 million inhabitants. The plans having a commitment for climate adaptation are 1703 (24%) which is linked to the fact that the initiative started with a mitigation only commitment and later expanded to include the adaptation commitment. An increasing trend is visible when comparing this figure to the previous released assessment with a cutoff date of March 2022, which showed 1138 plans with an adaptation commitment (Melica et al., 2022).

Results from the analysis of the RVA show that the most frequent climate hazards reported by the SECAPs of cities in the EU - 27 are *extreme heat* (present in 91% of the RVAs), *heavy precipitation* (in 89%), *droughts and water scarcity* (in 86%), and *floods and sea level rise* (in 85,6%). All these climate hazards show predominantly high/medium probability and impact.

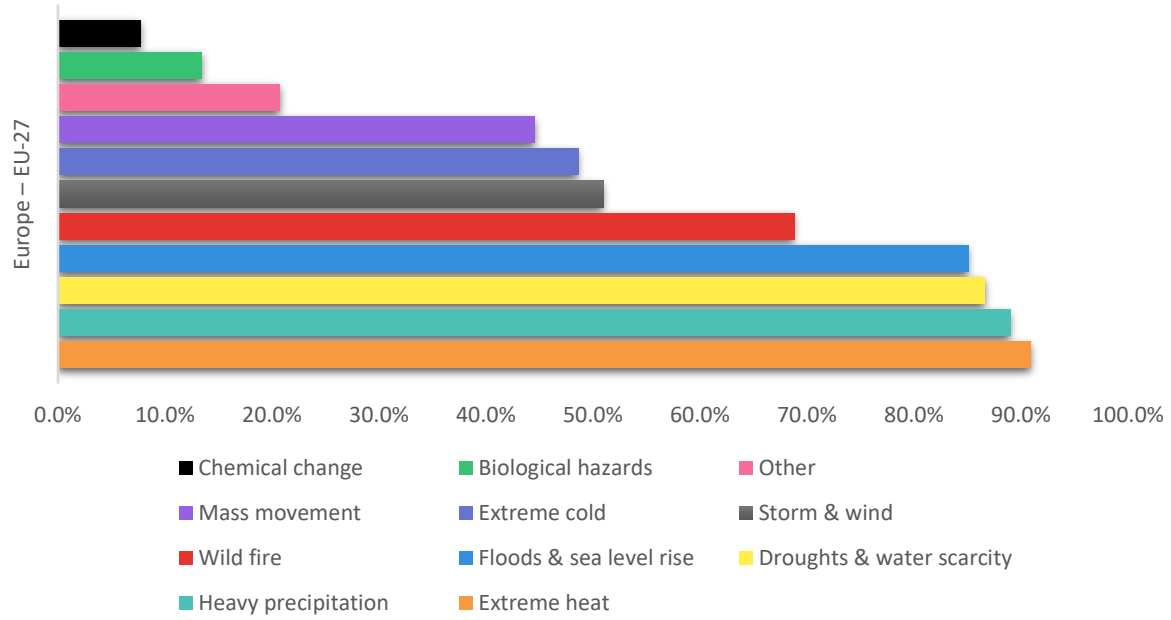


Figure 1 Most frequent climate hazards reported in SECAPs of signatories from EU-27

Only 16,6% (1747 out of 10475) of the reported climate hazards can be classified as "high-risk climate hazards", intended as hazards with both high probability and impact levels.

The most vulnerable sectors reported by SECAPs in EU-27 are *food and agriculture* (present in 65% of RVAs), *public health* (in 63%), *environment, biodiversity, forestry* (in 63%), *civil protection* (in 52%), *buildings* (in 55%).

Excluding the category of *all* and *other,* 7670 vulnerable population groups are mostly reported as exposed to climate hazards, as per the figure and table below.

Table 1. Groups reported as most vulnerable to specific hazards

Vulnerable groups	**Hazards (most reported)**
Older people, Children & Youth, Persons living with chronic diseases, Women and girls, Persons living in sub-standard housing, Low-income households	Extreme heat
Migrants and displaced	Heavy precipitation
Marginalised groups	Floods & sea level rise
Unemployed persons	Droughts & water scarcity

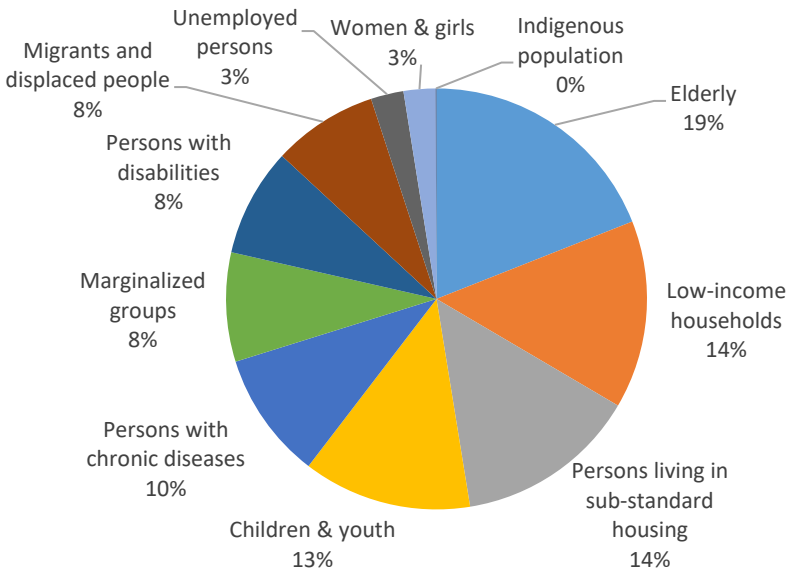


Figure 2. Most reported vulnerable population groups in the RVAs of EU–27 CoM signatories

More than 16000 adaptation actions are reported by signatories in EU-27, with an average of 9.5 actions per plan. A total of 8907 out of 16275 adaptation actions (54%) report which climate hazard(s) they are addressing (multiple hazards can be selected). Figure 3 shows the most addressed hazards by the actions.

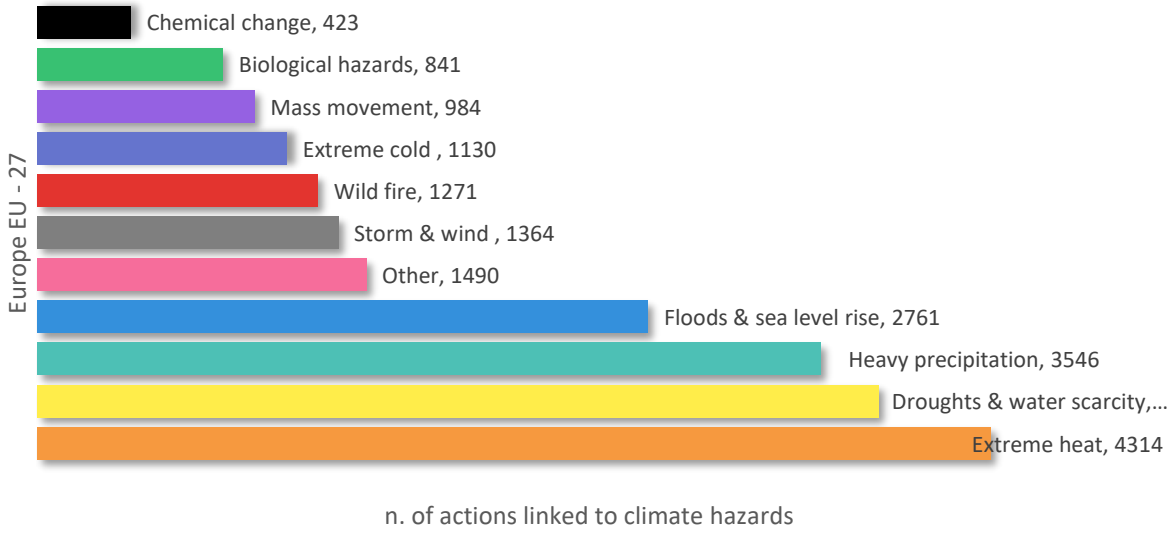


Figure 3. Adaptation actions and most addressed climate hazards in the SECAPs of EU – 27 CoM signatories

Figure 4 provides an overview of the areas where local authorities act to enhance their resilience. The most targeted sectors of adaptation actions by local authorities are: *Water supply & sanitation*, *Environment, Biodiversity, Forestry*, *Buildings* and *Land use planning*.

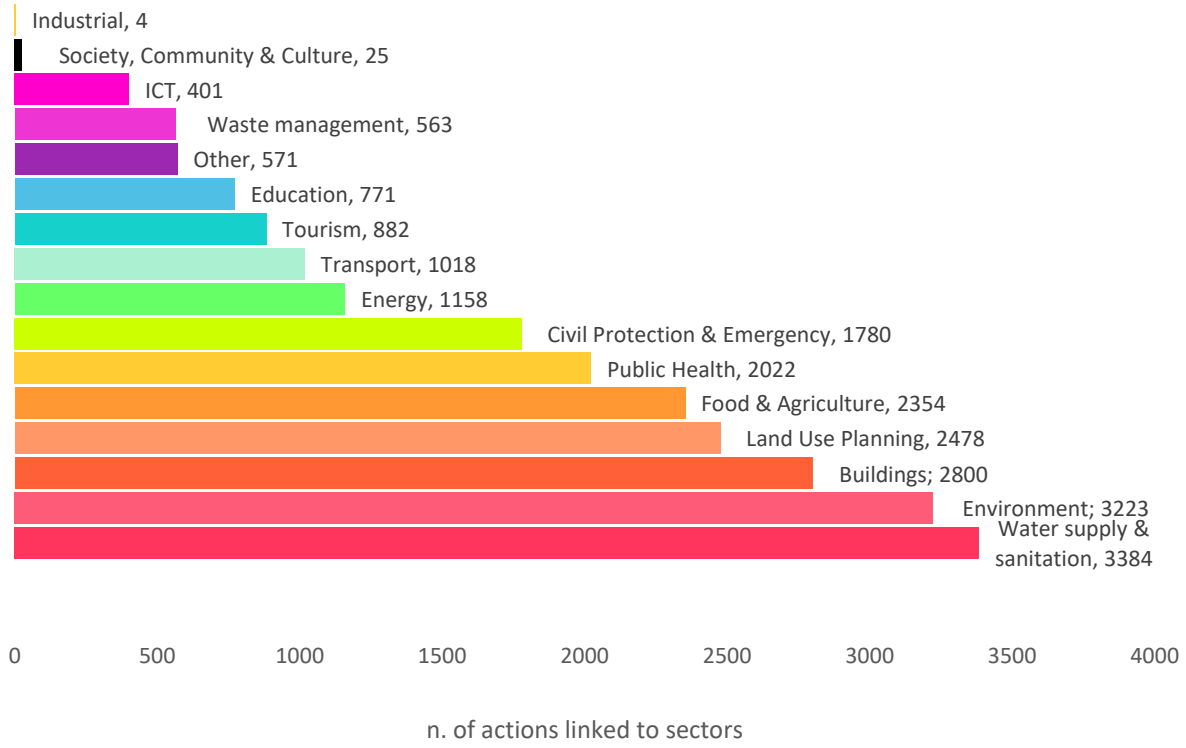


Figure 4. Adaptation actions and most addressed sectors in the SECAPs of EU–27 CoM signatories

The types of adaptation actions reported vary widely, with examples of nature-based solutions, early warning systems for extreme weather events, training and capacity building activities.

Conclusions

The CoM has proven instrumental in supporting cities to develop and implement adaptation strategies, highlighting the importance of integrating these considerations into urban planning and daily administration. Ongoing support and guidance for cities will continue enhancing their resilience, enabling a shift from emergency responses to a preventative approach. Further analysis will provide insights into the types of actions and instruments adopted by local authorities across the EU.

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Enhancing Community-Centered Psychosocial Crisis Management through Network-Orientated Approaches

Laura Aßmann[1], Verena Flörchinger[2], Vincenz Leuschner[2], Malena Garcia Lombardi[2], Olaf Neumann[1]
[1] Alice Salomon Hochschule Berlin (ASH), Germany, assmann@ash-berlin.eu
[2] Berlin School of Economics and Law (HWR), Germany,
verena.floerchinger@hwr-berlin.de

Abstract

Crises arising from natural hazards, terrorist attacks, forced migration, and pandemics have increasingly overlapped, resulting in poly-crises with lasting psychosocial impacts on societies. These dynamics, coupled with limited public sector resources, create significant challenges for subnational and local authorities. Civil society's role in self-organization and protective measures is key, emphasizing the need to integrate psychosocial considerations, civil society engagement, and preparedness into crisis management. Within the framework of a project, the research examines how community resilience can be enhanced through the development of network-oriented psychosocial crisis management. The study employs situational analysis and examines four contrastive case examples to ensure that the intended quality standards are applicable across diverse crisis scenarios and governmental administrative structures in Germany. Initial findings from the four case studies, as well as emerging cross-cutting insights, are presented.

Keywords: *Psychosocial crisis management; community resilience; network approach; state and civil society; disaster management*

Introduction

Crises arising from phenomena such as natural hazards, terrorist attacks, wars and forced displacement, and pandemics present substantial challenges to both the state and society. In recent years, crises have increasingly overlapped, resulting in poly-crises (WEF, 2023). Such dynamics affect not only infrastructure but pose a significant risk of generating negative psychosocial consequences for individuals and communities, many of which persist beyond the acute phase of the crisis (Leon, 2004). This complex situation, combined with the limited resources typically available to the public sector, poses significant challenges for subnational and local government authorities. Research has shown that the behavior of civil society – through protective measures or self-organization – plays a crucial role in managing crises effectively (Teräs & Kartoglu, 2023). Consequently, governments face the challenge of systematically addressing psychosocial aspects in crisis management, responding to the population's psychosocial needs, actively involving civil society in crisis response efforts, and integrating these considerations into the preparedness phase. This underscores the critical importance of close, scientifically informed collaboration between state and civil society actors in the domain of psychosocial crisis management. Within the framework of a research project, the aim is to enhance the quality and structure of network-oriented psychosocial crisis management in public administration, thereby strengthening community resilience in the long term. For this purpose, it analyzes prevailing attitudes and psychosocial emergency competency, decision-making logics, and cooperation models among state and civil society

actors in German crisis management over recent years. Emphasis is placed on concepts and theories emerging from research in civil protection, e.g., social space-oriented population protection (Spatscheck & Wolf-Ostermann, 2009), and community psychology, e.g., community resilience, citizen participation, empowerment, and diversity (Norris et al., 2008).

Methodology

The research project employs a qualitative, document- and interview-based methodology, with data analyzed through situational analysis, following the approach developed by Clarke (2021). While much qualitative research focuses on the meanings constructed by individuals, situational analysis extends this scope to examine how collective actors (e.g., groups or organizations) create meanings and how individuals establish commitments to such collective actors.

Case Studies

The project analyses four deliberately contrasting crisis cases in Germany: the racially motivated attack in Hanau 2020, the arrival of refugees from Ukraine in Berlin, the 2021 flood disaster, and drought and water scarcity in Thuringia. The case selection focuses primarily on differences in hazard type, onset speed (rapid vs. slow), duration of strain and urban versus rural context. A contrastive sample of cases was selected for the analysis to ensure that the intended quality standards are applicable across diverse crisis scenarios and governmental administrative structures. The comparison of these case studies highlights key elements of collaboration between public administration and civil society that foster community resilience. This comparative case study approach, which considers multiple crisis scenarios, represents an innovative contribution to the German academic community.

Challenges and Opportunities in the Context of Poly-Crisis

The research project is embedded in a context of structural challenges while also highlighting opportunities to strengthen community resilience. For example, the internationally defined crisis-management cycle, the psychosocial crisis-management cycle and community-resilience processes each operate according to their own temporality (fig. 1). These differing temporal dynamics generate distinct action logics, resulting in a mismatch between them. At phase transitions friction arises because actors from government, emergency services and civil society often struggle to appreciate one another’s perspectives.

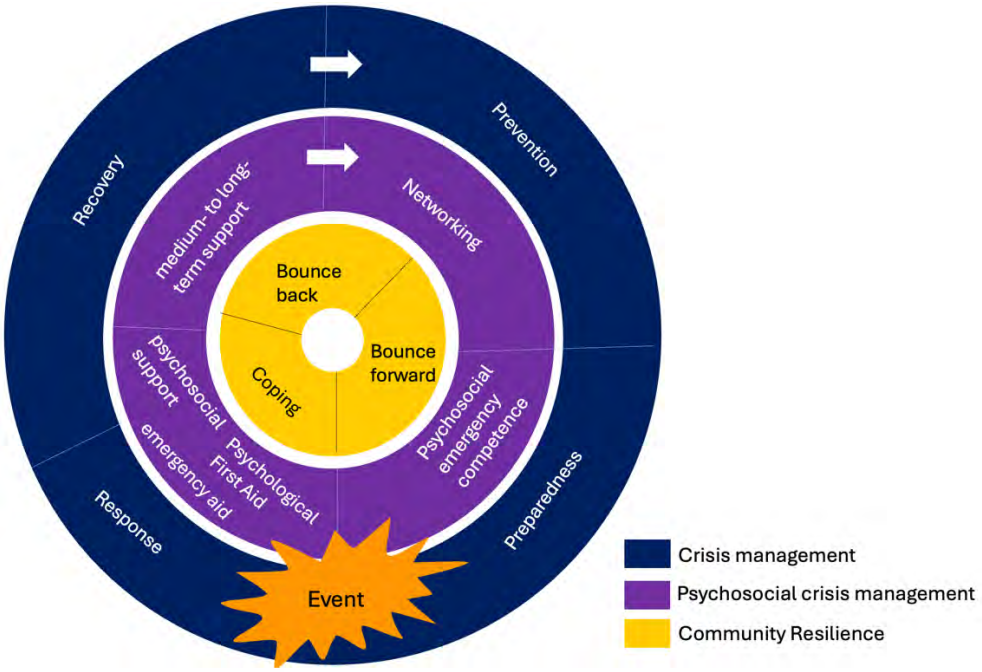


Figure 1. Integration of Community Resilience into the Crisis Management Cycle (Author's figure, adapted from the socio-ecological model by Norris et al.(2008) and the disaster management cycle).

It is also observed that poorly coordinated or overly short-term crisis-response measures that overlook psychosocial aspects can themselves act as stressors, triggering additional psychosocial crises and increasing the overall burden. At the same time, community resilience has emerged as a strategic approach within psychosocial crisis management: when psychosocial competencies, network building and adaptive capacities are embedded throughout all phases, a common language and shared understanding develop between responders and the population. The research project addresses these issues: drawing on the four case studies, it identifies challenges, potentials, and best practices, and explores what supports the development of collective efficacy and how authorities can foster this potential.

Results

A result of the project is to derive a framework that facilitates sustainable collaboration between state and civil society actors in psychosocial crisis management. This framework seeks to transcend immediate emergency responses and provide long-term suggestions.

At the midpoint of the project, the key findings from the four case studies will be presented in the panel "Resilience of Local Authorities", and initial cross-cutting insights will be identified.

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