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Knee-deep in two "bathtubs": Extending Holling's Ecological Resilience Concept for Critical Infrastructure Modeling and Applying it to an Offshore Wind Farm

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Multistability is a common phenomenon which naturally occurs in complex networks. Many engineered infrastructures can be represented as complex networks of interacting components and sub-systems which possess the tendency to exhibit multistability. For analyzing infrastructure resilience, it thus seems fitting to consider a conceptual framework which incorporates the phenomenon of multistability – the ecological resilience provides such a framework. However, we note that the ecological resilience misses some aspects of infrastructure resilience. We therefore propose to complement the concept by two model extensions which consider the generation of perturbations to the infrastructure service and the remedial actions of service restoration after regime shifts. The result is a three-layer framework for modeling infrastructure resilience. We demonstrate this framework in an exemplary disturbance scenario in an offshore wind farm. Based on this use case, we further demonstrate that infrastructure resilience can benefit a lot from the notion of multistability.

Keywords: System resilience, stability landscapes, resilience curves, degradation, disturbance sensitivity and propagation, critical infrastructures, dynamical systems, energy systems, offshore wind farms, modeling, maintenance.

1. Introduction

In 1973, Holling outlined his *ecological resilience* concept (Holling, 1973). Impelled by the idea that a system can possess multiple coexisting stable states (aka attractors), Holling argued that an ecosystem's ability to persist (i.e., its resilience) might be best captured by its capacity to remain in its current basin of attraction in the face of perturbations. The concept can be illustrated with a ball – representing the system state – in a *stability landscape* which determines the ball's movement in state space (bathtub I in Fig. 1). In this *basin metaphor*, a resilient system is one where the ball is far from any mountain crest and within a basin which is wide and steep (Walker et al., 2004).

In 2003, Bruneau et al. presented a conceptual framework for a quantitative resilience assessment Bruneau et al. (2003). To illustrate a measure which incorporates what they identified as the two desired "end" dimensions of resilience – robustness and rapidity – they presented a *resilience curve* which depicts the performance loss and restoration over the course of a specific disruption

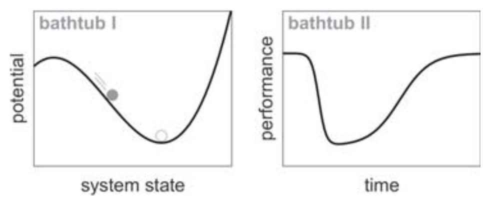

Fig. 1. The two resilience "bathtubs". Bathtub I: A ball in a stability landscape, the standard illustration for ecological resilience. Bathtub II: A resilience curve, the standard illustration for infrastructure resilience.

(as in bathtub II in Fig. 1). A resilient system is one which keeps the initial performance loss low (robustness) and recovers fast (rapidity).

Today, stability landscapes and resilience curves have established as standard tools for illustrating the resilience concept (see, e.g., Dakos and Kéfi (2022) and Mentges et al. (2023)), whereby the latter has met particular appeal in the field of infrastructure resilience. In this work, we argue that the ecological resilience concept – represented by the basin metaphor – has great merits for analyzing the resilience of infrastructures.

However, we also notice that the concept misses some important aspects of infrastructure resilience which are outlined by the resilience curve. We therefore propose two extensions to the concept – capturing the process of perturbation generation (extension 1) and the process of service restoration after a potential regime shift (extension 2).

In the following, we present some further background on stability landscapes and resilience curves (section 2). We then motivate the two extensions which lead to our proposal for a three-layer model framework for infrastructure resilience which includes the basin metaphor as its centerpiece (section 3). Finally, we demonstrate this framework in an exemplary disturbance scenario in an offshore wind farm (section 4) and draw conclusions on our work (section 5).

2. Background

2.1. *The stability landscape (bathtub I)*

Two key concepts of ecological resilience are the *basin of attraction* and *multistability*. A basin of attraction comprises the set of system states which evolve towards a specific attractor (Walker et al., 2004). Multistability refers to the situation that the phase space is populated by multiple basins (Mitra et al., 2015) and thus a disturbance can induce a regime shift by pushing the system above a basin boundary (see orange ball in Fig. 2a).

The distribution of basins within phase space can be depicted via so-called stability landscapes (Dakos and Kéfi, 2022). Assuming that a system is described by an ordinary differential equation $dx/dt = f(x, \mu)$, its stability landscape can be captured by the potential function

$$U(x, \mu) = -\int_{x_0}^{x} f(x, \mu)\, dx\ , \qquad (1)$$

where x denotes the system's state variable(s) and μ the system parameters. In a stability landscape (see bathtub I in Fig. 1), each valley depicts one basin – with the lowest point of the valley corresponding to the associated attracting equilibrium and the mountain crests to the basin boundaries.

For illustration purposes, the current system state is often portrayed by a ball moving within this landscape (Fig. 1). The ball-in-a-bathtub metaphor should, however, not be interpreted too literally (Meyer, 2016). An actual ball would accelerate according to the slope of the basin. By contrast, the ball in the basin moves downhill with a speed which is proportional to the slope of the landscape at its current position x. Accordingly, the ball cannot pass the bottom of a valley but approaches it asymptotically – Menck et al. (2013) provide an interesting adaption to the metaphor by portraying the stability landscape as being immersed in a highly viscous fluid such as honey.

2.2. *The resilience curve (bathtub II)*

The resilience curve highlights the capacities a system needs to have to cope with a disturbance. The two most fundamental coping capacities are (1) the capacity to keep the loss of performance low (absorptive capacity) and (2) the capacity to restore the performance (restorative capacity) (Mentges et al., 2023). While both capacities have been indicated by Bruneau et al. (2003), their two "end" dimensions miss that there are multiple aspects to both capacities. A system's absorptive capacity does not only depend on the robustness of its components (structural absorption) but also on the system's ability to prevent the further propagation of a disruption (dynamic absorption) (Poulin and Kane, 2021). The restorative capacity is not only determined by how fast (rapidity) but also by how much of the original performance level can be restored (recoverability) (Mentges et al., 2023).

2.3. *From bathtub I to bathtub II*

In the following, we shortly outline the connection between the stability landscape (bathtub I) and the performance curve (bathtub II).

In the basin metaphor, a perturbation corresponds to a displacement of the ball (Fig. 2a). Since the dynamics following a displacement are determined by the stability landscape (Fig. 2a), deriving the system state evolution over time is straightforward (Fig. 2b). There is, however, a difference between system state variables and system performance (Poulin and Kane, 2021), e.g., a system's performance might not be affected by minor state variable fluctuations. In order to obtain a performance curve (Fig. 2d) from a system tra-

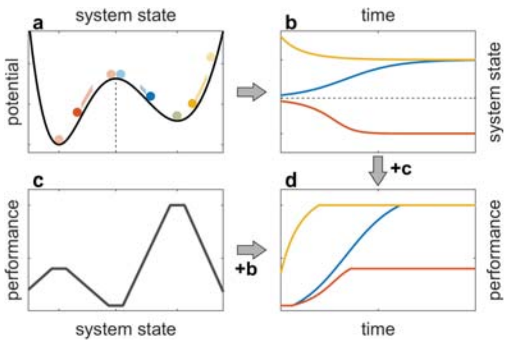

Fig. 2. From stability landscape to resilience curve. (a) Stability landscape with three different initial conditions. (b) Time series corresponding to the three initial conditions. (c) Transfer function which assigns a performance level to every system state. (d) Resilience curve for the combination of (b) and (c).

jectory (Fig. 2b), system states need to be mapped to specific performance levels (Fig. 2c).

3. Extending the basin metaphor

We see the basin metaphor as a well suited framework for infrastructure resilience. It captures the most common understanding of resilience as a system trait or ability (Mentges et al., 2023). This ability (the basin) is present at all times but only manifests in transient dynamics once the system is being disturbed. In this regard, the basin metaphor can form the broader conceptual framework which incorporates the resilience curve as a scenario-specific realization of system abilities (see section 2.3 and also Nikinmaa et al. (2020)).

Importantly, however, the basin metaphor teaches us that one such realization is not indicative of a system's overall resilience. Due to thresholds in the stability landscape, a small variation in the characteristics of a perturbation can make the difference between a fatal and a non-fatal outcome (Halekotte and Feudel, 2020) – e.g., a severe long-term or a transient system impairment (orange and blue trajectory in Fig. 2, respectively).

Lastly, the basin metaphor captures important aspects of a system's absorptive and restorative capacity (see section 2.2). Alas, it also misses aspects of both capacities. In the following, we will propose two corresponding extensions to the concept.

3.1. *Case 1: The static landscape*

In the classic case of a static landscape, the two aspects which the basin metaphor misses can be traced back to the question 'What moves the ball against the slope of the landscape?' (see Fig. 3a).

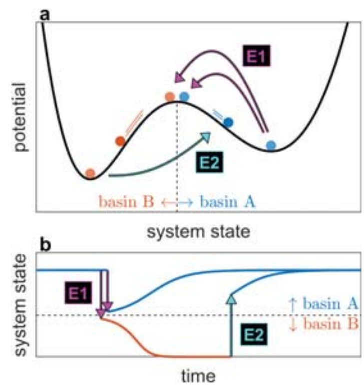

Fig. 3. Impact of the Perturbation Generation Extension (E1) and the Service Restoration Extension (E2) in a static stability landscape (a) and corresponding system trajectories (b). The extensions cover processes which move the ball against the slope of the landscape.

Extension 1: In the basin metaphor, a perturbation is described as a displacement of the ball. The cause of which is out of the scope of the stability landscape Meyer (2016). However, the cause of the displacement displays the interaction between system-external disturbance characteristics and system-internal coping capacities (see also Tamberg et al. (2022)), which is an important aspect of the structural absorption process (see section 2.2). We therefore propose a **Perturbation Generation Extension (E1)** which considers this interface. Technically, the extension should consist of a model which transforms an external disruptive event into a specific perturbation which can be used as an input for the dynamical system model – in this case, the initial displacement of the ball (magenta arrows in Fig. 3).

Extension 2: The basin metaphor concentrates on "the inherent stability behaviour of a system" (Tamberg et al., 2022). It thus excludes external interventions (Standish et al., 2014) and implies irreversible regime shifts. However, in an engineered infrastructure, interventions which allow to bring the system back to its pre-disturbance state after a regime shift exist (e.g., repair and maintenance), (Jackson et al., 2015). We therefore propose a **Service Restoration Extension (E2)** which describes corresponding actions. The output of this model can be an intentionally induced displacement of the ball back to the desired basin of system operation (cyan arrows in Fig. 3).

3.2. *Case 2: The dynamic landscape*

So far, we have treated the stability landscape as a static system trait. In reality, however, the shape of such landscapes is subject to change (see, e.g., Holling (1996)). In fact, the impact of many external stressors can well be described as a change in system dynamics, e.g., induced by the alteration of system parameters which affect the shape of the stability landscape. Describing the impact of disturbance in this way has the benefit that it allows considering its temporal course (e.g., μ_1 in Fig. 4a), which ultimately adds another dimension to potential system thresholds (see red and blue ball/trajectory in Fig. 4b-f).

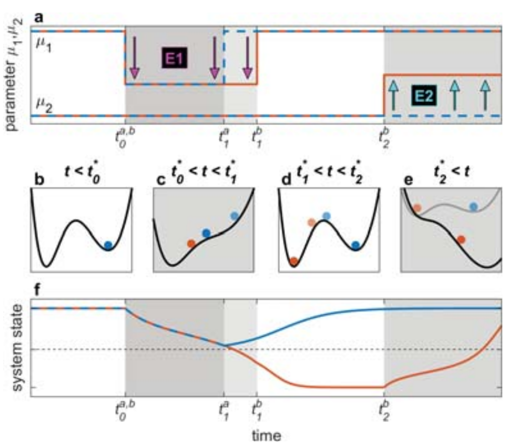

Fig. 4. Illustration of the Perturbation Generation Extension (E1) and the Service Restoration Extension (E2) in the case of a dynamic stability landscape. (a) The input from E1 and E2 is represented by a changing system parameter, μ_1 for E1 and μ_2 for E2. (b-e) Due to the parameter change, the stability landscape changes and the system evolves accordingly. (f) Time evolution of system state.

A change in system dynamics corresponds to a change of the stability landscape (see Fig. 4b-e). In this case, the ball does not have to be moved against the slope of the landscape to create a transient system response (see Fig. 4f). Instead, the ball evolves according to the new landscape(s). Nevertheless, the two extensions still apply – only that, in this case, the central question concerns the cause of the dynamically evolving stability landscape. Accordingly, the main difference is the required output of the two extensions. E1 should provide a disturbance-induced change of system dynamics (magenta arrows in Fig. 4a) and E2 should provide a repair- or maintenance-induced change of system dynamics altering the landscape in a way which allows the restoration of a desired regime (cyan arrows in Fig. 4a).

3.3. *The three-layer framework*

To conclude, we propose a three-layer framework (Fig. 5) that includes the two modeling extensions to the ecological resilience perspective. The following text introduces the individual layers.

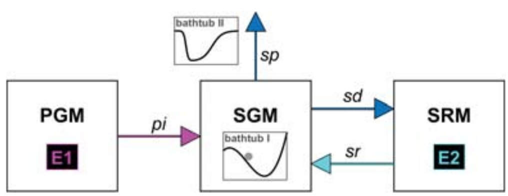

Fig. 5. The three-layer framework. **PGM** - perturbation generation model, **SGM** - service generation model, **SRM** - service restoration model; *pi* - perturbation injection, *sp* - service provision, *sd* - service disruption, *sr* - service restoration.

Service Generation Model (SGM): The core of the framework is a dynamical system model which describes the process of service generation and provision of an infrastructure, e.g., how a wind farm generates electricity. Conceptually, both the stability landscape and thus also the resilience curves are derived from the SGM. The model incorporates feedback loops, due to control and protection actions, which constitute the self-organization capabilities and the inherent stability behavior of the system. The actual output of the model is the service provision (*sp*) – which ultimately determines system performance. Perturbations are injected to the SGM as specific inputs (*pi*) from the first extension model (E1). Severe enough perturbations cause service disruptions (*sd*) which then trigger remedial actions of service restoration (*sr*) described by the second extension model (E2).

Perturbation Generation Model (PGM): The first extension (E1) describes the interface between external stressors and system-internal properties. It is responsible for the transformation of a specific disruptive event (stressor) into a perturbation which affects the dynamical system model in a specific way (e.g., deriving the structural damage to system components by natural hazard risk modeling Mühlhofer et al. (2023)). The PGM provides the external input to the SGM induced by a disruptive event as a perturbation injection (*pi*). This input can be presented in different ways, e.g., by an instantaneous change of state variables (static landscape) or by a transient or persistent change of system parameters or the structure of dynamical equations (dynamic landscape).

Service Restoration Model (SRM): The second extension (E2) describes remedial actions (*sr*), such as repair and maintenance, which are triggered by service disruptions (*sd*) once the SGM has entered a disrupted regime. In contrast to the PGM, processes in the SRM can be considered as system-internal and thus the SRM is not necessarily scenario-specific (but see Skobiej et al. (2021) or Panteli and Mancarella (2015)). It should further be noted that dynamics induced by the SRM (see, e.g., Skobiej et al. (2021)) can take place on much longer time-scales than dynamics induced by the PGM (time to restore > time to collapse). The output of the SRM (*sr*) can again be presented as a change of state variables or system parameters, leading to the restoration of system performance and functionality.

4. Use Case: Short circuit in an OWF

In the following, we demonstrate the three-layer framework in an exemplary disturbance scenario within an offshore wind farm (OWF). A detailed description of the OWF and scenario model can be found in Kulev and Sill Torres (2022a,b). We therefore provide only a brief description by establishing the relations between the models and the different layers of our framework (section 3.3).

4.1. *Model and scenario development*

First, we present a model of an OWF which is capable of describing the dynamical response to perturbations – corresponding to the Service Generation Model (SGM) in our framework (section 3.3). Second, we describe the disruptive scenario and its influence as a specific perturbation input to the SGM – corresponding to the Perturbation Generation Model (PGM) in our framework (section 3.3).

4.1.1. *Service Generation Model (SGM)*

The OWF model features an array of six offshore wind turbines (OWTs) arranged in three strings (Fig. 6). Each string contains two OWTs and two associated AC cables. The active power generated by the OWTs is transmitted through a 25 km long AC export cable to the onshore transformer substation. At the onshore substation, the voltage is raised (from 25 kV to 120 kV) and the power is fed into the onshore AC grid. The model also features control and protection systems, not depicted in Fig. 6. The OWF system dynamics are implemented in the Simscape Electrical Specialized Power Systems blockset under the MATLAB/Simulink environment.

4.1.2. *Perturbation Generation Model (PGM)*

As an exemplary scenario, we consider the case of a ship colliding with OWT22 (Fig. 6). We assume that the degree of mechanical damage can be considered as being proportional to the ship collision impulse. The mechanical damage at the conductor and insulation of OWT22 then determines the induced electrical fault – specified by the type (short or open circuit) and duration of the fault, and by the number of affected phases (1, 2 or 3).

We assume that the ship collision causes a 3-phase-to-ground short circuit with finite duration. The short circuit corresponds to a fault current between the phases and the ground at the terminals of OWT22. Technically, it can be regarded as a transient change of the system dynamics: For the duration of the short circuit, an equation is added

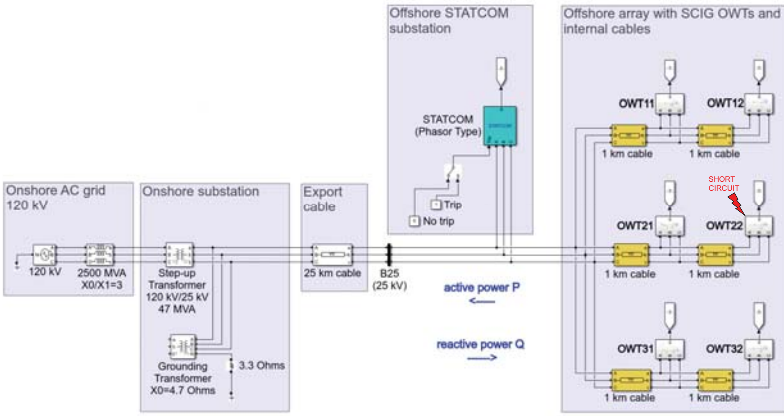

Fig. 6. Power system model of the offshore wind farm (OWF) with the applied short circuit at OWT22.

to the system which describes the dynamical evolution of the fault current, i.e., the SGM receives one additional state variable.

4.2. *Resilience curves*

First, we examine resilience curves which capture the evolution of system performance prior, during and after the occurrence of short circuits with different duration (Fig. 7). As a measure/indicator of performance we therefore employ the power generated by the OWF.

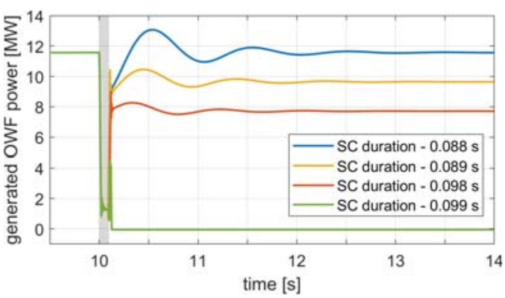

Fig. 7. Resilience curves of the OWF corresponding to four short circuits (SC) with different duration. Gray area marks the presence of the short circuit.

Prior to the short circuit, the system resides at a fully operational state representing constant system performance. Due to the short circuit, the performance level drops and remains low until the short circuit has ended. The system then enters a stage of performance restoration. During this stage it becomes apparent that the system exhibits threshold behavior whose outcome depends on the short circuit duration. If the short circuit is short enough, i.e., not longer than 0.088 s, the system performance is fully restored (blue curve in Fig. 7). Increasing the duration to 0.089 s leads to an AC undervoltage at OWT22 during the restoration stage. This undervoltage triggers a protection action which disconnects OWT22 from the grid. As a result, the power system does not reach its pre-disturbance performance level but settles on a steady state of reduced generated power (yellow curve in Fig. 7). A further increase of the duration up to 0.098 s leads to a more severe long-term performance loss (orange curve in Fig. 7). In this case, the whole string containing OWT22 and OWT21 is disconnected from the grid due to undervoltages at both wind turbines. At last, if the duration is at least 0.099 s a complete performance collapse is observed (green curve in Fig. 7). The operational conditions are so degraded that all OWTs get disconnected and thus the OWF generates no power.

4.3. *Multistability in the OWF*

The resilience curves (Fig. 7) indicate that the OWF model exhibits multistability. In dependence on the duration of the short circuit, four different attracting states are approached – representing performance survival (blue), two levels of

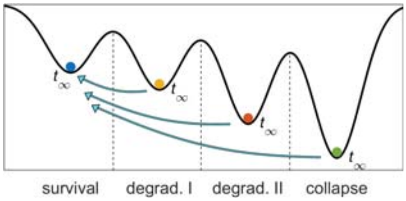

Fig. 8. Conceptual presentation of multistability in the OWF. The coexisting stable states, which are approached at different t_∞ after the short circuit, correspond to different levels of service degradation. Cyan arrows represent the impact of repair and maintenance actions which should be provided by a SRM.

performance degradation (yellow/orange) and a total performance collapse (green). This means that a sufficiently long short circuit pushes the system beyond the basin boundaries of its desired operational state to a specific basin of degraded operation, as depicted in Fig. 8.

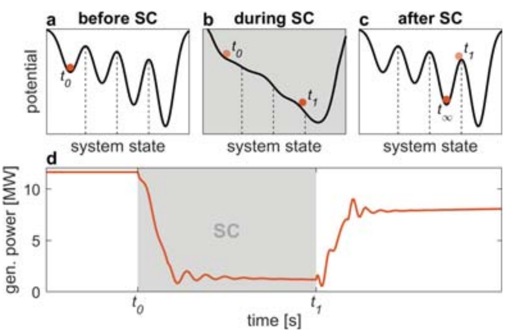

Fig. 9. Conceptual transfer from resilience curves to stability landscape(s) for the OWF. (a-c) The impact of the short circuit (SC) can be imagined as a transient change of the stability landscape. (d) This change starts with the initiation of the SC at t_0 and ends with its termination at t_1 (here $t_1 = t_0 + 0.098\,s$). After t_1 the system evolves according to its original landscape and approaches a stationary state at t_∞ ($t_\infty \gg t_1$).

The mechanism behind this regime shift is similar to the one outlined in section 3.2 – i.e., it is induced by a change of the stability landscape. Prior to the disturbance, the system resides at its desired state (Fig. 9a). Then, impelled by the short circuit, the dynamics of the SGM change – in accordance with the input by the PGM (see section 4.1.2). The new system dynamics correspond to a new stability landscape which determines the system evolution over the duration of the short circuit (Fig. 9b). After the termination of the short circuit, the system again evolves according to its original landscape but since it has been displaced over the course of the short circuit dynamics, it can now be located within another basin (Fig. 9c).

4.4. *What about the SRM?*

So far, we have not considered the Service Restoration Model (SRM) in our use case. However, the conducted simulations show that sometimes actions external to the self-organized system dynamics (SGM) are necessary to restore pre-disturbance performance levels (yellow, orange and green curves/balls in Fig. 7 and Fig. 8). Accordingly, in systems whose SGM exhibits multiple stable states, representing fully operational as well as degraded performance states, we need a SRM to describe corresponding repair and maintenance actions (indicated by cyan arrows in Fig. 8). A model which could complement our OWF setup in this regard is presented in Skobiej et al. (2021).

5. Conclusion

In this work, we argued that ecological resilience (the basin metaphor) can provide a strong conceptual foundation for analyzing the resilience of engineered infrastructures. The paradigm captures the understanding of resilience as a system ability (the landscape) and can incorporate the resilience curve as a scenario-specific realization of this ability. But most importantly, it considers the possibility that a system can possess multiple basins of attraction. This notion is insightful for infrastructure resilience where the associated attractors can correspond to different service degradation or impairment levels (see also Jackson et al. (2015)) – as we have shown in our OWF use case.

By aligning the basin metaphor with the essential coping capacities highlighted by the resilience curve, we have seen that the basin metaphor requires two extensions to cover the entire scope of infrastructure resilience. We therefore proposed two additional modeling layers – a perturbation generation model (PGM) and a service restoration model (SRM) – which complement the core dynamics captured by the service generation model (SGM). In our OWF use case, we have demonstrated the need for all three layers for describing infrastructures resilience.

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