Resilience assessment in a container terminal with fuzzy logic

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***Abstract*—This work transfers the application of fuzzy logic into the resilience assessment for ports and presents an approach to simplify the complex system of terminal processes so that the knowledge of experts could be transferred in a resilience assessment system. Therefore, a fuzzy logic using the connection of performance indicators is designed. The fuzzy logic is integrated into a container terminal simulation to assess the resilience of the main container handling processes. To demonstrate the applicability of the approach, an exemplary disruption scenario with a resilience enhancing measure is implemented and discussed.**

***Index Terms*—resilience assessment,fuzzy logic, container terminal, disruption simulation.**

I. Introduction

Understanding how a system works is important for the assessment of the system resilience. This paper combines a fuzzy logic approach for resilience assessment with a container terminal simulation of processes to analyze the system performance. There are different applications using key performance indicators (KPIs) concentrating on main processes for the resilience analysis [1], [2]. Other applications focuses on the influence of stakeholders on the resilience instead of the performance for the assessment of a container port, with for example scenario-based preference modeling and stakeholder mapping [3].

The authors of [4] present an approach that assesses resilience as a function of vulnerability and recoverability using stochastic measures of resilience, that is to account for uncertainty in information.

But there is no approach that integrates fuzzy information in the resilience assessment of ports, which could be done using fuzzy systems. A fuzzy system in this context consists of a fuzzifier, a knowledge base, a fuzzy-inferenz engine and a defuzzifier [5]. There exists different applications of fuzzy systems in other fields, like community resilience to quantify PEOPLE indicators with descriptive knowledge or for a node operational resilience evaluation of a digital network [6], [7]. Other examples are the use of multilevel fuzzy logic models (logic-linguistic models) to assess cyber resilience of critical energy infrastructures [8] and the use of fuzzy logic-based flood resilience measuring models [9].

This work transfers the application of fuzzy logic into the resilience assessment for ports and presents an approach to simplify the complex system of terminal processes so that the knowledge of experts could be transferred in a resilience assessment system. The aim of using fuzzy logic is to utilise expert knowledge in the resilience assessment process. The person who carries out the evaluation of functionality is not necessarily the same who, in the event of a malfunction, has to assess the resilience and derive measures for the operation in the event of a malfunction. Using the fuzzy logic, the person's knowledge about the processes can be passed on in a easily understandable way to persons from other areas.

This paper is organised as follows. Section II describes an container terminal simulation and the fuzzy system. The results of the simulations with resilience assessment are presented in Section III and discussed in Section IV. A conclusion and brief outlook concludes this work.

II. Simulation and Fuzzy System

The following section introduces the container terminal simulation and the fuzzy system.

A. Container Terminal Simulation

In a first step, a container terminal simulation for the performance measurement is implemented with Python. The simulation concentrates on the main processes of the terminal, the transportation, loading, unloading and storage of the containers (see Figure 1). Basis for the simulation is the process model that is described in [10]. The container handling equipment (CHE) in the simulation are straddle carriers (SCs) for the horizontal transports, storage in the yard and the truck loading, rail mounted gantry cranes (RMGs) for the train loading and quay cranes (QCs) for the ship loading. Disruptions of the processes are represented through longer process time, less number of CHE or drivers of the CHE. The ships arrive after a schedule. The trains and trucks arrive every x time steps calculated in dependency of the arriving ships. The container terminal processes are simplified for the implementation in the simulation, for example the CHE does only single moves and lifts, the unloading is completed before the loading starts and the container does not have a destination. The aim of the work is not to carry out a resilience assessment for a real use case, but to develop a test environment for the resilience assessment method. Thus, the simulation could be simplified as it only should present the main processes with the interlock of the different CHE and transport modes.

The basic scenario with normal operation was developed so that the waiting times are minimal where possible. Waiting times can still occur if there is an accumulation of orders at one point in time due to the random distribution. Figures 2 and 3 show the normalised productivity of the QC and the SC waterside for a period of two weeks separated in shifts with a duration of 8h. The QC and SC for trucks show hardly any fluctuation in productivity, as the basic scenario does not contain any disruptions. The productivity of the SC on the waterside is an exception, as there is much greater fluctuation. This fluctuation arises because the SCs have to wait until they can set down a container or pick it up from the QC. This waiting time is accepted, as the ship handling is the bottleneck in the terminal due to the large number of containers [11]. The productivity of the QC and SC for the waterside have a complete drop to -1 during shift 29, as no ships were loaded or unloaded during this period. This is due to the fact that there was no order for ship handling at this time.

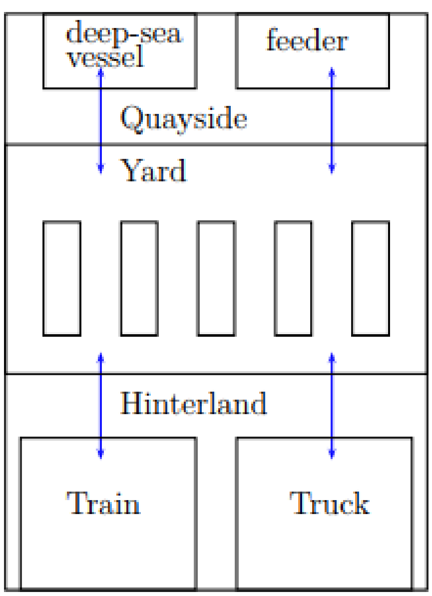

Fig. 1. Schematic representation of the container terminal for the simulation.

B. Fuzzy Logic for Resilience Assessment

The next step is the definition of a fuzzy system. The experts evaluate the relation of different performance indicators. The five indicators - container throughput, CHE productivity, CHE/ berth/ yard utilization, waiting time from CHE/ ships/ trucks/ trains and ship/ truck/ train turn around time - are identified as relevant and for the simulation usable indicators. To create a handy example, the measurement for the implemented scenario is limited to the CHE productivity and number of waiting trucks for parking. The normalised Productivity (P) for the CHE is calculated per shift from the Number of Cycles (NoC) per working minute:

$$P_{CHE} = \frac{NoC_{CHE} * NormalisedCycletime_{CHE}}{WorkTime_{CHE}} \quad (1)$$

A cycle starts with the pick up of the container, including the empty run to the container position, and finishes with the set down of the container when the connection to the CHE is released [12]. The normalised cycle time is the average cycle time for a CHE taken from the literature, sized down on cycles per minute. The number of waiting trucks for parking slots is

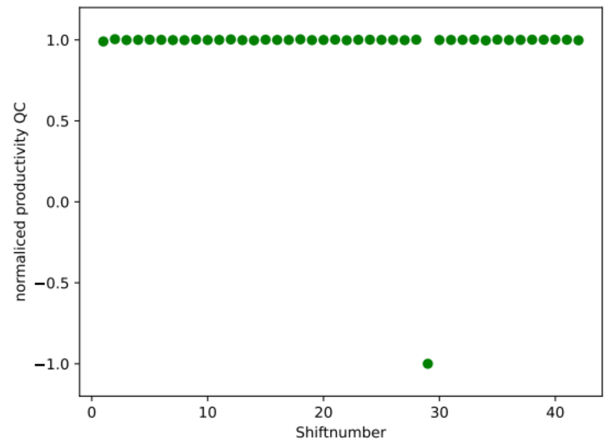

Fig. 2. Productivity of the QC during normal operation.

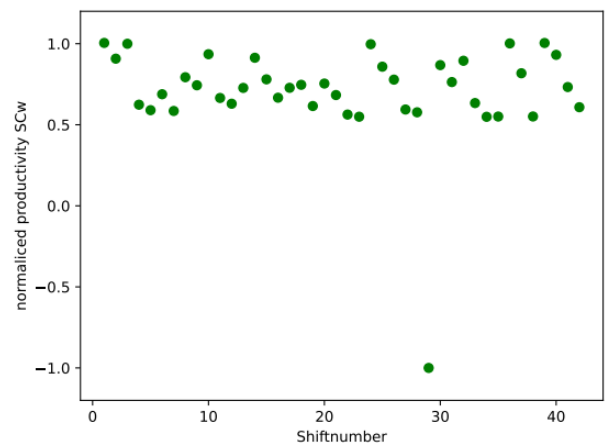

Fig. 3. Productivity of the SC from the waterside during normal operation.

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counted per shift and normalised with the overall number of trucks in the shift. The P_{QC} and $P_{SCwater}$ are the input for the functionality 1 (F_1) and the $P_{SCtruck}$ and $Wt_{parking}$ are input for a second functionality value (F_2). The functionalities (F_1 and F_2) are building the input for the resilience (R). That leads to the building of three knowledge bases which are generally described as followed:

1) IF P_{QC} AND $P_{SCwater}$ THEN F_1
2) IF $P_{SCtruck}$ AND $Wt_{parking}$ THEN F_2
3) IF F_1 AND F_2 THEN R

There are four different fuzzy sets used. The first fuzzy sets (Figure 4) are used for the resulting variables, F_1, F_2 and R. The second fuzzy sets (Figure 5) have the biggest possible overlap, where now more then two fuzzy sets overlap which each other. That creates a higher range of results without a higher degree of complexity in the calculation. The maximum x-value is 1.1 as that is the highest value for the normalised productivity. A value higher then 1 is possible, because an average value was assumed when normalising the productivity and not the best possible value. The fuzzy sets for the productivity from the SC on the waterside (Figure 6) are shifted to the left, so that the fuzzy sets for high and very high are bigger to better absorb strong fluctuations. This is necessary to take into account that the fluctuation is not mandatorily reduced to a disruption, but rather a result of the bottleneck, as explained in the section II-A. The fourth fuzzy sets (Figure 7) for the $Wt_{parking}$ is similar to the second fuzzy sets, with the difference that the maximum of the x-value is 1. The membership functions have a trapeze shape at the edges and a triangle shape otherwise (see Figure 4).

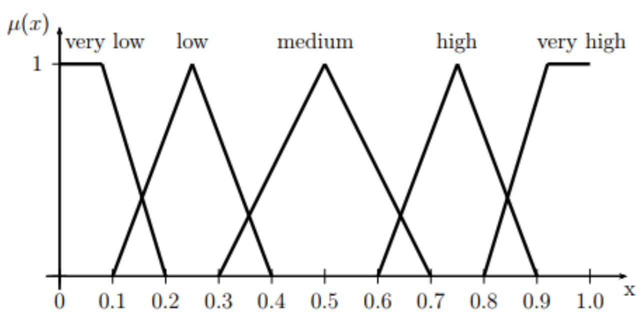

Fig. 4. Fuzzy sets for F_1, F_2 and R.

For the inference method the max-prod inference is chosen as it is less numerically expensive then the max-min inference [5]. And for the defuzzification the Center of Area method is selected [13].

The last step is the implementation of the developed fuzzy logic system in a simulation to show the functionality of the used methods. The link of the fuzzy system with the container terminal simulation makes it possible to run through different scenarios without having to evaluate each one individually by the experts.

For the implementation of the resilience evaluation in the simulation the special case that an input variable could not

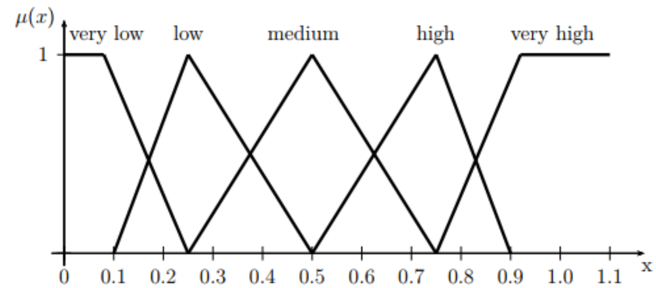

Fig. 5. Fuzzy sets for P_{QC} and $P_{SCtruck}$.

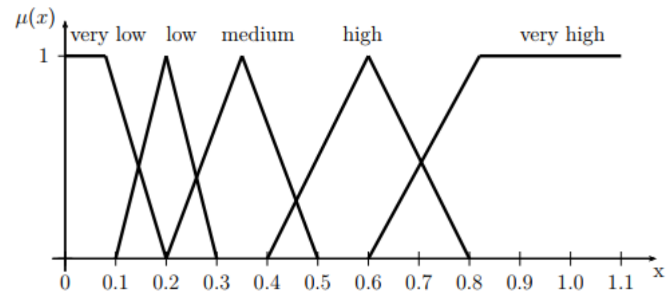

Fig. 6. Fuzzy sets for $P_{SCwater}$.

be calculated for a shift has to be taken into account trough a numerical default value. A productivity of -1 was preferred for the default value, as for example zero would lead to the assumption that the system is not working. But an incalculable KPI does not necessarily mean that there is a malfunction of the system, it could simply be that there is no train scheduled for that shift.

III. Results

For a suitable scenario the environmental conditions included should influence the system and its resilience. Environmental conditions are for example weather conditions such as strong wind, rain or fog. Wind can influence the working speed and in the event of a storm, work comes to a complete stop until the wind subside. After that, a higher utilisation of the terminal may have to be expected, as orders have accumulated. Another environmental condition

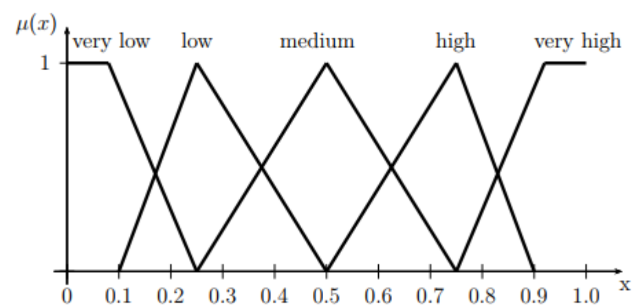

Fig. 7. Fuzzy sets for $Wt_{parking}$.

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is staff availability, for example, if employees are absent due to illness. Other environmental conditions could affect an individual transport mode so that it cannot transport containers to and from the terminal at all or only a restricted among of containers, for example if rail traffic is cancelled due to a line closure. In order to describe the relationship between system states and environmental conditions, causality diagrams are a graphical solution.

The disruption scenario selected is a heavy rain, which leads to some flooded areas where the SC are moving. The assumption is that the cycle time is raised due to longer distances and decreases again when the flooded area gets smaller (see Figure 8). It also leads to an undercutting of the main rail connection to the terminal, with the consequence that the containers from the trains are brought with trucks to the terminal. That mean a change in the modal split of the hinterland for the time the rail is not usable. This is included in the simulation trough an adjustment of the cycle time for the SC from 5 to 10 minutes for the first day after the heavy rain. Then, with a smaller area, the next day the cycle time is set on 8 minutes and on a third day as there are only small areas left the cycle time is set on 6 minutes, after a little more then three days the water finally disappeared so that the cycle time is regulated back to 5 minutes. The change of the modal split starts at the same time and ends after around two days. The modal split is changed from 0.48 to 0.2 for the amount of trains from all hinterland orders. A total downtime of the terminal during a longer raining period, which would lead to a backlog of handled ships, trains and trucks, is not part of the disruption scenario. Due to the fact that the container flow is completely controlled by the forwarder, which can also lead to a redirection of containers to other ports, the scenario would become too complex for a first use case to try out the method.

This scenario is then used to verify that the developed resilience assessment is suitable for the container terminal processes. The assumption is that the resilience will show a huge drop for the time of the disruption scenario, which is remarkable higher then normal variations. The second assumption is that the resilience drop is lower when a resilience increasing measure is implemented.

To show this effects on the resilience, from the disruption and the measure for resilience increase, three simulation settings with twenty simulation runs each are performed. Through the use of random distributions in the simulation, for the cycle times and the choice if a incoming order for the hinterland is a truck or a train, the simulation runs are similar, but not equal for the part that is not influenced trough the disruption. As a number of twenty simulation runs all show a strongly similar resilience course, the minimal difference was decided to be insignificant.

The simulation cycle with disruption shows a decrease of the resilience down to 0.25 (see Figure 9). The decrease to -1 which is also visible in the diagram is part of the normal operation as it implies that one of the input values has the value -1 for the shift, so that no resilience assessment is possible. Concrete for this normal scenario there is no ship scheduled for the shift number 29 and the ships arriving earlier are processed already.

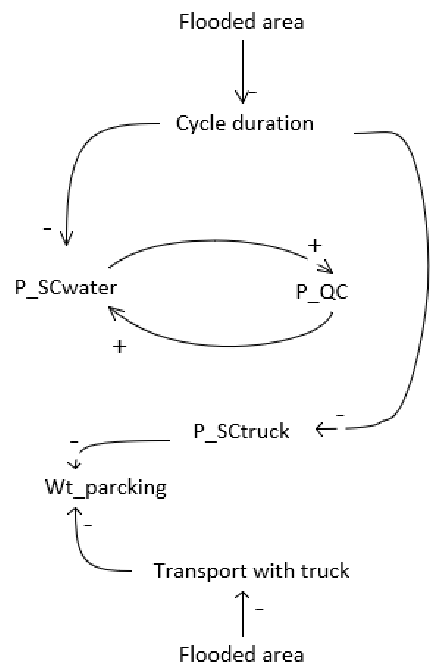

Fig. 8. Decreasing disruption scenario using a causal loop diagram.

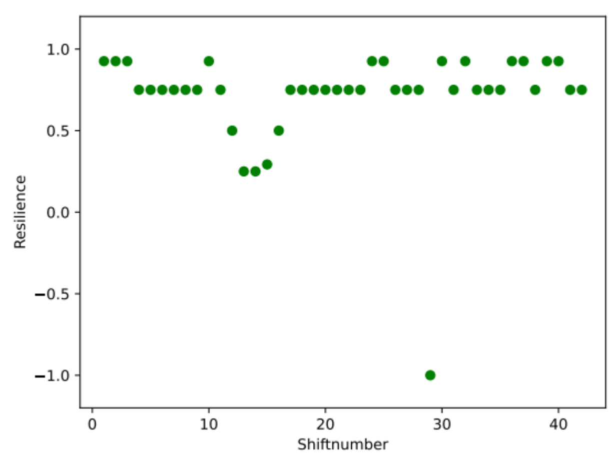

Fig. 9. Resilience values for a simulation run with disruption.

A comparison of the run with normal operation (see Figure 10) shows that the resilience in the disruption scenario decreased from a value between 0.75 and 1. The normal run furthermore indicate that there is a normal variation of the resilience of 0.25. The reason for that is the great fluctuation of the productivity from the SC at the waterside. As the ship loading and unloading is the terminals bottle neck [11], the SC waits for the QC so that the load and unload of the ship is as smooth as possible. And that leads to fluctuation in the

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productivity from the SC at the waterside which is then also displayed in the resilience evaluation.

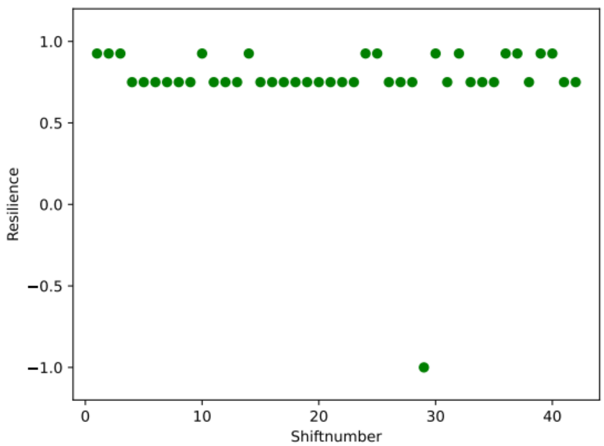

Fig. 10. Resilience values for a simulation run with normal operation.

The third simulation cycle is with a disruption and the implementation of a resilience increasing measure. For this purpose the number of truck parking slots is increased from 5 to 10. A parking slot means a place where the trucks are positioned for loading and unloading with a safety area for the truck drivers. The measure leads to a significantly smaller drop of the resilience (see Figure 11).

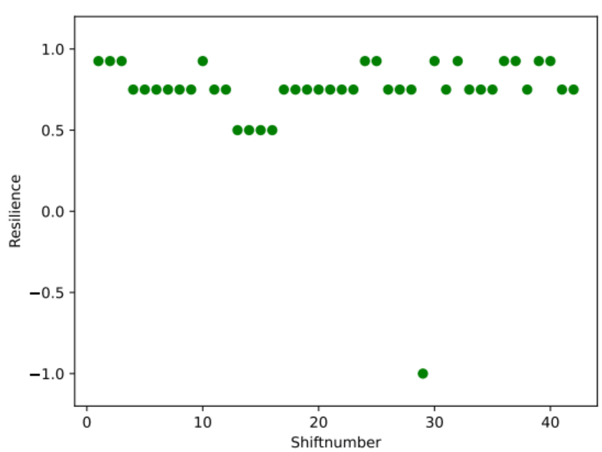

Fig. 11. Resilience values for a simulation run with disruption and measure.

In summary, the simulation runs show that the resilience reacts as expected to disruptions, which is a proof of concept for the resilience assessment method for container terminal processes.

IV. Discussion

The KPI system and the resilience assessment is a simple approach applied on the complex and huge system of a container terminal. The number of fuzzy logic rules is strongly increasing when there are a lot of KPI combined, which make an evaluation through humans more complex. So the idea is to implement something new with a simple start point, which is easy to evaluate, and then building up a bigger system, when there is more experience. As security and resilience are based on cooperation with the staff, the use of fuzzy logic to incorporate the employees in the process is important and justifies a simplification of the evaluation problem.

Another advantage of fuzzy logic is the use of If-Then-rules, because then the KPIs do not need to have a mathematical link to each other. However, a standardised recording period is required to link the KPIs using fuzzy logic. This means adjusting the KPIs, which are recorded differently. For example, the waiting time of the trucks is recorded for each order when the truck drives from the waiting area to the parking space. For the integration of the waiting time into the fuzzy system the recording of the KPIs was adapted, so that now the number of trucks waiting is recorded and not the time they wait. The number of trucks waiting could be recorded per shift and normalised with the total number of trucks for that shift.

The general choice of KPIs, which show an influence when a certain scenario occurs, is not so trivial. The productivity of the SC from the waterside is not the most suitable KPIs for the scenario evaluation, as the normal variations are so high that through the disruption added variation is not so remarkable (see Figure 12) compared with Figure 2. And this despite the fact that the fuzzy sets are adjusted with larger sets for ”high” and ”very high”. A simulation is here a helpful instrument

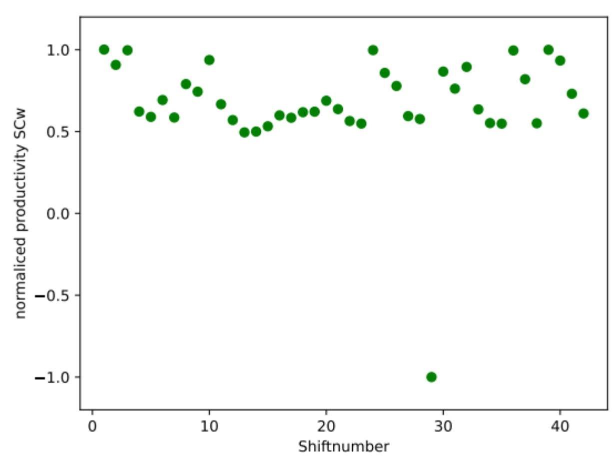

Fig. 12. Productivity of the SC at the waterside with disruption scenario.

to get insights into whether or not a combination of KPI is suitable for a group of scenarios. There exist many different scenarios, but every scenario which influences the time of the SC is not really visible in the productivity of the SC at the waterside and for the trains, but in the productivity of the QCs and of the SCs for the trucks. So these scenarios could be grouped depending on the part they influence and not on

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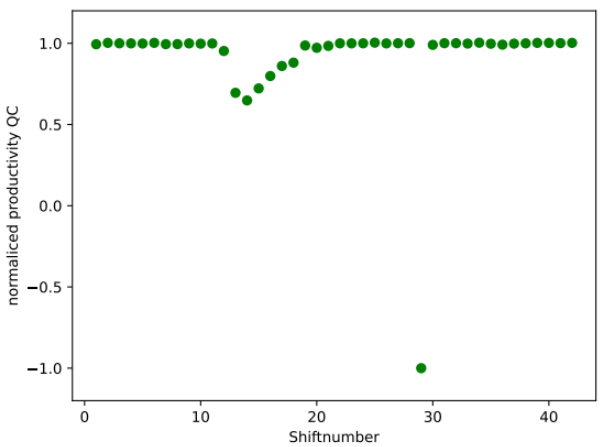

Fig. 13. Productivity of the QC with disruption scenario.

the type of the disturbance. For the testing of the resilience assessment a simulation is needed which could be connected with the assessment method, calculate the KPIs as needed for the assessment and include the disruption scenario. Here a self developed simplified simulation matched most of the requirements and so was preferred over a simulation from others which might be more detailed in the modelling of the processes, with less simplifications.

V. Conclusion

The example disruption scenario in the simulation showed that the developed resilience assessment is functional for a container terminal. To get a better understanding of the resilience assessment, the implementation of further examples is reasonable. Another future step is an exchange with terminal operators to understand their needs and to integrate them in the developed system. If several measures and scenarios are to be considered and a decision for one or a few measures has to be made, a next step is the connection of the system with a decision support system. Overall this work connected the resilience approach of fuzzy logic assessment with the logistics approach of performance indicators in a new assessment tool for container terminals.

References

[1] H. Carvalho, V. H. Machado, A. Barroso, S. Garrido Azevedo, and V. Cruz-Machado, “Resilience of Logistics Service Providers Facing a PortStrike: A Case Study,” in *Proceedings of the International Conference on Industrial Engineering and Operations Management*. [Southfield, Michigan, USA]: IEOM Society International, 2018.

[2] Y. Lv and Y. Gao, “Time-based resilience enhancement with dual berth allocation strategies in bulk cargo terminals under machinery failure scenarios,” in *2023 7th International Conference on Transportation Information and Safety (ICTIS)*. IEEE, Aug. 2023, pp. 2506–2511.

[3] A. Almutairi, Z. A. Collier, D. Hendrickson, J. M. Palma-Oliveira, T. L. Polmateer, and J. H. Lambert, “Stakeholder mapping and disruption scenarios with application to resilience of a container port,” *Reliability Engineering & System Safety*, vol. 182, 2019.

[4] R. Pant, K. Barker, J. E. Ramirez-Marquez, and C. M. Rocco, “Stochastic measures of resilience and their application to container terminals,” *Computers & Industrial Engineering*, vol. 70, pp. 183–194, Apr. 2014.

[5] S. Gote, C. Wanigasekara, and F. Sill Torres, “Use of Fuzzy Systems for Vulnerability Evaluation: An Example of a Container Terminal,” in *Proceedings of the MARESEC 2024*. Zenodo, 2024.

[6] M. De Iuliis, O. Kammouh, and G. P. Cimellaro, “Measuring and improving community resilience: A fuzzy logic approach,” *International Journal of Disaster Risk Reduction*, vol. 78, p. 103118, Aug. 2022.

[7] A. Ur-Rehman, J. Kamruzzuman, I. Gondal, and A. Jolfaei, “Fuzzy-based operational resilience modelling,” in *2022 IEEE 9th International Conference on Data Science and Advanced Analytics (DSAA)*. IEEE, Oct. 2022, pp. 1–8.

[8] Y. Brezhniev, “Multilevel fuzzy logic-based approach for critical energy infrastructure’s cyber resilience assessment,” in *2019 10th International Conference on Dependable Systems, Services and Technologies (DESSERT)*. IEEE, 2019.

[9] E. O. Olatunji, O. A. Adebimpe, and V. O. Oladokun, “A fuzzy logic approach for measuring flood resilience at community level in nigeria,” *International Journal of Disaster Resilience in the Built Environment*, vol. 14, no. 4, pp. 434–452, Mar. 2023.

[10] S. Gote, A. Gabriel, and F. Sill Torres, “Container terminal simulation for vulnerability assessment,” in *Proceedings of THE 13TH INTERNATIONAL DEFENCE AND HOMELAND SECURITY SIMULATION WORKSHOP*, ser. DHSS 2023. CAL-TEK srl, 2023.

[11] H. J. Carlo, I. F. A. Vis, and K. J. Roodbergen, “Seaside operations in container terminals: literature overview, trends, and research directions,” *Flexible Services and Manufacturing Journal*, vol. 27, no. 2–3, pp. 224–262, Jun. 2013.

[12] Terminal Industry Committee 4.0, “Cycle 2021.002,” 2021. [Online]. Available: https://tic40.atlassian.net/wiki/spaces/TIC40Definitions/pages/444923978/Cycle 2021.002

[13] R. Czabanski, M. Jezewski, and J. Leski, *Introduction to Fuzzy Systems*. Springer International Publishing, 2017, pp. 23–43.

DOI: 10.5281/zenodo.17119959