Identification and Testing of Resilience Strategies for Inland Waterway Transport

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Abstract. Transport and supply chain systems are increasingly exposed to climate change, infrastructure bottlenecks, and labour-related disruptions, yet Inland Waterway Transport (IWT) remains under-explored in terms of resilience strategies. The challenge is twofold: most existing frameworks are too generic and static, and IWT-specific practical strategies have not been systematically identified or validated. This study addresses this gap by developing a two-part methodology. The first part draws on a post hoc literature review from the ResC4EU project to identify a comprehensive pool of resilience strategies. The second part applies a scenario-based serious gaming methodology from Living Labs (LLs) of the ReNEW project, where disruptions such as heatwaves, droughts, storms, flooding and strikes were simulated to test and refine these strategies in realistic IWT contexts. The results demonstrate where theoretical strategies converge with practical needs, highlighting a backbone of strategies that are broadly applicable across scenarios (such as flexibility, visibility and digital capabilities) alongside scenario-specific strategies. The study provides an empirically grounded resilience framework for IWT and outlines pathways for embedding these strategies into digital tools and policy.

Keywords: Logistics · IWT · Resilience · Living Labs · Serious Gaming Approach

1 Introduction

Resilience has become a central concern in transport and supply chain systems, driven by the frequency and severity of disruptions ranging from climate change events (such as heatwaves and flooding and prolonged droughts) to labour disputes. IWT, as a critical component of Europe's multimodal transport system, faces specific vulnerabilities: climate-induced low water periods, lock closures and its dependence on infrastructure can halt traffic, while strikes amplify system fragility [1–3].

Yet, despite recognition of resilience as a policy and research priority, IWT has not received the same level of systematic resilience strategy development as other modes. Existing frameworks tend to be derived from general supply chain and transport models oriented toward manufacturing or global logistics, emphasising generic capabilities and strategies, with limited attention to the particularities of IWT operations and the need for proactive, context-specific strategies [3, 4].

© The Author(s) 2027
D. Esztergár-Kiss et al. (Eds.): TRAconference 2026, LNMOB, pp. 29–36, 2027.
https://doi.org/10.1007/978-3-032-36101-1_4

The objective of this study is therefore to close this gap by combining theory-driven strategy identification with scenario-based practical extension. The first part of the paper uses a post hoc literature review from the ResC4EU (Resilience for Supply Chains in Europe) project to consolidate resilience capabilities into actionable strategies in transportation and supply chain resilience. The second part applies a scenario-based serious gaming approach from the project ReNEW (Resilience-centric Smart, Green, Networked EU Inland Waterways) LLs, simulating disruptions like heatwaves, droughts, storms, flooding and strikes to test and refine these strategies in IWT con-texts. By doing so, the paper contributes both a conceptual framework and a validated set of resilience strategies tailored to IWT, grounded in both literature and practice.

2 Methodology

2.1 Part I: Post hoc Literature Review (ResC4EU Project)

The first part of the methodology builds on the ResC4EU project and wider supply chain resilience and transportation literature. A post hoc review synthesised resilience capabilities (such as flexibility, visibility, digitalisation, financial strength) into a structured set of resilience strategies. While originally framed as capabilities, they are here reframed as strategies that organisations can deploy to withstand, adapt to and recover from disruptions. This list forms the initial "strategy pool".

2.2 Part II: Scenario-Based Serious Gaming Methodology (ReNEW Project)

The ReNEW project focussed on increasing the resilience of IWT with different solutions, which were tested in four Living Labs (LL).

LL1 - Ghent's Multifunctional Synchromodality Resilient City Logistics Hub. LL1, Ghent's Living Lab, focused on the creation of a resilient logistics system serv-ing many functions. The Living Lab investigated how climate change events affect Ghent's City Logistics Hub operations. This LL focussed mainly on the development of a Smart Terminal and the design and demonstration of a Floating Modular Platform to provide emergency transport and power in crises.

LL2 – Smart Douro Inland Waterway Infrastructure Resilience Management. The Douro River is an important inland waterway in Portugal and is considered a feeding point of the Atlantic Corridor. LL2 concentrated on extreme weather events and illegal wastewater dumping. A digital twin was developed by combining data from riverbed sensors, weather forecasts and hydrological models. This virtual replica is used for predicting ship performance and the improvement for emergency planning, navigation, and passenger safety. Real-time monitoring of wastewater tanks was introduced to stop illegal dumping into the Douro River.

LL3 - EU IWT Network Resilience Mitigation Digital Twin App. This LL aimed to build and showcase a planning and mitigation app to promote modal shift. This route-planning app includes a module for real-time adjustments to barge routes and speeds, mitigating terminal delays. Improving inland navigation logistics and

strengthening resilient infrastructure capacity during events are key features of this platform.

LL4 - Resilience Promoting Autonomous Zero-Emissions Barges. LL4 aimed to create a fleet of smaller and increasingly automated vessels in order to strengthen the resilience of the overall IWT system. An autonomous barge (X-barge) was designed to show how resilient IWT infrastructure can be. In LL4, the barge type's performance in various conditions, such as low water and severe weather, was evaluated.

Identification of Measures Using an Adapted Serious Gaming Approach. In order to increase the motivation of practitioners to join a research task, a business game can be used. The setting of a game offers a relaxed environment that can support motivation and stimulate discussion among the participants. According to researchers in this field [5] a business game can encourage participants to discuss and learn which resilience measures can be used and how to collaborate in order to cope with disruptive events. Business games offer a safe platform where participants can test and experience new measures and the resulting consequences without the risk of real negative effects. A business game [5] was used to identify measures to improve against the impact of climate change. In this game, players mimic the roles of different actors in a food supply chain and are con-fronted with different scenarios.

The second part of this study adapts a serious gaming approach involving the four ReNEW LLs in order to get input on mitigation measures for different scenarios. In-stead of abstract evaluations, real-world disruption scenarios were presented to LL participants, including IWT operators, terminals and municipalities. Six scenarios were tested: "Heatwave", "Drought", "Storm", "High water", "Flooding" and "Strike".

For each scenario, participants discussed two questions: "What would you do now utilizing existing measures?" and "What could you do strategically to avoid similar disruptions in the future?".

The serious gaming approach encouraged practitioners to articulate both immediate responses as existing measures and longer-term resilience measures, which could be used as future measures.

Connecting the two Parts. The combined method thus bridges theory and practice: Part I provides a structured pool of resilience strategies and Part II stress-tests and identifies measures under realistic IWT disruption conditions, which can be linked to the pool of strategies of Part I.

3 Findings

3.1 Capability-Based Strategy Pool (Part I)

Part I identified several resilience strategies. Previous authors [6–9] describe flexibility in sourcing as the ability to quickly change inputs or the mode of receiving inputs. They also mention flexibility in order fulfillment as the ability to rapidly adjust outputs or the mode of delivery. Another strategy is capacity which is a skill to change manufacturing processes or adapt to new products, mix or volumes efficiently. Efficiency is the strategy to produce outputs with minimum resource requirements, which was also called in their

reports. The authors also mentioned visibility as the knowledge of the status of operating assets and the environment and adaptability as the ability to change operations in response to challenges or opportunities. Anticipation (capability to discern potential future events or situations) and recovery (skill to restore from events) are also reported in their work. Broad distribution or decentralisation of assets defines the strategy dispersion. These authors also specify collaboration and trust as strategies to work effectively with other entities for mutual benefit. Security is another strategy that aims at defence against deliberate intrusion or attack. The authors also mention financial strength and interpret it as the capacity to absorb fluctuations in cash flow. According to several papers [10–13] digital capabilities contain skills, technologies, processes and resources that enable an organisation to effectively advantage digital technologies. Risk appetite and culture is another strategy, which is a skill to recognise, assess and address risks and uncertainties in the supply chain [8]. Following the concept of sustainability [12, 14, 15] defining social sustainability as a strategy to ensure the social sustainability of employees during the production and delivery of products and meeting the requirements of stakeholders. Several studies [14–16] describe ecological sustainability as a skill to ensure ecological efficiency and sustainability during the production and delivery of products.

These strategies serve as the theoretical foundation, set the strategy pool and were tested in Part II.

3.2 Scenario Testing Results (Part II) and the Convergence Between Theory and Practice

In the following section, the responses from the four ReNEW LLs on the six scenarios regarding existing and future measures are described. The mentioned measures are mapped to the resilience strategies pool in Part I.

Heatwave. As existing measures LLs highlighted operational adjustments (such as adjusted operating hours, alternative routing), monitoring river conditions, informing clients, usage of protective measures (for infrastructure) and weather forecast analysis. Future measures include digital twin deployment for predictive planning, resilient infrastructure development, resilience planning and training, community engagement and public awareness, vessel planning systems and alternative vessels. Mapping these measures to the strategies of Part I, these responses converge with flexibility, anticipation, visibility, adaptability and digital capabilities.

Drought. Existing measures such as operational adjustments (alternative routing, adjusted schedules and reduced vessel loads), alternative vessel types and information of clients were mentioned. Predictive analytics using digital twins, resilient infrastructure development and creation of prediction models for water levels were highlighted as future measures. These measures link closely with flexibility, adaptability, visibility, anticipation and digital capabilities.

Storm. The LLs noted the different existing measures: suspension of operations, securing vessels and equipment, monitoring of weather and water level and informing clients. Future measures include the use of digital twins for predicting storm impact and hydrological models, resilient infrastructure development, advanced monitoring infrastructure for weather and water levels, alternative vessel types and contracts to recoup costs.

These answers are associated with flexibility, anticipation, visibility, digital capabilities, adaptability, recovery and collaboration.

High Water. Responses for existing measures ranged from suspension or scaling back of operations, alternative routing, securing vessels and equipment, monitoring of weather and water level and informing clients. Future measures include the use of digital twins for predicting impact and hydrological models, resilient infrastructure development, advanced monitoring infrastructure for weather and water levels, alternative transport solutions (modal shift), alternative vessel types and contracts to recoup costs. This aligns with flexibility, anticipation, visibility, digital capabilities, adaptability and collaboration.

Flooding. As existing measures LLs mentioned suspension of operations, securing vessels and equipment, monitoring of weather and water levels, informing clients, alternative vessel types and alternative transport solutions (modal shift). Future measures comprise the use of digital twins for predicting impact and hydrological models, resilient infrastructure development, advanced monitoring infrastructure for weather and water levels, alternative vessel types and contracts to recoup costs. These converge with flexibility, anticipation, visibility, digital capabilities, adaptability and collaboration.

Strike. Only a few existing measures were identified such as operational adjustments (alternative transport solutions, alternative routing, implementation of contingency plans, prioritisation of critical shipments), alternative routing and informing clients. Future measures include the usage of hubs, alternative vessel types (especially autonomous vessels), automation of locks, resilient infrastructure development and vessel planning system. These measures align with flexibility, visibility, adaptability and collaboration.

4 Discussion of the Results

As described in Fig. 1, strategy flexibility is one approach that is already used by a majority of LL and can mitigate negative effects in different scenarios. This includes adjusted operating hours, alternative transport and a changed loading scheme. Also, visibility was mentioned often for several scenarios, but is mainly used by LL2 and LL4. For this strategy, the LL mentioned the information of the public or clients at events. Some LL plan to use adaptability in the future. Using alternative vessel types was described often. For anticipation only two LL reported the creation of prediction models. Limited responses were given for the strategy recovery. Most prominent answers were comprehensive resilience plans and drills. The strategies collaboration and trust and digital capabilities were mentioned only as future strategies, which include especially digital twins. Many measures were mentioned for the heatwave and storm scenarios. In contrast, drought and especially strike only a few suitable measures were identified.

These findings suggest that while the broader resilience literature provides a solid foundation, certain IWT-specific challenges (such as strikes, water-level fluctuations) require tailored strategies. The scenario strike of Part II also shows that the strategy list of Part I addresses labor disruptions only partially.

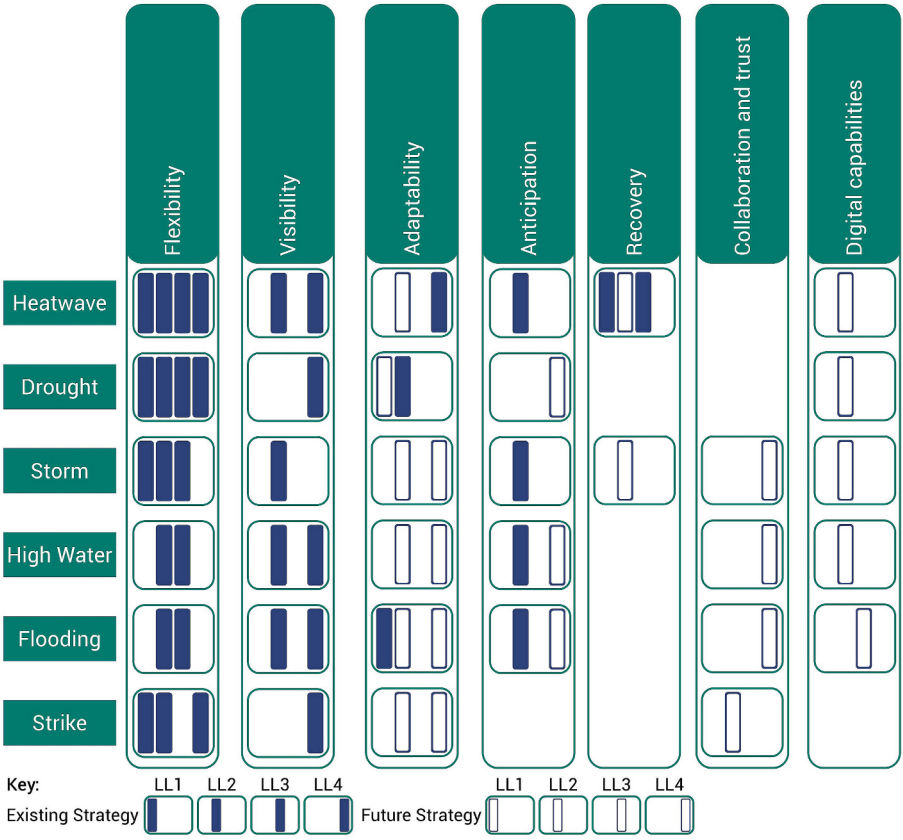

Fig. 1. Responses of LL on existing and future measures for scenarios

5 Conclusions

This study developed and applied a two-part methodology to identify and validate resilience strategies for IWT. The first part produced a comprehensive pool of strategies grounded in broader supply chain resilience research. The second part, a scenario-based serious gaming exercise, stress-tested these strategies under realistic IWT disruptions.

Findings show strong alignment between theory and practice in areas such as flexibility, adaptability, anticipation and digital capabilities. At the same time, gaps remain, especially for labour-related disruptions, where strategies are less developed. The results underscore that resilience in IWT cannot rely on abstract strategies alone; it must be contextualized and validated in sector-specific scenarios.

Limitations include reliance on simulated scenarios rather than real-world crisis responses and the fact that LLs represent experimental rather than operational environments. Future research should validate strategies with a broader set of IWT stakeholders, integrate the strategy pool into digital decision-support tools and evaluate effectiveness

under actual disruption events. Overall, this integrated methodology bridges the gap between abstract capabilities and operational strategies.

Practitioners in the IWT domain benefit from the paper because they can use the identified strategies to increase the resilience of their transports. Scientific researchers can reuse the concept of an adapted serious game approach and can use the findings of this study for further research in the domain of resilience.

Acknowledgement. This research was supported by the European funded projects "ResC4EU – Resilient Supply Chains for Europe" (Project number: 101137643) and "ReNEW – Resilience-centric Smart, Green, Networked EU Inland Waterways" (Project number: 101069682).

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