MIGRATION LAYERS AND CORRIDOR RESILIENCE ON THE DANUBE–BLACK SEA LOGISTICS ROUTE

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1. **ABSTRACT:** Logistic corridors are often described as technical structures shaped by economic or engineering choices. We look at them as systems that include people, environments, and technologies that influence movement and exchange. We introduce the Migration Layers Corridor Model (MLCM). In this model, a corridor functions as a living system formed through interactions between natural dynamics, infrastructure, socio-economic relations, and ongoing green and digital transformations. For this research, the Danube-Black Sea Canal was used as a case study. Political and environmental decisions shaped the existence of this canal, and it has now acquired its role as a logistic corridor. The MLCM includes four layers: the Natural-Hydrological layer, the Built Infrastructure layer, the Socio-Economic and Logistics layer and the Green-Digital Resilience layer. The assessment of these layers provides a comprehensive picture of how human, material, ecological and technological movements shape a corridor. The model supports planning practices and can be used in the decision-making process. It can become an example for research on other corridors. The research results can be used for strategic, circular economy and infrastructure decisions in the logistics chain.

2. INTRODUCTION

Technical indicators are frequently used to describe logistics corridors. In practice, they are evaluated based on capacities, routes, tonnage, and multimodal nodes. They are much more important, and the metrics don't capture all the useful aspects. Corridors are represented by lines on the map and converge into areas with multiple forms of movement. Goods travel different routes, people travel for different reasons, and technologies are input or output variables. The definition of a corridor has changed due to different time variables, and regional development is influenced by the economic periods of the country

[1]. Sustainability and the principles of the circular economy influence the efficiency and capacity of infrastructure to adapt to environmental forces [2], [3]. For this research, the Danube-Black Sea Corridor was considered, and the history is complex [4], [5]. Construction began between 1949 and 1953. This period was politically controversial. Work was then resumed in line with a changing economy. Opinions varied at the time. In many ways, the route took on a new function as a replacement for misdirected freight following recent delays in the Black Sea. Resilience and adaptability are important aspects of this vision.

The MLCM is used to understand these dynamics. A corridor is more complex than a simple technical structure, people and labour move, engineering systems change, and technologies advance [6]. We examine how aging infrastructure adapts to the principles of the circular economy and constitutes itself as a socio-industrial intersection where a digital and sustainable future meets a complex history [7]–[11].

This paper pursues the following objectives: Ob1: to map the historical and ecological transformations of the Danube–Black Sea Canal as a logistics corridor; Ob2: to develop the MLCM as a multidimensional framework for smart and resilient inland waterway corridors; and Ob3: to illustrate how simplified analytical indicators can be embedded into this framework. The paper offers answers for the following questions: RQ1: How do natural hydrological, infrastructural, socio-economic and green digital 'migration layers' co-evolve along the Danube–Black Sea logistics route?, and: RQ2: In what ways can these interacting layers be translated into operational indicators for assessing corridor resilience and sustainability?

3. BACKGROUND. LITERATURE REVIEW

In recent decades, research on the Danube–Black Sea Canal has expanded significantly, reflecting the continuous changes in the landscape, economy and environment of the region. Early studies focused on geopolitical arguments, construction conditions and expected economic gains, especially the strengthening of Constanta Harbour within the international transport network [1]–[4]. Subsequent research has increasingly documented the hydrological and ecological effects of the canal, including habitat changes, loss of biodiversity, invasive species and long-term changes in water and sediment dynamics [5], [12], [13], [14]. Recent contributions have expanded the scope of analysis, including the perspectives of social, archaeological and regional development, and since 2022, renewed geopolitical attention has highlighted the logistical role of canals under circumstances of conflict-driven reorientation and economic reorientation.

In addition to this case-specific literature, several corridor research fields are directly related to the current research. Recent research into the resilience of transport networks highlights how corridors react to climate, operational and geopolitical disturbances through mechanisms such as redundancy, diversification and adaptive governance strategies, while articulating methodological challenges in quantifying resilience at system levels [15], [16]. Research into multi-layer logistics and transport networks has shown that infrastructure, flows and governance can be described as interconnected layers, preferably through inter-layer transit nodes and common dependencies, where the damage of one layer extends to other layers [17]. In addition, research on inland waterways highlights a range of threats and risks, including natural phenomena, operational disruptions and emerging risks such as cyberattacks, that must be taken into account within waterway resilience frameworks [18]. Research into logistics social technology systems further considers transport corridors to be configurations in which technical assets, institutions and human practices develop together, rather than independently function, indicating that digital and social conditions play an essential role in systemic resilience [19]. MLCM uses these observations to integrate hydrology, infrastructure, socio-economic, and green digital dimensions into a single conceptual framework for inland waterway corridors.

In this model, the Danube–Black Sea Canal is interpreted as a multilayered socio-technical corridor, allowing an assessment of resilience and adaptation capacities that emphasizes interaction between layers rather than isolation of performance indicators. Despite this diversity, literature consistently points out two unresolved shortcomings: a lack of a strong longitudinal monitoring framework and a limited integration of social, ecological and operational aspects from a unified analytical perspective. In this regard, existing studies tend to focus solely on logistical performance, environmental impacts or social impacts. This fragmentation limits the assessment of the resilience of corridors under contemporary conditions of climate change, digitalization and geopolitical shocks.

The present study proposes a conceptual framework that integrates hydrological, infrastructure, socio-economic, and green digital dimensions and positions the Danube–Black Sea Canal as a dynamic logistics corridor, whose sustainability depends on coordination monitoring, technology adoption, and workforce preparation.

Taken together, the literature points to a small number of recurrent interaction patterns, summarized below as conceptual propositions.

4. THE MIGRATION LAYERS CORRIDOR MODEL (MLCM)

In line with the cultural perspective of the hosting institution, the model is aligned with the idea of restoring balance and functional soundness in corridor systems, seen here through the combined roles of digital technologies, environmental monitoring, and workforce capacity in supporting resilient and sustainable logistics.

4.1 A multidimensional framework for understanding smart and resilient waterway corridors

Logistics corridors have traditionally been conceived as linear infrastructures that facilitate the movement of goods in space. However, due to the growing complexity of the global supply chain and the need for rapid digitization and carbon free, it is necessary to better understand how different modes of transport intersect in the same corridor. The MLCM proposes four layer analytical structures to understand logistics corridors as dynamic migration spaces shaped by physical movements of cargo, water flow, socio-economics, ecology, and technology. MLCM defines four interdependent layers that shape the long-term development, strategic role, and resilience of transportation corridors. These layers are not isolated, but interact continuously over time and form multi-scale mobility ecosystems. By applying this framework to the Danube-Black Sea Canal, this paper demonstrates how historical infrastructure can be redefined as intelligent, green and adaptive corridors suitable for emerging sustainability challenges.

Before introducing the MLCM model, it is necessary to map the succession of mobility regimes that shaped the corridor across different historical periods (Figure 1). The following timeline provides a synthesized overview of these shifts, from forced and state-directed migration to contemporary market-driven flows and future green-logistics transitions.

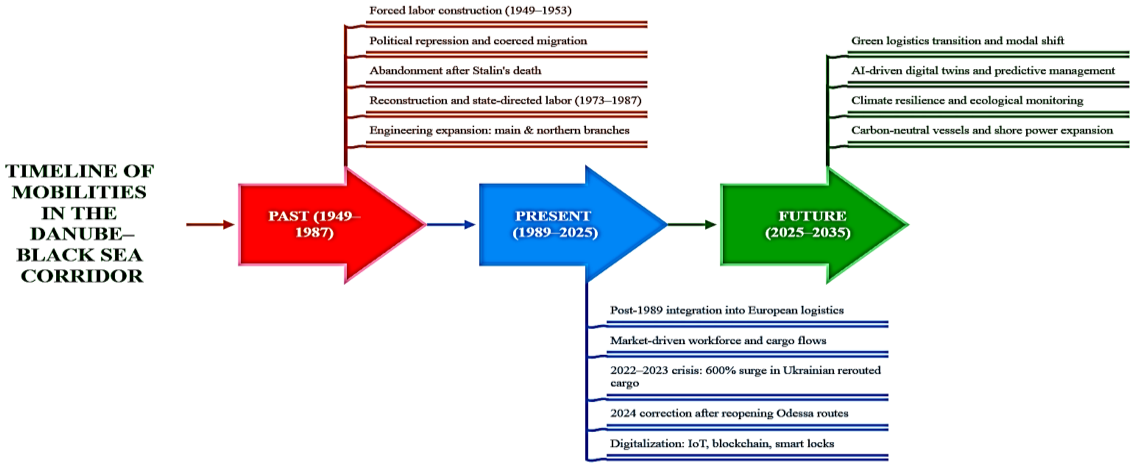

Figure 1: Timeline of Mobility in the Danube-Black Sea Corridor (author's own research)

4.2 The natural-hydrological layer (NHL)

In waterway corridors, hydrological dynamics are well understood by experts [20], [21]. The MLCM framework layer gains here a different meaning: it becomes the system's anchor, the migration emerging point. Migration meaning refers not only to water and sediment flows but to the ecological and operational shifts that ultimately shape the corridor's long-term resilience. For the Danube-Black Sea Canal, hydrological migration highlights three interlinked processes that constrain and enable all higher-level interventions: i) water-level variations influenced by Danube discharge and Black Sea backflow; ii) sediment mobility shaping navigability and dredging regimes; iii) ecological movements connected to salinity, climate pressures, and the canal's artificial morphology. Seen through this lens, the hydrological layer does not state the obvious - it reframes it. It shows that environmental migration precedes and conditions any infrastructural, economic, or technological decision within the corridor.

4.3 The built-infrastructural layer (BIL)

The second layer focuses on the physical infrastructure that gives the corridor a concrete form. In this case, "immigration" captures how infrastructure changes over time, whether it is built, expanded, modernized, repaired or completely rebuilt. The history of the Danube–Black Sea Canal shows such infrastructure migrations in three different phases: (1) the first construction under forced labor conditions between 1949 and 1953; (2) the large-scale reconstruction of the waterways of 1973–1987, which changed the shape of modern mechanical equipment; and (3) the digital transformation after 2000, marked by intelligent locks, automated terminals and advanced monitoring systems. In this layer, migration includes not only physical changes, but also technical knowledge movement, adoption of new technologies and gradual infrastructure adjustment in response to changes in requirements. It "travels" through cycles of wear, renewal, and redesign. Seeing this mobility helps us evaluate the canal's long-term competitiveness and its ability to connect with future smart multimodal networks.

4.4 The socio-economic and logistic layer (SELL)

The third layer focuses on the socio-economic forces that give life to the corridor. In this context, "migration" refers to the movement of people, goods, capital, and institutions - all the elements that continuously reshape the corridor's role in regional logistics. These elements continuously shape the corridor's role in regional logistics. Several forms of mobility intersect here. Labor patterns have shifted from the coercive workforce of the early decades to today's market-based labor. Cargo flows have evolved from bulk agricultural and mineral goods to containerized and higher-value traffic. Capital and investment priorities move with market demand. Cross-border cooperation and institutional frameworks add further layers of change. Between 2022 and 2024, the Black Sea shipping route collapsed, resulting in the temporary transformation of the Danube corridor into an important emergency export route due to geopolitical pressure, highlighting the labor migration that shaped the phases of the canal's construction and modernization, and reminding us that human mobility has always been embedded in the corridor's operation. Today, socio-economic migration includes a different kind of transition: the workforce adjustments required for green logistics - from reskilling and digital competencies to new operational practices shaped by automation and smart technologies. In this sense, the socio-economic layer reveals how people, markets, and institutions "move" together, constantly redefining the canal's purpose and possibilities.

4.5 The green-digital resilience layer (GDRL)

The last layer represents the most recent forms of transformation of migration in the logistics corridor. Migration refers to the movement of data, such as 1) real-time cargo tracking, blockchain verification, and IoT sensor flow), 2) energy systems (transfer of fossil fuels to electricity, hydrogen, and renewable energies), 3) carbon emissions (transfer of roads to inland waterways), 4) operational control towards artificial intelligence-driven predictions and digital twin environments. This layer is at the center of the EU Green Deal and the Rhine-Danube digital corridor initiative. It transforms the Danube-Black Sea route into a smart logistics ecosystem where information moves faster than cargo. In this context, resilience depends on the ability of the corridor to move from i) analogue governance to digital governance, ii) high-emission mobility to low-emission, and iii) to react to prediction operations. The green digital layer is the strategic boundary for future development of the corridor.

4.6 Interdependence of the four layers. A multi-mobility ecosystem

The power of MLCM lies in treating these four layers as interacting systems and not as separate categories (Figure 2). Their interactions create corridors that respond to ecological pressures through water management, modernize infrastructure based on environmental conditions, transform socio-economic mobility through infrastructure capacity, and transform them into digital, carbon-free ecosystems through technological migration. In the case of the Danube–Black Sea Canal, these interactions show that corridors marked by historical traumas may become an important factor in regional green transition. They show that resistance is not only about technical stability, but also about the ability of corridors to integrate multiple migration flows, environmental, material, human and digital, into a coherent and adaptive system.

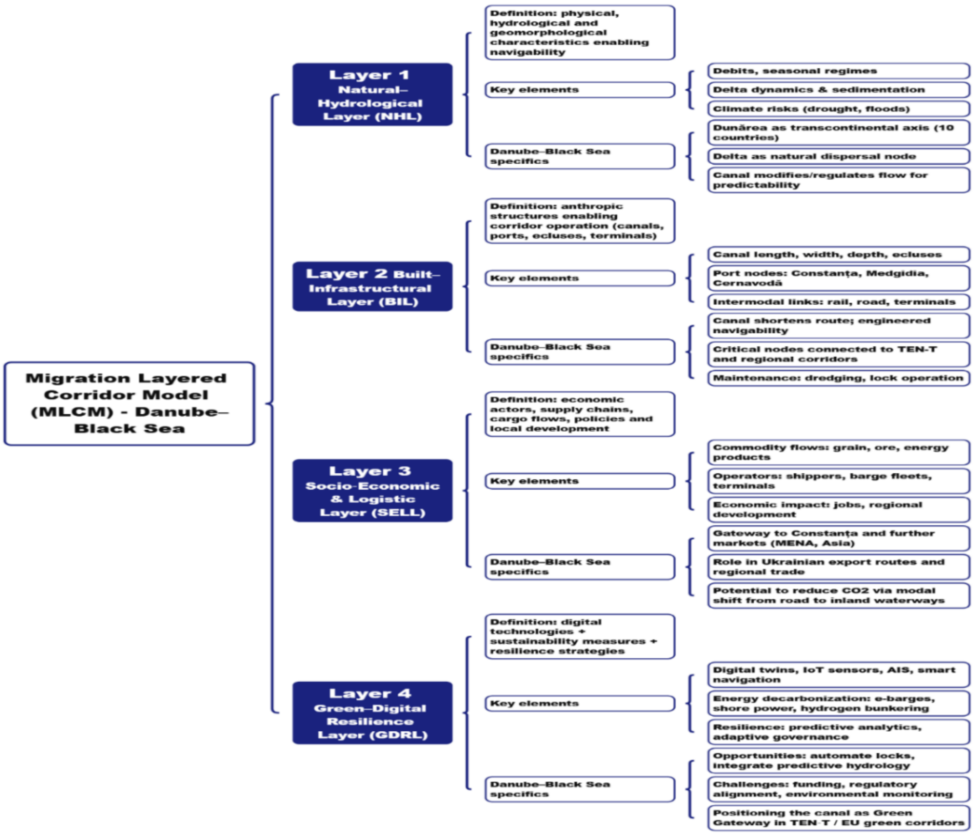

Figure 2: Proposed MCLM (author's own research)

Taken together, the four migration layers suggest a set of conceptual relationships that clarify how corridor resilience emerges from their interaction rather than from any single layer in isolation. P1. Corridor resilience increases when hydrological variability is continuously monitored and operationally integrated into infrastructural management, rather than treated as an external constraint. P2. Socio-economic freight migration amplifies or mitigates hydrological and infrastructural constraints depending on institutional coordination and digital readiness. P3. Green-digital transition enhances corridor resilience when environmental performance and digital control systems evolve in tandem with operational demands. Unlike many corridor resilience approaches that focus on single-layer performance (for example, infrastructure condition, traffic volumes, or environmental risk in isolation), MLCM is explicitly designed to capture interactions between hydrological, infrastructural, socio-economic, and green-digital layers. This interaction-focused perspective is particularly relevant for inland waterways, where environmental variability, logistics adaptation, and digital transition are tightly coupled but often analysed separately.

5. APPLICATION OF MLCM: APPLIED TECHNICAL INDICATORS & ANALYSIS

To demonstrate the practical application of the migration corridor model (MLCM), we have incorporated our analysis into verified technical indicators extracted from CN ACN's operational reports, European Commission publications, hydrological evaluation of the ICPDR and port sustainability data. These values cover the volume of goods, the navigational conditions, sediment dynamics, energy efficiency, digital coverage, and modal shift emissions, and allow models to interface with the engineering realities rather than remaining theoretical structures. These indicators are intentionally simplified and serve an illustrative role within the conceptual model (e.g. simplified navigational sensitivity or freight migration elasticity). It is intended to illustrate how MLCM (Figure 2) can incorporate quantifiable parameters, rather than replace established technical standards.

5.1. Operational Analysis within the MLCM Framework

Building on the conceptual definitions introduced in Section 4, Section 5 illustrates the hydrological, infrastructural, socioeconomic, and green-digital layers using selected operational indicators relevant to the Danube–Black Sea corridor (Figure 3). The objective is to connect quantitative data with the multilayer corridor model (MLCM) and highlight key dependencies that affect the corridor's stability, capacity, and sustainability. The indicators grouped in Figure 3 are then interpreted in Sections 5.1 and 6 as inputs to the four MLCM layers and as starting points for the analytical indicators introduced later.

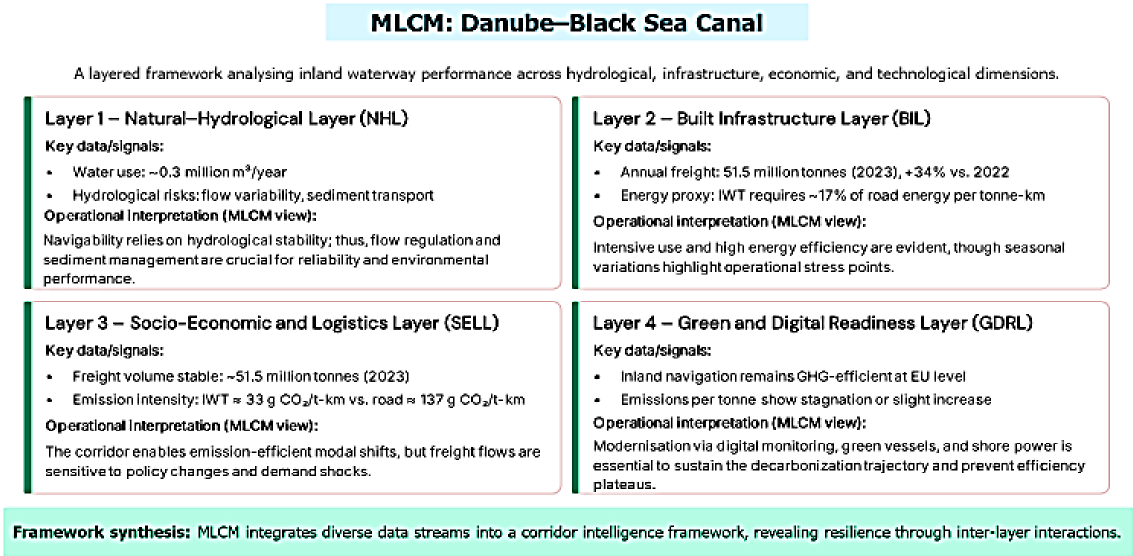

Figure 3. Operational Indicators and Interpretations for the Danube–Black Sea Corridor

5.2. An overview of the MLCM implications and applicable findings

Each layer introduces constraints and adaptive capacities that interact dynamically within the MLCM structure. The **NHL** faces limitations from seasonal flow patterns, allocation rules, and ecological restrictions, which, although manageable, require continuous calibration of operational management. The **BIL** reveals patterns of intense traffic and uneven temporal distribution, implying that performance monitoring and maintenance planning must remain integral to daily operations, not restricted to long-term cycles. Within the **SELL**, rising freight volumes express the canal's increasing role in regional connectivity. Modal shift potential depends on market conditions, cost levels, and logistics reliability, all of which shape the system's resilience. The **GDRL** indicates a structural need for investment and coordinated strategies. Low-carbon technologies, emission monitoring, and digital control tools define how the corridor can comply with European targets for sustainable and climate-neutral mobility. Overall, the integrated interpretation confirms that the Danube–Black Sea corridor functions as a complex, interdependent system balancing efficiency, environmental responsibility, and strategic relevance at regional and trans-European levels.

6. ANALYTICAL INDICATORS AND PROPOSED EQUATIONS (MLCM APPLICATION)

The contributions of this paper are primarily conceptual. Instead of competing with detailed hydraulic or economic models, the proposed MLCM integrates existing and emerging knowledge of the Danube–Black Sea Canal from a comprehensive corridor perspective. In sections 6.1 and 6.2, the two indicators of Critical Navigability Index (CNI) and Elasticity of Freight Migration (EFM) were intentionally simplified and played an illustrative role. They transform the selected hydrological and socio-economic dynamics into measurable terms and provide a direct interface between four layers of the framework and operational data. Although these indicators do not replace established engineering measures or complete hydraulic simulations, they provide the starting point for future quantitative work that can be further calibrated, validated and integrated into more advanced models of waterway performance and corridor resistance.

6.1. Critical Navigability Index (CNI)

The first analytical indicator is the Critical Navigability Index (CNI), which links the available water depth on a navigable section to the draft of a given vessel class. CNI expresses the share of the depth profile that remains as under-keel clearance and thus indicates how close navigation is to critical conditions for that vessel. The indicator is defined as:

$$CNI = \frac{H_{min} - D_{schip}}{H_{min}} \quad (1)$$

where all variables are defined in Table 2 (Nomenclature and interpretation of indicators). CNI is a dimensionless ratio in the interval [0, 1]. Values close to 1 correspond to generous under-keel clearance and comfortable navigability margins for the considered vessel class, while values approaching 0 indicate near-critical conditions in which small hydrological changes can significantly affect safe passage. In the context of MLCM, CNI provides a compact way of linking hydrological variability (changes in H_{min}) to infrastructural constraints (vessel characteristics) within the natural-hydrological and built-infrastructural layers. It does not aim to capture dynamic effects such as squat, unsteady water-level variations, or detailed vessel–channel interaction, which are normally addressed through more advanced hydraulic models.

6.2. Elasticity of Freight Migration (EFM)

The second analytical indicator is the Elasticity of Freight Migration (EFM), which connects socio-economic migration processes to disruption events affecting the corridor. EFM measures how strongly freight volumes respond to routing or geopolitical shocks. It is defined as:

$$EFM = \frac{\Delta Q}{\Delta R} \quad (2)$$

where ΔQ represents the change in freight volume handled by the corridor (in tonnes) and ΔR denotes the magnitude of the disruption, expressed as a dimensionless disruption index (see Table 2 also). EFM is a dimensionless elasticity. Values greater than 1 indicate that freight volumes react strongly to disruptions (high sensitivity and rapid rerouting), while values below 1 suggest that the corridor can absorb shocks with relatively limited changes in cargo flows. Within MLCM, EFM is used as a conceptual bridge between the socio-economic and logistics layer and the broader disturbance environment (e.g. conflict, regulatory change, modal access restrictions). In applied studies, ΔR can be constructed as a composite index that aggregates indicators such as duration of port closures, extent of restricted maritime capacity, and severity of regulatory constraints.

6.3. Nomenclature and interpretation of indicators

The variables used in the CNI and EFM indicators are summarised in Table 1.

Table 1. Nomenclature for CNI and EFM

Symbol	*Unit*	*Meaning*
$\boldsymbol{H_{min}}$	m	Minimum available water depth on the navigable section.
$\boldsymbol{D_{schip}}$	m	Vessel draft.
$\boldsymbol{C}$	m	Under-keel margin ($C = H_{min} - D_{schip}$).
$\boldsymbol{CNI}$	–	Critical Navigability Index (relative clearance).
$\Delta\boldsymbol{Q}$	t	Change in freight volume on the corridor.
$\Delta\boldsymbol{R}$	–	Routing or geopolitical disruption index.
$\boldsymbol{EFM}$	–	Elasticity of Freight Migration.

For CNI, values close to 1 indicate generous safety margins, while values close to 0 signal near-critical navigability for the considered vessel class. This indicator thus provides an intuitive proxy for resilience under hydrological stress and helps identify sections where even modest drops in water level may lead to significant operational constraints. For EFM, values greater than 1 reflect corridors in which cargo flows are highly elastic with respect to disruptions (for example, during the 2022–2023 Black Sea disruptions, when freight rapidly migrated towards the Danube-Black Sea route), whereas values below 1 correspond to more inelastic behaviour, where institutional and infrastructural factors maintain flows despite shocks. In this paper, EFM is treated as an illustrative conceptual indicator that invites future empirical estimation using long-term traffic and disruption data.

6.4. Role and limitations within MLCM

Both CNI and EFM are deliberately simple and are presented as illustrative MLCM indicators. Their purpose is to show how hydrological and socio-economic migration can be expressed in quantitative terms and linked back to the four layers of the framework. In practical engineering applications, these indicators should be combined with established metrics such as detailed under-keel clearance calculations, hydrodynamic simulations, traffic models and econometric analyses of freight flows. Future work can refine, calibrate and validate the two indicators using longitudinal data, thereby strengthening the quantitative backbone of MLCM-based assessments. Figure 4 presents the established engineering metrics and the two illustrative indicators (CNI and EFM) used in this paper, grouped under the four MLCM layers. The indicators summarized in Figure 4 are derived from publicly available operational and policy datasets, including national inland waterway statistics, European Commission transport and energy benchmarks[1], ICPDR hydrological reports, ICCT and EEA emission databases, and port-level sustainability disclosures[2]. The figure synthesizes these heterogeneous sources for comparative and illustrative purposes within the MLCM framework; detailed source references are provided in the main text and bibliography. The insights from the application analysis show both the potential for transformation and the operational limits of canals in the current regional context. These findings support the strategic recommendations that follow. Future applications of MLCM should include calibration and sensitivity analysis of CNI and EFM against long-term hydrological and traffic records, as well as their integration with established hydraulic and econometric models of inland waterway performance. Figure 4 links the illustrative indicators CNI and EFM with established engineering metrics, clarifying how these simplified measures can be positioned within broader assessment practices.

[1] https://medblueconomyplatform.org/wp-content/uploads/2025/05/the-eu-blue-economy-report-2025.pdf
[2] https://transport.ec.europa.eu/transport-modes/inland-waterways_en

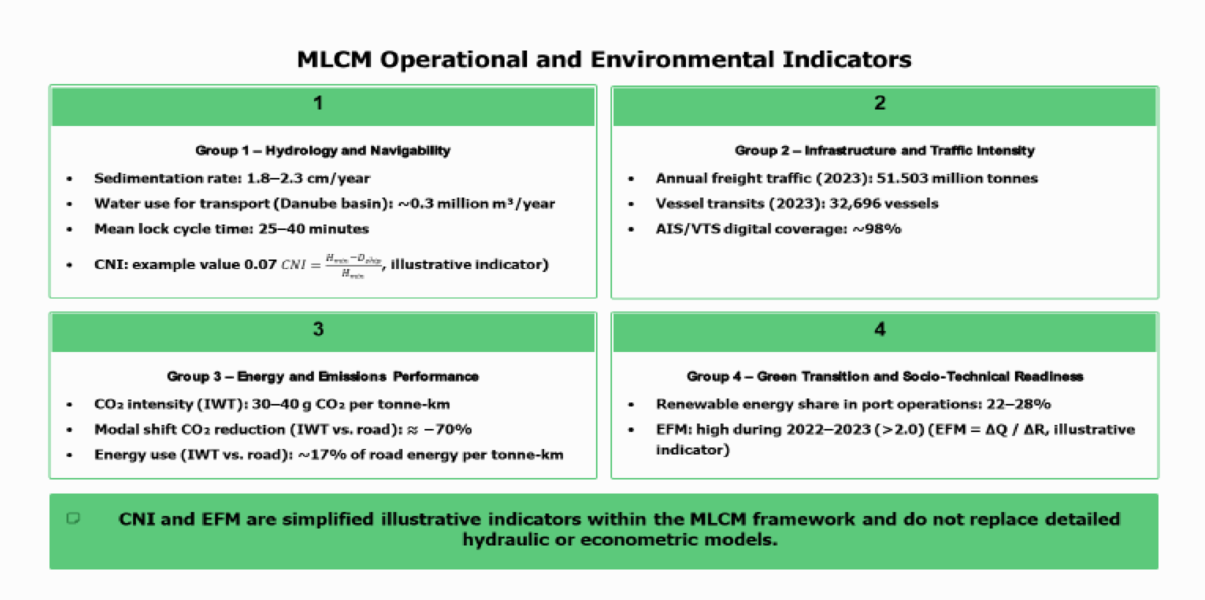

Figure 4. Illustrative Analytical MLCM Indicators (author's own research)

7. IMPLEMENTATION CHALLENGES AND PHASED USE OF THE MLCM FRAMEWORK

The MLCM provides a structured approach to thinking about resilient logistics corridors, but applying it in practice is neither instantaneous nor straightforward. Different types of obstacles appear at different moments, and they depend heavily on how institutions, data systems and investments are organised along the corridor [22]. In the short run, roughly the first one to three years, the main difficulties are practical and organisational. Existing data on traffic, hydrology, infrastructure condition and environmental performance are usually collected by separate authorities and stored in incompatible formats. The issue is less the absence of data, and more the fact that they are fragmented and hard to combine. A realistic first step is therefore not to build a completely new system, but to link what already exists: basic data sharing agreements, common templates for key indicators and gradual interconnection of current monitoring platforms. Over a medium term horizon of about three to seven years, other constraints start to dominate. In many sections of the corridor, infrastructure is already ageing, staff must acquire digital and environmental competencies, and investment resources compete with other policy demands. Developing a smart, low‑carbon corridor therefore requires targeted spending on upgraded traffic management and safety systems, more efficient low‑emission vessels, and structured training programmes for technical and operational personnel. European funding instruments, public–private partnerships and corridor‑level governance platforms can help align and coordinate such investments. Over time, these implementation issues become more structural, as climate change increases hydrological uncertainty and technological cycles shorten, making premature obsolescence a tangible risk. If some regions attract more capital than others, development along the corridor can continue to be uneven. Under these conditions, MLCM is most useful as a tool for strategic reflection: it helps authorities and operators build scenarios, test assumptions and adjust policies rather than optimise a single fixed plan. Long-term use of the framework relies on continuous monitoring, periodic revision of indicators and active exchange of lessons with other corridors that face similar pressures. Seen in this phased perspective, MLCM is less a one-off project and more a living framework. Its value grows as data becomes more compatible, cooperation between institutions improves, and digital as well as green technologies mature and diffuse along the corridor.

8. CONCLUSIONS

The results obtained through this research show that this canal exerts both ecological pressure and economic value, as reported in several research areas. The lack of sustainability reporting contributes to the sketchy image of the canal. The important role of the Danube-Black Sea Canal in regional logistics is confirmed by this research. It is currently being reassessed as a component of a more complex logistics corridor that promotes sustainable mobility and regional connections. Ecological pressure, significant hydrological interventions and effects on nature are important aspects of the research. To sum up, we present potential pathways for this necessary change. While rivers have historically carried cultural and symbolic meanings, this paper addresses mobility analytically through the MLCM, translating such layered dynamics into a framework suitable for logistics and policy analysis. Within this context, MLCM offers a structured lens for prioritising interventions across layers, from hydrological monitoring and infrastructure renewal to digital control systems and workforce training, supporting a phased transition towards a more resilient Danube–Black Sea logistics corridor.

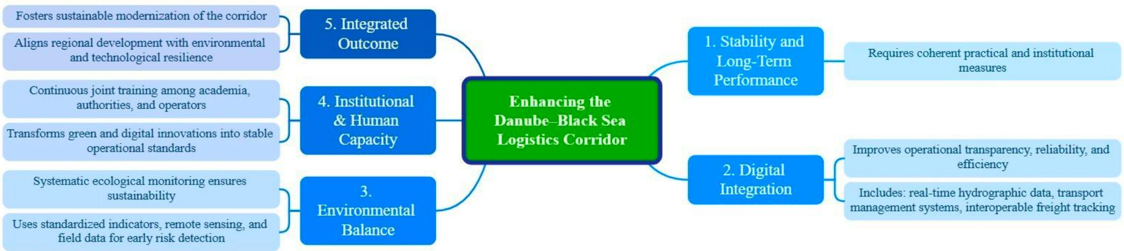

Figure 5: Pathways to Change

8. DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES

During the preparation of this work, the authors used Consensus and Writefull in order to support literature searching and assist with language accuracy. After using this tool/service, the authors reviewed and edited the content as necessary and took full responsibility for the content of the publication.

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