Backlog Traps, Congestion and Sustainable Transition in Port Systems: A System Dynamics Approach

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Abstract. Ports are simultaneously experiencing rising cargo flows, system congestion, and more stringent environmental standards. This article proposes examining the transition to sustainable ports from a system dynamics perspective, using the Backlog Traps model to demonstrate why operators' and ports' frequency hinder the circular economy and investments in decarbonization initiatives, despite their long-term benefits. The task backlog is the outcome of compounded operational and environmental demands, such as delays, Carbon emissions, congestion, and waste, that diminish the resources at hand for long-term improvements. In transport hubs such as seaports and dry ports, backlog traps degrade transport efficiency and generate congestion, which, in turn, has important side effects, including longer transit times and increased CO2 emissions, thereby indirectly worsening environmental quality. In the context of this framework, the aim is to improve efficiency optimization as a key mechanism for reducing emissions and environmental impacts in congested contexts. Circular economy solutions are considered to the extent that they contribute to reducing the carbon footprint of port and hinterland operations.

Keywords: Backlog Traps · Congestion and the Sustainable transition · A system dynamics approach

1 Introduction

In recent decades, Port Systems (PS) have evolved into complex socio-technical systems integral to global logistics and supply chain networks. This transformation is primarily attributed to rising cargo volumes, expanded hinterland connectivity, and the increasing integration of maritime transport within global production systems. Concurrently, ports face mounting pressure to comply with stringent environmental regulations and support broader sustainability and circular economy goals [1].

Although the necessity for sustainable port systems is widely acknowledged, implementation remains inconsistent and frequently delayed. Conventional explanations focus on financial, technological, and regulatory challenges. However, these factors do not

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fully account for the internal dynamics influencing decision-making processes within port systems.

During their day-to-day operations port authorities and port operators often face pressures due to congestion, delays and capacity constraints. Consequently, short-term solutions relegating long-term strategic investments and resources are derived from structural improvements, hindering sustainable transformation.

This paper suggests that such dynamics can be better understood within the framework of the backlog traps model, grounded in System Dynamics theory [2, 3], as it enables the analysis of feedback loops, time delays and non-linear interactions present in complex systems. It also offers a framework for understanding how operational pressures, investment behavior and system performance evolve together over time.

The Theoretical Framework introduces System Dynamics and clarifies why feedback structures and temporal delays are fundamental for interpreting port congestion. The Methodology formalizes the Backlog Traps model and incorporates multi-actor port behavior into the backlog capacity interaction. The Causal Loop Analysis and Case Study examine the reinforcing and balancing mechanisms at play, with the Trieste case demonstrating how operational and governance constraints perpetuate congestion. The Discussion unpacks these dynamics and draws attention the systemic conditions that allow backlog traps to persist. The Conclusion then reflects on how more coordinated governance, timely investment, and efficiency-oriented interventions can help steer port systems toward more sustainable trajectory.

2 Theoretical Framework

System Dynamics methodology developed in the mid-1950s at the Massachusetts Institute of Technology (MIT) by Jay W. Forrester [4], is the methodology that enables understanding and modelling the behavior of complex systems, such as ports, logistic networks and environmental transition. It offers an approach to describe the structural features of feedback loops, delays, congestion and nonlinear relationship that are typical of real-world systems. Forester's essential works Industrial Dynamics [4], Urban Dynamics [5] and World Dynamics [6], revealed that complex systems operate paradoxically and that intervention in them without considering the structures of feedback often produces unforeseen outcomes. The methodology found international application in the publication of the book "The Limits to Growth" (Club of Rome) by co-authors Donella Meadows, Dennis Meadows, Jørgen Randers and William Behrens [7], using the World3 model. The study showed how population, industrial production, resource use and pollution interact with each other through reinforcing and balancing feedback loops. Later works Limits to Growth: The 30-Year Update [8] and Randers' 2052: A Global Forecast for the Next Forty Years [9] reinforced the role of SD in long term sustainability analysis as a tool of studying environmental boundaries, resource dynamics and global transitions.

Later, John Sterman, director of the MIT System Dynamics Group, extended the methodology to the fields of organizational learning, climate policy and operational management, his textbook Business Dynamics [10] is now the global standard for system dynamics modelling. Donella Meadows developed system thinking as practical thinking

and Peter Senge introduced system dynamic into organizational strategy through his book The Fifth Discipline. Barry Richmond made dynamic modelling accessible to a non-technical audience by developing the STELLA/I Think software environment. Russell Ackoff, though working more broadly in systems science, contributed essential insights on holistic problem solving and the management of "messes" complex, interconnected challenges that cannot be decomposed into isolated parts.

2.1 System Dynamics in Transport, Logistics and Sustainability

SD has also been widely applied in transport, logistics, port operations and environmental sustainability. For the formation of congestion, infrastructural bottlenecks, investment delays, for the analysis of traffic formation, infrastructural bottlenecks, investment delays, modal shifts, environmental impact phenomena, which are characteristic of the problems of the backlog traps and sustainability challenges faced by ports and inland terminals.

H. David Ford, Khalid Saeed, and Yaman Barlas were among the first to apply SD to infrastructure investment and congestion dynamics. Ford's work on project management and capacity expansion [11] highlighted how delays in investment decisions can create reinforcing loops of congestion. Saeed's research on policy resistance [12] demonstrated that well-intentioned interventions often fail when underlying feedback structures are ignored. Barlas contributed methodological advances in model validation and sensitivity analysis [13], providing tools to rigorously test dynamic hypotheses an essential step when modelling port capacity and backlog accumulation.

Navid Ghaffarzadegan and Hazhir Rahmandad expanded SD into the study of capacity constraints, resource allocation, and delay driven instabilities. Their work on workforce bottlenecks, service delays and dynamic resource misallocation offers direct parallels to port operations, where limited birth capacity, crane availability, and hinterland connection can trigger cascading congestion [14, 15].

Lars-Göran Mattsson and Jonas Eliasson applied Sd principles to transportation system, focusing on model shifts, congestion feedback and long-term infrastructure planning. Their work demonstrated that transport networks behave as tightly coupled systems where congestion in one node propagates through the entire network an insight critical for multimodal port hubs [16].

Ruth Madlener and Reinhard Madlener contributed significantly to SD applications in energy transitions and environmental policy. Their models of emission dynamics, technology adaption and policy feedback provide a conceptual foundation analyzing environmental footprint of port operation [17, 18].

Giuliano, O'Kelly and Rodrigue although not always explicitly using SD produced influential research on port logistics, hinterland capacity and terminal capacity that align closely with SD concepts. Their findings support the SD prospective that ports must be understood as nodes embedded in broader logistical and spatial systems with feedback driven behavior [19–21].

Bichou and Gray advanced systems thinking in port performance, resilience and supply chain integration. Their work shows that port performance emerges from the interaction of multiple subsystems terminal operations, hinterland logistics, regulatory frameworks and market dynamics [22, 23].

The research of Acciaro, Gritsenko and Parola dedicated to the study of sustainability, environmental management and strategic transition in ports, emphasizes that sustainability in ports is determined by delayed investments, through regulatory responses, technological expansion cycles and behavioral responses [24–26]. These characteristics make SD particularly suitable for the structural peculiarities of ports, where such dynamics are ubiquitous:

- Backlog traps and reinforcing congestion loops,
- Delays in capacity expansion and investment responsiveness,
- Nonlinear relationships between throughput, emissions and operational efficiency,
- Policy feedback shaping long-term sustainability trajectories,
- Interdependencies between port operations, hinterland logistics and environmental outcomes.

For these reasons, SD provides a robust methodological foundation for analyzing backlog traps and designing policies that support a sustainable transition in port systems. Nonetheless, an element to be considered is the multi-layered, multi-scalar nature of ports. On one side in fact ports operate as interfaces among long-range networks, therefore as nodes in a regional or global set of connections; on the other side, ports host a set of complex activities within different and specialized terminals.

The nature of ports makes them interface between sea and land, therefore implying a set of interactions on the seaside with the maritime routes, and with the land connections. Very often they are inserted or close to urban areas, igniting process of interaction and possibly friction with the urban fabric. Port operations and activities can be therefore related to sea-side operations and external operations in land connections. Different agents are therefore involved in such a framework. This multi-institutional environment includes public port authorities, who act as cluster managers regulating infrastructure, and private terminal operators focused on maximizing operational efficiency. Effectiveness is further shaped by the heterogeneous expectations of users, including shipping lines, cargo owners, and 3PL/4PL providers. Moreover, the essential role of dock labor and the integration of inland transport providers create a performance continuum spanning maritime, terminal, and hinterland domains [27, 28].

More specifically, delving into the in-port operations, different sets of agents and activities can be highlighted: the agents and subjects directly and specifically involved in terminal activities can be categorized into management and ownership entities, the operational workforce, logistics intermediaries, and technical service providers. These actors operate within the maritime-land interface, facilitating the transfer of cargo and passengers.

Management and Ownership Entities include Port Authorities, as the primary owners and operators, most of them organized under the landlord model, acting as “cluster managers”, regulating infrastructure, managing maritime access (like dredging and navigation aids), and overseeing the relationships with terminal customers.

Terminal Operators (Port Holdings): These are often private entities that lease terminal facilities through concession agreements. They are responsible for day-to-day operations, investing in superstructure (such as cranes and yard equipment), and managing the specific cargo type the terminal is designed for (e.g., containers, liquid bulk, or dry bulk).

The Operational Workforce (Dock Labor). These are dockworkers - a fundamental production factor for terminal performance including specialized Operatives, as crane operators (or winchmen), straddle carrier/forklift drivers, and signalmen (hatch tenders) who supervise cargo movement, Lashers and Tallymen: securing and releasing cargo on ships, while tallymen (checkers) keep records of the weight and quantity of goods and check for damage. Are included supervisory Staff, foremen and supervisors managing specific groups of workers, typically assigned to one ship's hatch or shoreside crane. Technical Support: Mechanics and electricians responsible for maintaining terminal equipment. Administrative and White-Collar Staff are involved in management, information technology (IT), marketing, and legal matters.

Terminal Users and Decision-Makers include Shipping Lines (Carriers), as the primary buyers of terminal services, providing the vessels that require berthing and cargo handling. Some lines are vertically integrated, operating their own terminals (e.g., MSc). Part of this set are Cargo Owners (Shippers): Including manufacturers, retailers, and exporters/importers who determine the flow of goods. Their satisfaction is a key measure of terminal effectiveness. These are integrated by 3PL (Third Party) and 4PL (Fourth Party) Providers acting as supply chain integrators, often managing the outsourcing of transportation, warehousing, and distribution on behalf of shippers.

Technical and Intermediary Support Agents involve Nautical Service Providers, as pilots and tug operators who ensure the safe navigation of ships through access channels and into berthing basins; Intermediary Agents, as Freight forwarders and ship agents handle the booking, consolidation (like Less than Container Load cargo), and tracking of shipments; Regulatory Agents: Customs officials conduct inspections and process documentation, directly impacting "mean-time customs clearance" and terminal fluidity.

Inland Integration Agents are the fundamental agents allowing the port-region/global land connectivity, by means of Trucking Companies and Rail Operators: These subjects are vital for the hinterland operations of the terminal, providing the land-based connection to markets. Efficient interaction between terminal gate systems and these operators is critical to avoiding bottlenecks.

Research on port economics points out the ongoing tension between operational efficiency, expanding capacity and long-term strategic growth. Challenges in planning and forecasting also affect the efficiency with which port systems develop [29]. The Backlog Traps concept shows that when operational and environmental pressures build up without being addressed, it becomes harder for a system to invest in long-term improvements.

3 Methodology

The backlog traps model introduced here offers a dynamic representation of how operational pressures, investment behavior and environmental constraints interact over time to influence port performance. At the core of the methodology is a System Dynamics model structured around interacting stocks, flows and feedback loops. Two state variables backlog and capacity capture the evolution of port performance. Backlog represents the accumulation of operational and environmental pressures within the system, while capacity reflects the system's ability to process these pressures. Their interaction is formalized through a set of differential equations.

Backlog B (t) evolves according to the difference between operational pressure and system capacity:

$$\frac{dB(t)}{dt} = P(t) - C(t)$$

Where P (t) denotes demand driven operational pressure and C (t) represents the system's effective capacity. When capacity exceeds pressure, backlog decline, when operational pressure exceeds capacity, backlog grows. This formulation captures the fundamental dynamic underlying congestion formation.

Capacity C (t) evolves as a function of investment and congestion effects:

$$\frac{dC(t)}{dt} = \alpha I(t) - \beta B(t)$$

Here, α indicates the effectiveness of investment in increasing capacity, whereas β captures the negative impact of congestion on system performance. This equation embodies a duality in the evolution of capacity: investment expands capacity, while congestion erodes it.

Investment behavior is modelled as a decreasing function of backlog:

$$I(t) = I_{\max} - \gamma B(t)$$

This behavioral rule reflects decisionmaker's tendency to prioritize immediate operational needs during in heigh - pressure situations. As backlog of deferred tasks grows, attention and resources shift toward short-term firefighting, reducing the capacity to invest in long-term improvements. This mechanism is central to the formation of backlog traps.

Capacity refers not only to physical infrastructure but also to effective capacity. The latter is formed through coordination, planning and digitalization and enables capacity to be increased without the need for a proportional physical expansion and is particularly important for ports with spatial or regulatory constraints [1].

The model also incorporates the multi-actor nature of port systems. Ports operate as socio-technical environments where performance emerges from the interaction of diverse agents. Port authorities steer long term development by shaping strategic planning, infrastructure expansion and regulatory oversight, thereby influencing the direction and the timing of major investments decisions. Terminal operators oversee day-to-day cargo handling, equipment deployment and workforce scheduling, directly affecting operational efficiency and congestion levels. Hinterland operators particularly rail carriers in the case of Trieste determine the speed and reliability of inland flows, with rail bottlenecks often becoming critical constraints. Shipping lines influence peak demand through vessel scheduling and service frequency, while customs and regulatory agencies affect clearance times and administrative delays. Logistics providers and freight forewords further shape demand patterns and routing decisions. These mechanisms jointly shape how backlog accumulates, how capacity is utilized and how responsive the system is to new investments, making a dynamic modelling approach particularly suitable for capturing the complexity of port systems.

To contextualize the model, it is essential to outline the operational structure of a standard container terminal. Terminal operations unfold through a sequence of independent processes, beginning with vessel arrival and berthing, followed by quay crane operations, yard storage and handling, and finally gate or rail dispatch. Each stage introduces potential bottlenecks at the berth, within yard operations, in rail dispatching, and across administrative procedures. These constraints interact along the entire operational chain, and their system-wide implications are formalized in Section 4 through the reinforcing congestion loop.

Beyond rail-related constraints, hinterland congestion is also shaped by truck arrival patterns and parking availability. Evidence from agent-based modelling shows that inadequate truck parking facilities and uncoordinated gate arrivals can amplify queuing, increase dwell times, and propagate congestion across the terminal–hinterland interface. Such findings, including those demonstrated in the study "Reducing congestion in port hinterlands: an agent-based modelling case study of truck parking facility impacts," highlight how small-scale behavioral frictions can escalate into system-wide backlog accumulation. Integrating these dynamics into the Backlog Traps framework underscores the importance of accounting for both modal diversity and behavioral variation when analyzing port performance.

Taken together, the methodology offers a dynamic and behaviorally informed lens of examining how operational pressures, investment decisions and environmental constraints interact to shape system outcomes. By capturing these interdependences, the Backlog Traps model provides a novel perspective for understanding the persistent challenges of congestion and delayed sustainability transition in port systems.

4 Causal Loop Analysis

This section develops the causal logic underlying backlog formation and congestion dynamics in port systems. Building on system dynamics theory, the analysis focuses on how reinforcing and balancing mechanisms interact to shape operational performance. Two causal loop diagrams (CLDs) are presented to illustrate the general backlog trap and its specific manifestation in the Port of Trieste.

Figure 1 illustrates the basic feedback structure governing congestion dynamics in port systems. The diagram illustrates one reinforcing loop (R1) and two balancing loops (B1 and B2) which together shape the dynamic evolution of backlog and capacity over time. The reinforcing loop R1 captures the self-sustaining congestion mechanism: as backlogs increases, congestion intencifies, reducing transport efficiency and slowing processing rates, which in turn further amplifies backlog growth. This dynamic reflects the endogenous nature of congestion formation, in which operational delays and resource constraints reinforce one other through a positive feedback loop.

The balancing loop B1 depicts the investment-driven response. Growing demand puts pressure on capacity expansion, encouraging investments that increase physical or infrastructural capacity. Increased capacity eases congestion and gradually reduces backlog, creating negative feedback that stabilizes system performance. However, when investment decisions are delayed or insufficient, the balancing effect weakens, and the reinforcing loop to dominates.

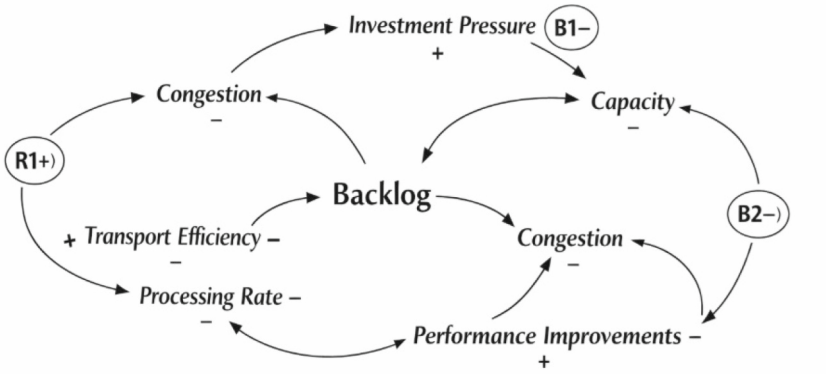

Fig. 1. General Backlog Trap: Reinforcing and Balancing Feedback Loops

The balancing loop B2 represents performance-oriented responses. Operational improvements such as process optimization, digitalization, and coordination raise effective capacity without requiring proportional physical expansion. Enhanced efficiency counteracts backlog growth, forming a second stabilizing mechanism [30, 31].

Together, the three loops describe the dynamic interaction between short-term operational pressures and long-term adaptive responses. The backlog trap arises when the reinforcing loop (R1) operates faster than the balancing loops (B1 and B2), resulting in a persistent congestion and delayed sustainability transition. This structure underscores the importance of timely investments and continuous performance improvements as complementary strategies for achieving resilient and sustainable port operations.

4.1 Trieste Specific Backlog Trap

Figure 2 adapts the general backlog trap to the specific operational and governance context of the Port of Trieste. Trieste's dependence on rail makes it sensitive to disruptions, a dynamic detailed further in Sect. 5 [32].This operational chain reinforces backlog through the same mechanism as R1 in Fig. 1 The same balancing mechanisms (B1/B2) apply, though their effectiveness is constrained by governance complexity.

Figure 2 presents the backlog trap as it manifests in the Port of Trieste, emphasizing the port's structural dependence on rail-based hinterland connectivity and the governance complexities that shape its operational performance.

The diagram extends the general backlog trap by specifying the causal mechanisms through which rail disruptions propagate across terminal operations, generating a self-reinforcing congestion spiral. The reinforcing loop R1 captures this dynamic: rail disruptions increase yard occupancy, which reduces quay crane productivity and prolongs vessel turnaround times. Longer turnaround times contribute to backlog accumulation, which further intensifies congestion and exacerbates rail disruptions. This loop reflects the tightly coupled nature of Trieste's intermodal chain, where disturbances in rail evacuation rapidly translate into system-wide congestion.

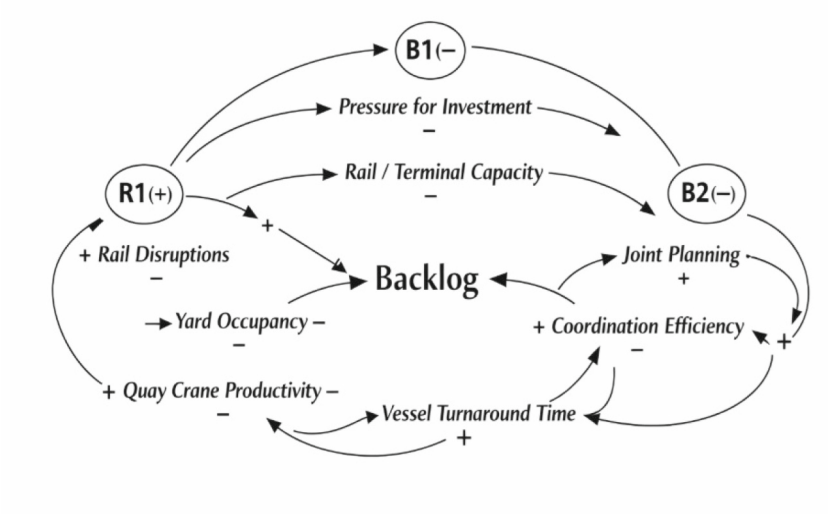

Fig. 2. Trieste-Specific Backlog Trap: Reinforcing and Balancing Feedback Loops

Two balancing mechanisms counteract this reinforcing dynamic. The balancing loop B1 represents investment-driven responses aimed at expanding rail and terminal capacity. As backlog increases, pressure to expend infrastructural improvements intensifies, promoting measures such as additional rail sidings, upgraded intermodal yards, or modernized terminal equipment. Enhancing capacity alleviates yard congestion and mitigates bottlenecks, thereby contributing to reduction of backlog. However, in Trieste, implementation of such investmments is frequently slowed by multilevel governance structures, regulatory requirements, and coordination challenges across national and transitional rail systems. These delays undermine the stabilizing effect of B1, allowing the reinforcing link to dominate during peak pressure periods.

The balancing loop B2 captures coordination-based responses. Growing backlog stimulates joint planning efforts among port authorities, terminal operators, rail carriers, and customs agencies. Improved coordination enhances scheduling efficiency, synchronizes train routes, and reduces administrative delays, thereby increasing operational capacity and curbing backlog growth. This loop highlights the importance of organizational and procedural improvements, which can be deployed more rapidly than physical investments.

Together, the three loops illustrate how Trieste's congestion dynamics emerge from the interaction of operational dependencies, infrastructural constraints, and governance structures. Under rail disruption conditions, the dominance of the reinforcing loop R1 explains the port's vulnerability to systemic congestion, while the delayed or partial activation of balancing loops B1 and B2 explains the persistence of backlog traps. This structure highlights the need for integrated investment strategies and strengthened multi-actor coordination to enhance the port's resilience and support sustainable transition.

Figures 1 and 2 establish the causal logic of backlog formation and its specific manifestation in Trieste. However, these diagrams focus primarily on feedback mechanisms.

To fully understand how these loops emerge from the underlying structure of port operations and governance, Sect. 5 introduces Fig. 3, an integrated model that synthesizes operational processes, actor roles, and feedback dynamics into a unified framework.

5 Case Study: Port of Trieste

The Port of Trieste provides an ideal context for applying the causal loop framework developed in Sect. 4. As a rail-oriented gateway on the TEN-T Baltic-Adriatic and Mediterranean Corridors, Trieste's performance is shaped by the interaction of operational constraints, governance structures, and systemic feedback mechanisms. The port of Trieste is the Northern port in the Adriatic Sea; it is the first Italian port for tonnage handled and is located at the border with Slovenia. It is characterized by its role as an international and free port, thanks to a privileged regime inherited from the past belonging to the Austro-Hungarian Empire and supported by an important rail network that allow a high percentage of transit commercial traffic to be travel by train towards inland European destinations. The port is also physically interconnected to the city of Trieste, as well as characterized by geographical constraints as the need to overcome the Karst Plateau to be connected to the national and international rail and road network. To represent these interconnections, Fig. 3 presents an integrated model that combines the operational chain, stakeholder management, and feedback loops, which together determine port efficiency.

Figure 3 presents an extended causal structure that captures the interaction between operational constraints and institutional dynamics in shaping port efficiency. The diagram depicts the systemic feedback underlying congestion in the Port of Trieste, emphasizing how physical bottlenecks and governance delays interact to create self-perpetuating inefficiencies.

At the core of the model lies the reinforcing loop R1, which depicts the escalation of congestion through the relationship between backlog, rail bottlenecks, and terminal throughput. As queues increase, rail congestion worsens, leading to higher yard congestion and reduced productivity for the port cranes. This decline in operational efficiency reduces terminal's throughput, which in turn increases queue volumes. The loop illustrates a classic positive feedback mechanism where congestion perpetuates itself through interdependent operational variables.

Surrounding this central dynamic are three balancing mechanisms. The investment-driven loop B1 captures long-term mitigation through infrastructure expansion. Rising backlog stimulates rail and terminal investments, which after a policy delay reduce congestion and stabilize throughput. The delay mark (//) signifies the temporal lag between decision-making and implementation, a critical feature of Trieste's institutional environment. The efficiency-driven loop B2 represents short-term managerial responses, such as digital scheduling and intermodal synchronization. These operational improvements enhance efficiency and throughput, counteracting the reinforcing congestion cycle. The newly introduced governance coordination loop B3 formalizes the institutional dimension: governance pressure fosters joint planning and implementation efficiency, which ultimately reduces backlog. This loop highlights the role of multi-actor coordination among the Port Authority, terminal operators, customs, and rail companies.

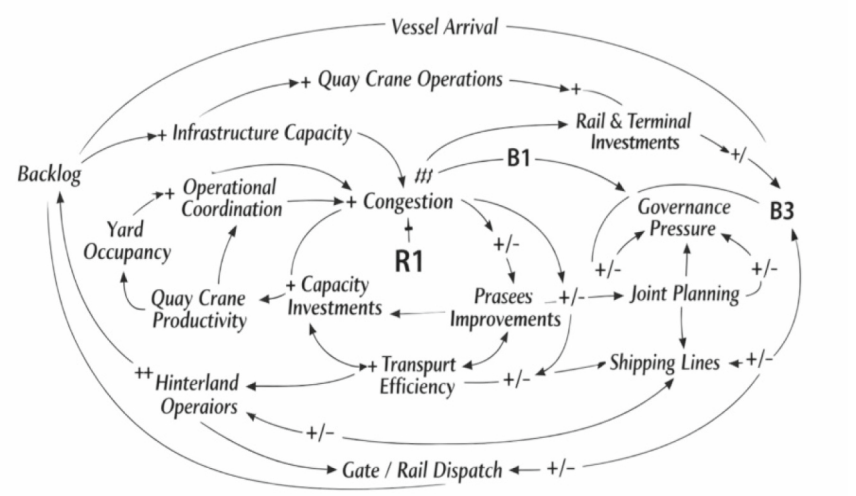

Fig. 3. Trieste-Specific Backlog Trap (Enhanced Version)

Two additional sub-structures enrich the model's realism. The modal-shift sub-loop shows adaptive behavior under rail constraints: when rail bottlenecks intensify, truck utilization rises, temporarily alleviating congestion but potentially increasing external costs such as emissions and urban traffic [33]. The hinterland feedback connects inland dispatch efficiency to effective throughput, emphasizing Trieste's dependence on hinterland evacuation capacity a distinctive characteristic of its rail-oriented logistics system [34].

Overall, the enhanced diagram advances the analytical representation of Trieste's port dynamics by integrating physical, institutional, and temporal dimensions. It distinguishes between short-term operational feedback and long-term management responses, thus offering a comprehensive framework for diagnosing systemic bottlenecks and identifying levers for sustainable improvement.

5.1 Application to the Port of Trieste

Trieste's operational and management characteristics of Trieste correspond directly to the structure presented in Fig. 3. The port's heavy reliance on rail transport means that infrastructure works, any reduction in rail access, due to a lack of rail wagons or border delays, immediately affect yard occupancy and the productivity of the port cranes. These operational dependencies correspond to the R1 reinforcing loop, where reduced outbound capacity increases congestion and delays.

Although Trieste is predominantly rail-oriented, truck-based hinterland flows also contribute to congestion dynamics. Agent-based modelling research on truck parking facilities demonstrates that parking shortages, queue spillovers, and unregulated arrival patterns can significantly increase gate congestion and extend dwell times. While these

dynamics are less dominant in Trieste compared to rail bottlenecks, they represent complementary mechanisms that can reinforce the same backlog formation processes captured in the R1 loop. Incorporating such multimodal interactions provides a more comprehensive understanding of how hinterland constraints shape terminal performance (Fig. 4) [35].

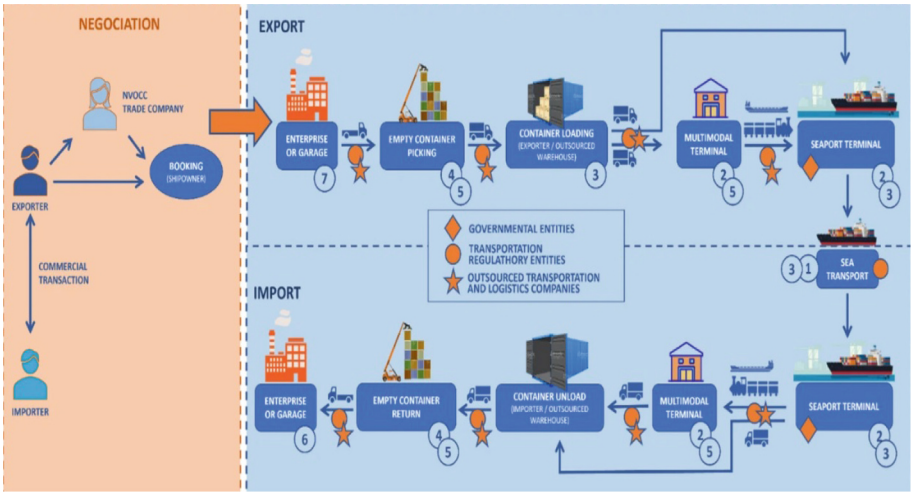

Fig. 4. Agent-based modelling of truck parking facility impacts on hinterland congestion (adapted from Reducing congestion in port hinterlands: an agent-based modelling case study of truck parking facility impacts)

The governance layer is equally significant. The port authority's strategic focus on rail development, the terminal operator's decisions on resource allocation, the scheduling practices of shipping lines, and the regulatory role of customs jointly shape the port's ability to manage peak demand. These interactions of stakeholders underpin the B1 and B2 balancing loops, where investment and efficiency improvements can alleviate congestion, but often face delays or coordination difficulties.

Considering the Trieste case within the integrated framework of Fig. 3, this section demonstrates how systemic congestion arises from the interaction of operational constraints, governance structures, and behavioral responses. The model provides a systematic framework for interpreting Trieste's performance challenges and identifying leverage points for improving resilience and efficiency.

6 Discussion

The results of this study emphasize the importance of interpreting port congestion and sustainability challenges from a systematic rather than exclusively operational perspective. Whereas traditional analysis often attributes congestion to a lack of infrastructure or to an increase in demand, the backlog trap approach shows that bottlenecks are fundamentally shaped by behavioral responses, institutional arrangements, and delayed

investments decisions. When operational pressures intensify, decision-makers prefer short-term firefighting measures over long-term capacity development, which further reinforces the condition, which leads to a buildup of deferred orders.

In the port of Trieste, this dynamic is particularly acute, as rail movements bear the main burden of cargo outbound traffic. When infrastructure works, rolling stock constraints or gaps in border coordination led to rail disruptions, their impact quickly spreads through the terminal, causing storage areas to become overloaded and reducing crane productivity. This process aligns perfectly with the R1 reinforcing loop logic, which shows how local disruptions turn into systematic congestion.

At the same time, insights from agent-based modelling studies on truck parking facilities underscore the need to consider multimodal and micro-behavioral factors. Even in rail-oriented ports such as Trieste, truck-based hinterland flows can introduce additional frictions that interact with existing bottlenecks. A shortage of parking, unregulated arrival patterns, and queue spillovers can significantly increase gate congestion and prolong dwell times, reinforcing the same delay-generation mechanisms reflected in the SD model. Including these multimodal interactions enables a more comprehensive understanding of how internal regional constraints within the shape terminal operations.

A deeper study of each specific port will require a richer empirical foundation, particularly through interviews with key actors across the operations and management chain. Such qualitative inquiry is essential for uncovering the internal and external components of congestion costs that remain hidden in aggregate indicators. Port efficiency is shaped by geographical constraints, terminal specialization, and governance models, which can generate competitive tensions even within the same port under otherwise similar conditions. These structural and institutional features raise an important question for future research: how should investment responsibilities be distributed among the different stakeholders, and in what proportion, to overcome inefficiencies and reduce the formation of accumulation? Addressing this question requires not only technical modelling but also an understanding of stakeholder incentives, power imbalances, and the economic logic guiding investment decisions within complex port ecosystems.

Taken together, the integration of System Dynamics and agent-based modelling perspectives offers a promising direction for future research. SD captures the macro-level feedback structures that drive long-term system behavior, while ABM provides granular insights into how individual actors collectively shape congestion patterns. Combining these approaches can support the design of more effective policies-such as coordinated gate appointment systems, dynamic truck parking allocation, or adaptive rail scheduling that address both structural and behavioral sources of inefficiency.

7 Conclusions

The paper presents the first results on reflections on the application of a System Dynamic Approach to ports to tackle backlog Traps, Congestion and Sustainable Transition in ports. To do that, a model is developed to analyze where and in which terms the backlog traps form.

The analysis reveals that congestion does not stem solely from a lack of physical capacity, but it arises as a systemic consequence of investments, short-term operational

priorities and coordination gap among stakeholders. These observations highlight that there is no simple technocratic or infrastructural fix for sustainable transition of ports. It is necessary to address the behavioral and governance dynamics that contribute to the increase in accumulated backlog. At the same time, a conceptual representation of the backlog trap in the port of Trieste has been presented.

The case of the Port of Trieste illustrates how structural dependencies particularly its reliance on rail-based hinterland evacuation can amplify vulnerability to disruptions. Even when rail is the dominant hinterland mode, complementary mechanisms such as truck-based flows and gate-side frictions can reinforce the same congestion loops.

Agent-based modelling studies clearly show that micro-level behavioral dynamics can accumulate and lead to a decline in system-wide efficiency. When these multi-modal observations are incorporated into the cumulative cargo burden framework, a more comprehensive picture emerges of how congestion gradually propagates from the port to inland areas and creates cascading bottlenecks.

The study suggests that further research is required to identify how congestion costs and the investments commitments are being apportioned among various stakeholders of the port. To develop effective governance and financing solutions, it is important to identify who benefits from efficiency, who bears the costs of delays and who has the resources and motivation to invest. This knowledge is fundamental to overcoming structural barriers limiting operational efficiency and decarbonization efforts.

To summarize, the results moved away from a reactive management logic and show that sustainable port performance must be addressed through systematic specialization in coordination structures including both operational integrations, on one hand being developed further into what new investment strategies should look like across stakeholder systems. Ports that fail to address backlog traps risk being locked into self-reinforcing cycle of congestion, efficiency and decarbonization delay, which significantly threatens their long-term competitiveness and environmental commitments.

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Authors' Contribution Conceptualization, materials and resources all authors. Methodology, model adjustment and theoretical perspective Giuseppe Borruso.

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