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A Dynamic Business Modeling Approach to Port Sustainability: The Western Sicily Port Authority Case

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ABSTRACT

Ports are critical nodes in global trade and economic development, yet they generate substantial environmental and social externalities—including greenhouse gas emissions, air, noise, and water pollution, and adverse impacts on host communities—that demand integrated and forward-looking governance. Despite growing policy attention and the diffusion of green technologies, the systematic integration of sustainability into port strategic planning, governance, and performance management remains limited and fragmented. Existing tools—environmental indicator dashboards, Balanced Scorecard adaptations, and stand-alone System Dynamics applications—capture either the multidimensional nature of sustainability or its temporal dynamics, but rarely both within a coherent business-model architecture. This study addresses that gap by adopting and adapting the Dynamic Business Model for Sustainability (DBMfS) to the port context. The framework combines a sustainability-oriented Business Model Canvas with System Dynamics to map causal relationships among strategic resources, processes, performance drivers, outputs, and Triple Bottom Line outcomes. The framework is illustrated through an in-depth case study of the Western Sicily Port Authority. The analysis shows how the DBMfS can support port managers in revealing interdependencies, anticipating feedback effects, monitoring performance through hierarchically organized key performance indicators (KPIs), and aligning strategies with the United Nations Sustainable Development Goals.

1 | Introduction

Ports are crucial nodes in international trade and economic development. Handling more than 80% of global trade by volume (UNCTAD 2022), they facilitate international commerce, generate employment opportunities, and support industrial and logistics activities, contributing substantially to national and regional prosperity (Del Giudice et al. 2021; Gavalas 2024; UNCTAD 2024). At the same time, port operations generate significant environmental and social externalities—including greenhouse gas (GHG) emissions, air, noise, and water pollution, and health-related concerns for nearby communities—that require careful and proactive management (Acciaro 2015; Benamara et al. 2019; Ducruet et al. 2024; Langenus and Dooms 2018; Lee et al. 2019; Notteboom et al. 2022).

Growing global awareness of these externalities has positioned sustainability as a strategic priority for the maritime sector (Acciaro 2015; Roh et al. 2016), in line with the 17 Sustainable Development Goals (SDGs) introduced in 2015 by the United Nations to balance economic growth with environmental protection and social well-being (United Nations General Assembly 2015). By aligning their strategies with the SDGs, ports can become key actors in promoting sustainable development (Caliskan 2022; Di Vaio et al. 2021; Gu et al. 2023; International Association of Ports and Harbors 2020).

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In response to these challenges, the international and European regulatory framework has progressively tightened environmental requirements for maritime transport and port operations. At the global level, the IMO's 2023 GHG Strategy advances maritime decarbonization by setting a net-zero ambition by or around 2050, complemented by interim milestones for 2030 and 2040 that establish specific targets for emissions intensity reductions, the adoption of zero and near-zero emission fuels and technologies, and cuts in total GHG emissions (Glavinović et al. 2023; IMO 2023a, 2023b). At the EU level, FuelEU Maritime and AFIR accelerate the transition toward cleaner shipping by tightening limits on ships' fuel GHG intensity and promoting the deployment of shore-side electricity (OPS) and other zero-emission solutions at berth (European Commission 2023; European Parliament and Council 2023a, 2023b).

Alongside these regulatory developments, growing attention has been devoted to managerial practices and technological innovations aimed at mitigating port environmental impacts: energy efficiency programs, waste management strategies, emissions reduction measures, dock electrification through cold ironing, and the integration of renewable energy sources such as solar and wind (Ashrafi et al. 2019; Bjerkan and Seter 2019; Enelx and Legambiente 2021; Notteboom et al. 2022; Othman et al. 2022). Digitalization and automation further enhance decision-making, operational efficiency, and safety, and recent evidence shows that digital initiatives in ports can effectively contribute to multiple SDGs simultaneously (Almeida and Okon 2024). In this context, ports have progressively evolved from traditional cargo-handling sites into integrated multimodal logistics hubs (Notteboom and Haralambides 2020; Notteboom et al. 2022).

Despite this momentum, the systematic integration of sustainability into port performance management, governance, and accountability frameworks remains limited and often fragmented. Although many port authorities have introduced sustainable practices and adopted new technologies in response to regulatory pressures, these initiatives are often implemented *ad hoc* and not fully embedded in long-term strategic planning and control systems (Ashrafi et al. 2019; Gavalas 2024; Shabib et al. 2025). Moreover, a large share of existing studies still prioritizes environmental aspects over the economic and social pillars of sustainability, overlooking the multidimensional nature of port performance (Di Vaio and Varriale 2018; Martins et al. 2024).

Existing managerial tools illustrate complementary but partial responses to this challenge. Environmental indicator dashboards monitor pressures but are weakly tied to strategy and long-term value creation (Styliadis et al. 2022). Balanced Scorecard (BSC) adaptations link KPIs to strategic objectives but typically produce static, snapshot evaluations (Sislian and Jaegler 2018). Stand-alone System Dynamics (SD) applications capture feedback loops and temporal evolution, but tend to focus on specific operational subsystems and are rarely embedded in a coherent business-model architecture (Li et al. 2019; Zhang et al. 2025; Zhong et al. 2023). What is missing is a framework that simultaneously (i) represents the multidimensional and interdependent nature of port sustainability, (ii) captures its temporal and feedback dynamics, and (iii) anchors both within a strategic business-model logic that links resources, processes, KPIs, and Triple Bottom Line outcomes.

To address this gap, this study adopts and adapts the Dynamic Business Model for Sustainability (DBMfS) proposed by Cosenz et al. (2020)—originally developed for private firms—to the port context. The DBMfS combines a sustainability-oriented Business Model Canvas (Bocken 2015; Bocken et al. 2018; Osterwalder and Pigneur 2010) with System Dynamics, integrating the structural representation of value creation and its dynamic, feedback-driven evolution into a single architecture. Adopting a systemic and dynamic perspective can capture and address the inherent complexity of port systems (Abdelkafi and Taeuscher 2016). The framework is illustrated through an in-depth case study of the Western Sicily Port Authority (AdSP MSO).

To achieve this objective, the paper addresses the following research questions:

RQ1. *How can the DBMfS support port authorities in embedding the environmental, social, and economic dimensions of sustainability into strategic planning, governance, and performance management?*

RQ2. *How can an SD-based business modeling approach support decision-making, performance measurement, and evaluation through the use of sustainability-oriented key performance indicators (KPIs)?*

The paper makes three explicit contributions. First, it extends the DBMfS—so far applied to private firms—to public infrastructure organizations governed by hybrid public–private logics, demonstrating its relevance and adaptability for port authorities. Second, it offers an integrative response to the limitations of existing port sustainability tools (indicator dashboards, BSC, stand-alone SD) by combining the multidimensional view of the Triple Bottom Line, the structural logic of the Business Model Canvas, and the temporal logic of SD within a single coherent framework. Third, it derives a hierarchically organized KPI architecture—performance drivers, outputs, and outcomes—that links operational levers to long-term sustainability outcomes and to specific UN SDGs, thereby supporting both forward-looking planning and backward diagnostic analysis of performance gaps.

The remainder of the paper proceeds as follows. Section 2 frames sustainability in the port sector and introduces the Triple Bottom Line as a conceptual framework. Section 3 critically synthesizes the literature on sustainability performance management in port authorities and positions the contribution of the study. Section 4 presents the DBMfS methodology, research design, data sources, and operationalization procedure. Section 5 illustrates the application of the framework through an in-depth case study of the Western Sicily Port Authority. Section 6 discusses theoretical and practical implications and acknowledges limitations. Section 7 offers concluding remarks and identifies avenues for future research.

2 | Framing Sustainability in the Port Sector

The port sector plays a pivotal role in the global economy, enabling international commerce and contributing to job creation, industrial development, and tourism (Gavalas 2024;

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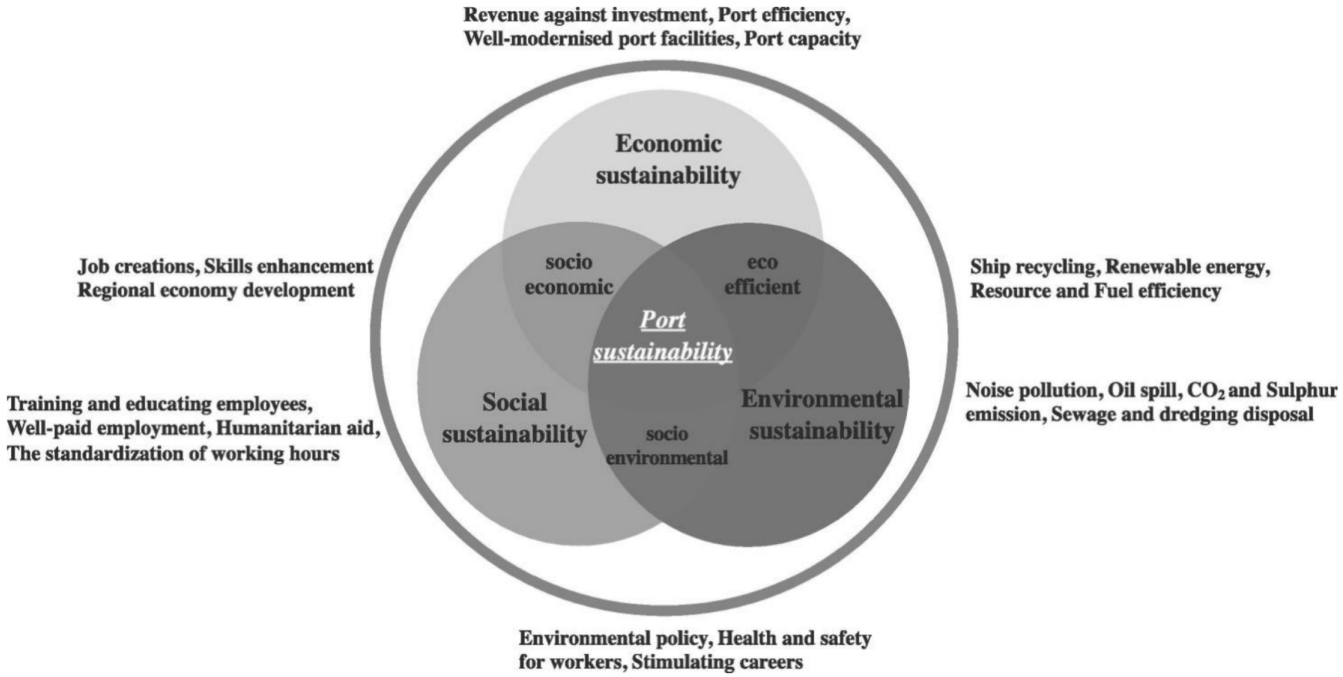

FIGURE 1 | Interaction of the Triple Bottom Line dimensions of port sustainability. *Source:* Adapted from Lim et al. (2019, 50).

UNCTAD 2022, 2024). At the same time, the sector is undergoing profound transformations driven by a range of contemporary global challenges, including globalization, digitalization, and automation, as well as rising environmental pressures, social concerns, and security risks. These shifts are reshaping governance structures and operational agendas, prompting ports to adopt innovative and strategic management frameworks that enhance efficiency, strengthen competitiveness, and support long-term sustainability goals (Dooms and Vaggelas 2023).

The growing environmental challenges of the twenty-first century—air and water pollution, climate change, and ecological degradation—have raised significant societal concerns and redirected public policy and academic debate toward the sustainability of ports (Gu et al. 2023). In addition to their economic significance, ports generate substantial environmental and social impacts that require urgent, integrated responses (Acciaro 2015; Ducruet et al. 2024; Langenus and Dooms 2018). Due to their reliance on fossil fuels, port and maritime transport activities contribute to air pollution by emitting GHGs such as CO_2, NO_x, and SO_x, thereby exacerbating climate change and global warming (Benamara et al. 2019; Lam and Notteboom 2014; Lee et al. 2019). This, in turn, contributes to floods, hurricanes, and droughts, raises sea levels, and alters oceanic circulation patterns (Alamoush et al. 2020, 2022; Sadiq et al. 2021). Port activities also generate noise, odor emissions, and waste accumulation (Ministero dell'Ambiente 2020; Peris-Mora et al. 2005; Široka et al. 2021). Exposure to such pollutants negatively affects the health and well-being of local communities living near ports (Ducruet et al. 2024). As a result, a major challenge for ports lies in reconciling operational efficiency with the imperative to protect environmental and social well-being (Benamara et al. 2019).

In recent decades, growing awareness of the negative externalities caused by port operations—which are expected to increase further due to the rising volume of maritime trade and the growing demand for port services and related land transportation—has further reinforced the focus on port sustainability (Cheon 2017; Gilman 2003; Lim et al. 2019; Lun et al. 2016; Psaraftis 2016; Puig et al. 2014; Wooldridge et al. 1999).

As ports are increasingly called to integrate environmental and social concerns into their activities (Beleya et al. 2015; Roh et al. 2016), scholars have progressively adopted a more integrated view, exploring the interplay among environmental, social, and economic dimensions of port sustainability and emphasizing the need for holistic approaches (Lam and Notteboom 2014; Martins et al. 2024). This evolution has led to the widespread adoption of the concept of "Port Sustainability", which encapsulates the necessity for ports to simultaneously mitigate environmental impacts, stimulate economic development, and address social needs (Serra et al. 2023). Port sustainability is typically conceptualized through three interdependent dimensions—environmental, economic, and social—that interact with one another, as shown in Figure 1 (Lim et al. 2019, 50; Martins et al. 2024; Stein and Acciaro 2020).

Environmental sustainability focuses on mitigating the negative impacts of port activities, including noise pollution, ship and vehicle emissions, and energy consumption (Lim et al. 2019; Narula 2014). Social sustainability refers to enhancing the quality of life for local communities, reducing accidents and incidents in ports, and improving employees' security and healthcare (Alamoush, Ballini, and Ölçer 2021; Narula 2014). Economic sustainability, on the other hand, refers to the port's economic performance and must be achieved without compromising social and environmental goals (Alamoush, Ballini, and Dalaklis 2021). As crucial nodes of international trade, ports must also strive to remain competitive in a highly globalized environment (Dooms and Vaggelas 2023).

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Despite the conceptual integration of the three pillars of sustainability within the Triple Bottom Line framework, practical implementation remains fragmented. Many port authorities continue to address environmental, social, and economic aspects in isolation, lacking a cohesive long-term sustainability strategy (UNCTAD 2022). Moreover, most existing research focuses predominantly on environmental sustainability, often overlooking the economic and social dimensions (Di Vaio and Varriale 2018; Martins et al. 2024). This misalignment between conceptual frameworks and managerial practice underscores the need for structured tools to operationalize the Triple Bottom Line in port strategic planning, governance, and performance management. Section 3 critically reviews how the existing literature has responded to this need.

3 | Managing Port Sustainability Performance: A Critical Synthesis

Although the sustainability of ports is increasingly acknowledged at the policy and strategic levels, port management practices have traditionally remained largely business-oriented, with a primary focus on financial balance and operational efficiency rather than on long-term sustainability planning (Becker and Caldwell 2015; Bjerkan and Seter 2019; Di Vaio and Varriale 2018; Martins et al. 2024). The tools and frameworks developed in response to growing sustainability pressures can be grouped into five main families, each addressing part of the challenge but leaving important limitations open.

3.1 | Environmental Indicator Approaches

A first stream relies on environmental performance indicators related to emissions, air quality, waste, and energy use (Di Vaio et al. 2018; Peris-Mora et al. 2005; Puig et al. 2014, 2015). These approaches are useful for monitoring environmental pressures and demonstrating regulatory compliance, but they share two recurrent shortcomings: they focus almost exclusively on the environmental pillar, and they remain weakly connected to strategic decision-making and long-term value creation (Styliadis et al. 2022). Although formally included in the port sustainability framework, the social dimension has received comparatively less attention in the literature, and the assessment of social impacts and externalities generated by port activities remains largely underexplored (Styliadis et al. 2022). Yet, ports can positively influence well-being and quality of life in local communities by generating direct and indirect employment, increasing income, and offering education and training opportunities (Alamoush, Ballini, and Ölçer 2021; Artal-Tur et al. 2016). At the same time, operational activities and port expansion projects can produce negative externalities—primarily environmental—that degrade local welfare, increase social costs, and exacerbate conflicts between ports and their host cities (Parola and Maugeri 2013; Styliadis et al. 2022).

3.2 | Economic and Socio-Environmental Assessment Models

A second stream extends the analysis to economic and socio-environmental impacts. As highlighted by Styliadis et al. (2022), fewer studies have examined the economic dimension of sustainability, including local economic impacts of port activities, regional development, and value creation in terms of employment and economic growth (Artal-Tur et al. 2016; Bottasso et al. 2013; Marner and Klumpp 2020). Some authors have used Input/Output models to evaluate port economic performance (Braun et al. 2002; Chang et al. 2014). Other contributions address health and social externalities—for example, by estimating the social cost of carbon emissions (Lee et al. 2014), by modeling health impacts of cruise ship emissions through impact-pathway analysis (Chatzinikolaou et al. 2015; Maragkogianni and Papaefthimiou 2015), or by proposing socially responsible measures and indicators of Occupational Health, Safety, and Security alongside environmental management (Antão et al. 2016; Beškovnik and Bajec 2015). These contributions broaden the analytical scope, but they typically address dimensions sequentially rather than jointly, and they lack a unifying strategic architecture that links them to the port authority's long-term strategy and value-creation processes.

3.3 | Strategic Management Control Tools

A third stream introduces management-control tools to integrate sustainability into port performance measurement. Although still limited in port-related applications, the Balanced Scorecard (BSC) offers a promising framework for integrating environmental KPIs and other strategic indicators (Divandri and Yousefi 2011; Praharsi et al. 2021). Sislian and Jaegler (2018) propose a Sustainable Maritime Balanced Scorecard (SMBSC) that explicitly incorporates the Triple Bottom Line to promote sustainability-oriented port management. These approaches show that sustainability can, in principle, be embedded within structured performance measurement and control systems. However, they remain largely static: they offer snapshot evaluations and capture neither the feedback loops, time delays, and trade-offs that characterize sustainability dynamics nor the causal links between operational levers and long-term outcomes. The literature continues to highlight persistent challenges, including the inherent complexity of port systems, the fragmentation of sustainability approaches, and the lack of adequate managerial competencies (Divandri and Yousefi 2011).

3.4 | System Dynamics Applications in Ports

A more recent stream applies System Dynamics (SD) modelling to port systems to capture feedback effects and evolving performance trajectories—for example, in carbon taxation policies and intermodal transport (Zhong et al. 2023), in resilience and ripple effects in multimodal container operations (Zhang et al. 2025), or in specific operational subsystems (Li et al. 2019). SD is particularly well suited to representing accumulation processes, delays, and nonlinear interactions (Forrester 1961; Sterman 2000). However, existing SD applications in the port sector tend to focus on isolated operational issues and are rarely embedded in a strategic business-model architecture or systematically linked to Triple Bottom Line outcomes and KPIs.

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3.5 | Sustainable Business Models

In parallel, a growing literature on sustainability-oriented business models argues that organizations must explicitly design how they create economic, environmental, and social value over the long term (Bocken 2015; Bocken et al. 2018; Geissdoerfer et al. 2018; Schaltegger et al. 2016). In the port domain, business-model thinking has been used to envisage "ports of the future" (Salsas et al. 2022), to explore industry-level sustainability-oriented models (Langenus and Dooms 2018), and to analyze value creation through corporate sustainability (Stein and Acciaro 2020). However, traditional business models often prove static and insufficient to capture the evolving complexity of the port context, which is shaped by a multiplicity of stakeholders, regulatory pressures, global economic dynamics, and environmental challenges. Recent literature, therefore, advocates systemic and dynamic approaches to represent and manage the interactions among strategic variables over time (Haezendonck 2021; Bordoli et al. 2023).

3.6 | Positioning of the Present Study

Taken together, the literature reveals a persistent gap. Existing tools either capture the multidimensional nature of sustainability (BSC adaptations and composite assessment models) *or* its temporal and feedback dynamics (stand-alone SD applications), but rarely both within a coherent strategic architecture that links resources, processes, KPIs, and Triple Bottom Line outcomes. A recent systematic review confirms that, although sustainability frameworks and technologies are proliferating in the port domain, their effective integration into strategic decision-making and real-world implementation remains limited (Shabib et al. 2025). Responding to this gap, the present study adopts and adapts the Dynamic Business Model for Sustainability (DBMfS) developed by Cosenz et al. (2020), which integrates a sustainability-oriented Business Model Canvas with SD modeling. With respect to environmental dashboards and BSC-based approaches, the DBMfS adds an explicit representation of feedback loops, time delays, and causal pathways that link strategic processes to long-term outcomes. With respect to existing SD applications in ports, it embeds the dynamic logic into a coherent business-model architecture that explicitly distinguishes resources, processes, performance drivers, outputs, and Triple Bottom Line outcomes, and links them to a hierarchically organized set of KPIs aligned with the UN SDGs. This integration—applied for the first time to a port authority—is the central methodological and theoretical contribution of the present study.

4 | Methodology

4.1 | The Dynamic Business Model for Sustainability

Ports operate as complex adaptive systems characterized by intricate interdependencies among multiple actors, resources, and strategic variables, generating dynamic complexity through feedback loops, time delays, and nonlinear relationships (Bianchi 2016; Sterman 2000). Static analytical frameworks prove inadequate for capturing these dynamics, as they fail to account for feedback mechanisms and temporal evolution essential to understanding how strategic interventions produce sustainability outcomes over extended time horizons. Responding to this need, the study adopts the DBMfS framework originally developed by Cosenz et al. (2020), which integrates business model logic with SD modeling to map sustainable value-generation processes through a systemic and adaptive lens.

The DBMfS framework builds on an adapted version of the Business Model Canvas, originally proposed by Osterwalder and Pigneur (2010) and subsequently revised by Bocken (2015) and Bocken et al. (2018), to explicitly incorporate the environmental, social, and economic dimensions of sustainable value creation. As illustrated in Figure 2, the resulting DBMfS canvas comprises eight fundamental building blocks that delineate how organizations operationalize sustainability within their strategic architecture: key stakeholders, strategic resources, value proposition, key processes, customer segments, cost structure, revenue streams, and outcomes. The value proposition building block is subdivided into three interconnected components—performance drivers, outputs, and outcomes—that distinguish between critical success factors affecting operational processes, short-term operational results, and long-term impacts on the broader socio-economic and environmental context within which the organization operates (Cosenz et al. 2020). The outcomes building block is framed around the economic, environmental, and social value generated by the organization, thereby incorporating the Triple Bottom Line as measurable long-term impacts of sustainability-related activities.

In this framework, the methodological contribution of SD lies in its capacity to map and simulate the causal interdependencies among business model elements within closed feedback structures that capture endogenous dynamics and enable experimentation with alternative strategic configurations (Forrester 1961; Sterman 2000). Unlike linear analytical approaches, SD explicitly models accumulation processes, feedback effects, time delays, and nonlinear interactions that characterize complex organizational systems, thereby helping decision-makers understand counterintuitive phenomena and identify high-leverage intervention points (Morecroft 2007; Warren 2008). Moreover, SD facilitates collaborative model-building processes that engage diverse stakeholders, foster shared understanding, and support consensus-building around strategic priorities—attributes particularly valuable in port governance contexts characterized by multiple constituencies with potentially conflicting interests (Rouwette 2011; Voinov and Bousquet 2010).

4.2 | Research Design, Case Selection, and Data Sources

The empirical application of the DBMfS framework relies on an in-depth single case study design focusing on the Western Sicily Port Authority (Autorità di Sistema Portuale del Mare di Sicilia Occidentale, hereafter AdSP MSO). While single-case studies have historically been subject to concerns about generalizability, contemporary methodological scholarship recognizes their distinctive value for theory elaboration, the exploration of novel theoretical frameworks, and the generation of rich

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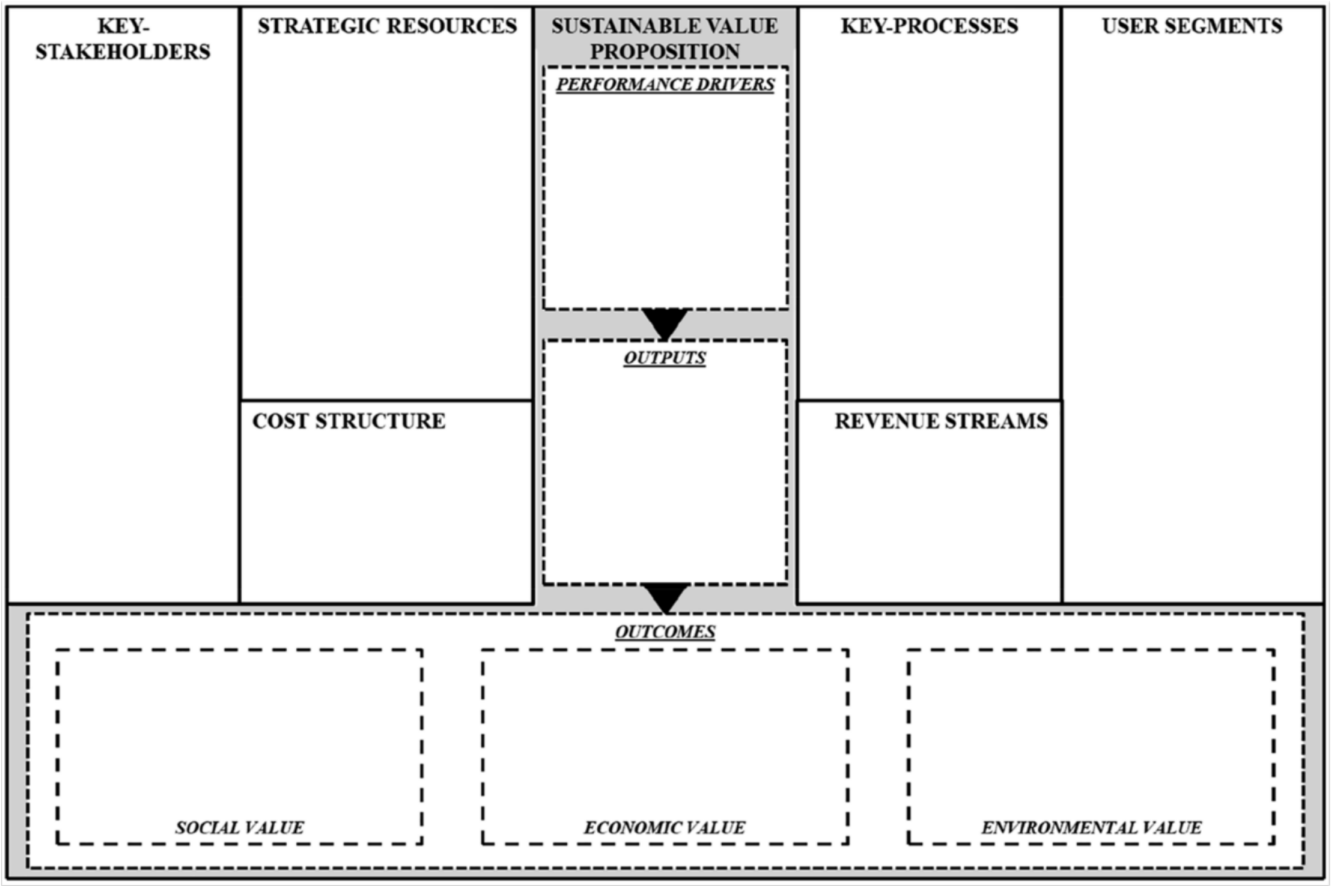

FIGURE 2 | The Dynamic Business Modeling for Sustainability canvas. *Source:* Adapted from Cosenz et al. (2020, 658).

contextual insights that illuminate causal mechanisms (Eisenhardt and Graebner 2007; Siggelkow 2007). As Flyvbjerg (2006) argues, the strategic selection of information-rich cases enables researchers to achieve analytical rather than statistical generalization, in which theoretical propositions are refined through intensive examination of exemplary instances. The case study method is particularly appropriate when research objectives center on understanding how and why complex phenomena unfold in real-world organizational contexts, especially when the boundaries between the phenomenon and its context remain indistinct (Yin 2018).

In this investigation, the DBMfS framework serves as a novel theoretical lens, and its operationalization in the port sustainability domain requires an intensive examination of how abstract conceptual elements translate into concrete organizational practices, strategic processes, and measurable performance indicators. The AdSP MSO case serves as a revelatory case, as characterized by Yin (2018), providing access to the systematic integration of dynamic business modeling principles with Triple Bottom Line sustainability management within port governance structures. The epistemological stance underlying this research aligns with what Gioia et al. (2013) term systematic inductive theory building, in which empirical observation informs theoretical refinement through iterative engagement with organizational reality. Rather than testing predetermined hypotheses, the study uses the case to explore how sustainability-oriented business modeling operates within the distinctive institutional, operational, and stakeholder configurations that characterize port authorities. The single-case design enables a depth of analysis unattainable through multi-case comparison, thereby permitting detailed tracing of causal pathways linking strategic resources and processes to sustainability outcomes across environmental, social, and economic dimensions (Eisenhardt and Graebner 2007). The case thus functions not as a sample from which to generalize statistically, but as an exemplar through which to refine theoretical propositions and demonstrate proof of concept for a novel analytical framework (Siggelkow 2007).

The AdSP MSO was selected through purposive sampling as an information-rich and theoretically relevant case (Palinkas et al. 2015; Patton 2015). The selection was guided by four criteria: (1) a documented commitment to sustainability strategies evidenced by comprehensive sustainability reporting; (2) availability of detailed institutional documents and multi-year performance data; (3) the simultaneous implementation of multiple sustainability initiatives—waterfront regeneration, dock electrification, and renewable energy adoption—enabling the analysis of interdependencies across the Triple Bottom Line dimensions; and (4) suitability for exploring how a port authority can systematically embed environmental, social, and economic sustainability into strategic planning and performance management.

The empirical reconstruction is based on the systematic analysis of the official documentation produced by the AdSP MSO

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between 2021 and 2025. The corpus comprises: the Sustainability Report (AdSP MSO 2022a); the Integrated Plans of Activities and Organisation for 2024–2026 (AdSP MSO 2024a) and 2025–2027 (AdSP MSO 2025); the forecast budgets for 2024 (AdSP MSO 2023) and 2025 (AdSP MSO 2024b); the Performance Report for 2023 (AdSP MSO 2024c); the Port System Strategic Planning Document (DPSS) (AdSP MSO 2022b); the Energy and Environmental Planning Document of the Port System (DEASP) (AdSP MSO 2021); and documentation on the waterfront regeneration project (Carta 2024; Carta et al. 2025). These sources were complemented by figures published by the Italian Court of Auditors (Corte dei Conti 2024).

Documents were analyzed through a structured thematic procedure. First, each document was read in full and coded against the eight building blocks of the DBMfS canvas to extract strategic resources, key processes, performance drivers, outputs, and outcomes related to the three sustainability pillars. Second, the resulting elements were triangulated across documents to ensure consistency between strategic intentions (DPSS, DEASP, PIAO), planned investments (forecast budgets), and reported performance (Performance Report, Sustainability Report). Third, the three core sustainability processes selected for in-depth modeling—waterfront regeneration, dock electrification, and renewable energy adoption—were identified based on their explicit prominence in the materiality analysis of the Sustainability Report and their simultaneous coverage across planning, budgeting, and reporting documents.

Documentary analysis was complemented by interactions with selected members of the AdSP MSO. These took the form of three semi-structured exchanges held during the modeling process with managers responsible, respectively, for strategic planning and control, environmental and energy planning, and waterfront regeneration. They were not designed as a primary data-collection instrument, but as a triangulation and validation device aimed at: (i) clarifying operational assumptions that could not be inferred from documents alone; (ii) verifying the plausibility of the causal logic mapped through the DBMfS; and (iii) assessing the feasibility and managerial relevance of the proposed KPIs. Notes from these exchanges were used to refine the variable identification and the causal mapping. Internal validity was further strengthened through source triangulation across institutional documents and through iterative cross-checking between the emerging causal structures and the Authority's planning and reporting narratives.

The study is therefore positioned as a qualitative, theory-elaboration application of the DBMfS rather than as a quantitative simulation exercise. The boundary conditions of this design choice—and the avenue it opens for subsequent quantitative work—are discussed in Sections 6.3 and 7.

4.3 | Operationalization of the DBMfS

Following Cosenz et al. (2020), the DBMfS was operationalized through four iterative steps. The provenance of each element—literature, empirical case, or both—is made explicit below.

4.3.1 | Variable Identification

The variables populating each building block of the canvas were identified through a combined deductive–inductive procedure. The taxonomy of building blocks (strategic resources, key processes, performance drivers, outputs, outcomes) and the Triple Bottom Line articulation of outcomes were derived deductively from the DBMfS literature (Bocken 2015; Bocken et al. 2018; Cosenz et al. 2020) and from the broader literature on sustainable business models. The specific variables populating each block—for example, "pier regeneration coverage", "green energy production ratio", and "yearly CO_2 emissions"—were derived inductively from the documentary analysis of the AdSP MSO planning and reporting documents and refined through interactions with Authority members.

4.3.2 | Causal Relationship Mapping

The causal relationships among variables were elicited by combining (a) theoretical propositions on sustainability dynamics drawn from prior SD and sustainability-management literature (Cosenz et al. 2020; Sterman 2000) and (b) the empirical narratives reconstructed from the AdSP MSO documents. The resulting causal structures were then iteratively refined through the interactions with Authority members, who validated the plausibility of each link and the existence of the relevant feedback effects. The mapping captures feedback mechanisms and interdependencies across the Triple Bottom Line dimensions, in line with the systemic perspective of the DBMfS.

4.3.3 | KPI Definition

A comprehensive set of indicators was defined to enable, over time, the monitoring and evaluation of the evolution of economic, social, and environmental sustainability performance and the detection of potential performance gaps with respect to sustainability targets. The KPI architecture combines indicators drawn from the existing port-sustainability literature (e.g., yearly CO_2 emissions, share of green energy, number of visitors, m^2 of green areas; Peris-Mora et al. 2005; Puig et al. 2014; Serra et al. 2023) with case-specific indicators developed to capture distinctive features of the AdSP MSO strategy (e.g., "pier regeneration coverage", "business density", "relative waterfront image"). KPIs were organized into three hierarchical categories—performance drivers, outputs, and outcomes—to mirror the structure of the DBMfS value proposition and to support both forward-looking planning and backward diagnostic analysis.

4.3.4 | Validation

The integrated framework—variables, causal relationships, and KPI specifications—was validated through the same interactions with selected members of the AdSP MSO. Validation focused on three explicit dimensions: the substantive accuracy of the causal mapping relative to actual operational practice; the feasibility of data collection for each proposed KPI; and the managerial relevance of the framework for supporting strategic decision-making in the port context. Adjustments arising from this validation were incorporated into the final version of the model presented in Section 5.

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The following section illustrates the application of the DBMfS to the AdSP MSO case, presenting the three core sustainability processes analyzed, the resulting causal mappings, and the comprehensive KPI framework developed.

5 | The Western Sicily Port Authority Case Study

This section presents the empirical application of the DBMfS to the AdSP MSO case study. The AdSP MSO is a non-economic public entity established within the Italian port governance reform introduced by Legislative Decree No. 169 of 4 August 2016. It is responsible for coordinating, promoting, and managing port activities in Palermo, Termini Imerese, Trapani, Porto Empedocle, Licata, Gela, and Sciacca. The Authority's mission is to implement a sustainable development strategy that meets global market demands while ensuring the environmental, social, and economic sustainability of port operations.

As a first step in applying the DBMfS, the key variables involved in sustainable value-generation processes were identified and grouped into their building blocks. Three key processes were selected as the main levers of sustainable value creation, as illustrated in Figures 3 and 4: (i) waterfront regeneration; (ii) dock electrification through cold ironing systems; and (iii) energy efficiency enhancements through the adoption of renewable energy sources. These processes are explicitly reported in the Authority's main planning and reporting documents and align with the materiality analysis conducted in the Sustainability Report, which highlights decarbonisation, energy efficiency, waste and emissions reduction, port–city integration, and local development as strategic priorities (AdSP MSO 2022a).

The key stakeholders of the AdSP MSO include public entities, private investors, the local community, and potential new investors. Among the public stakeholders, the main actors are the Italian Ministry of Infrastructure and Transport, the Italian Ministry of Ecological Transition, the Sicilian Region, local authorities, and international institutions such as the European Union. The Authority relies heavily on public–private partnerships (PPPs) with private companies to fund strategic infrastructure projects. One of the most significant private stakeholders is the Free Group—comprising Free Energia, Free Energy Saving, and Lux Master—which contributes to financing and supporting innovative solutions to enhance energy efficiency and facilitate the transition to renewable energy.

The Authority's financial resources primarily come from public funds and private investments, with a smaller share generated from port activity revenues. These resources are primarily allocated to projects that support ecological transition, technological innovation, and environmental regeneration, in line with the AdSP MSO's strategic commitment to sustainable development.

Figure 3 maps the dynamics underlying the sustainable value generation processes associated with waterfront regeneration.

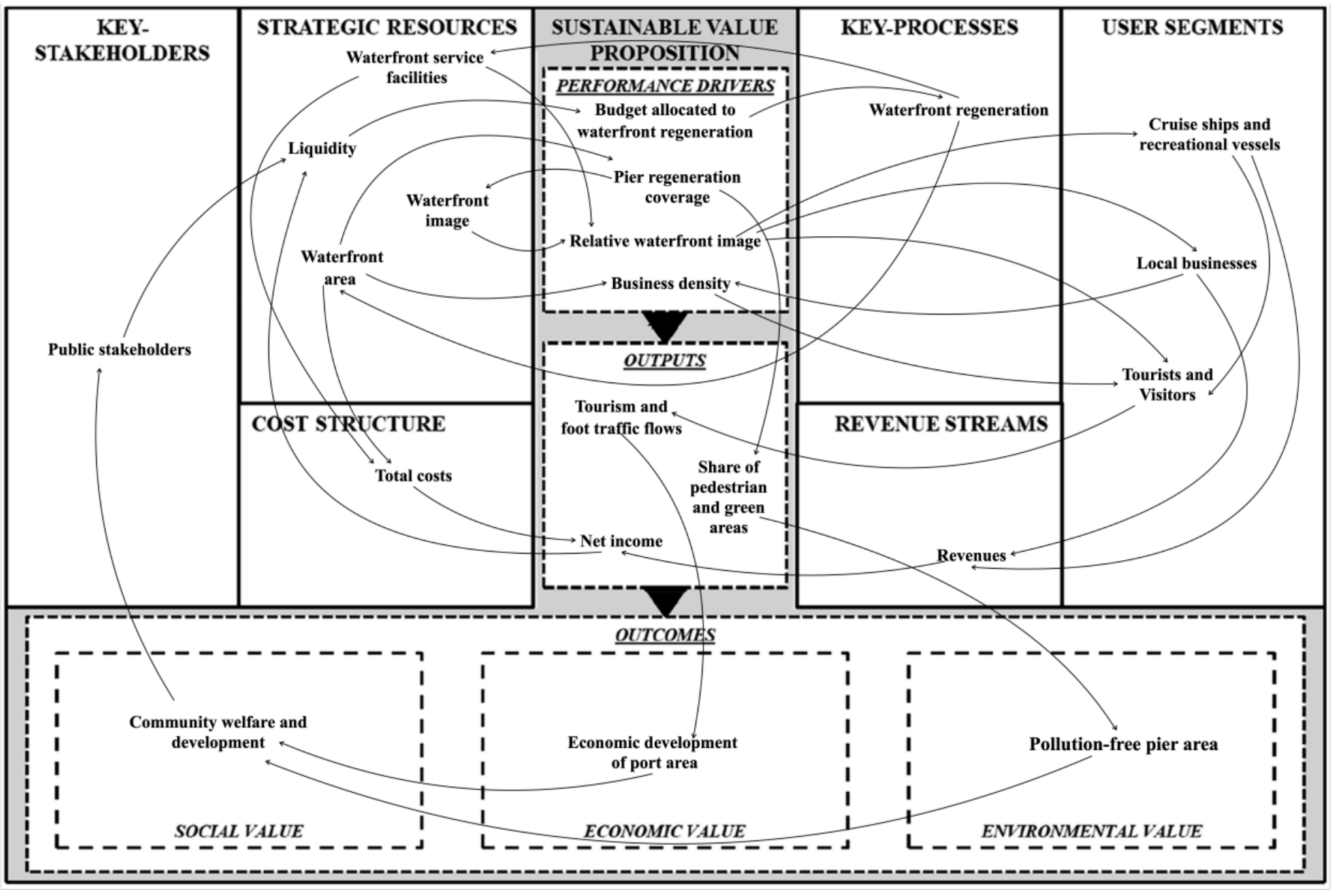

FIGURE 3 | The DBMfS canvas applied to the Western Sicily Port Authority: the waterfront regeneration process. *Source:* Author's elaboration.

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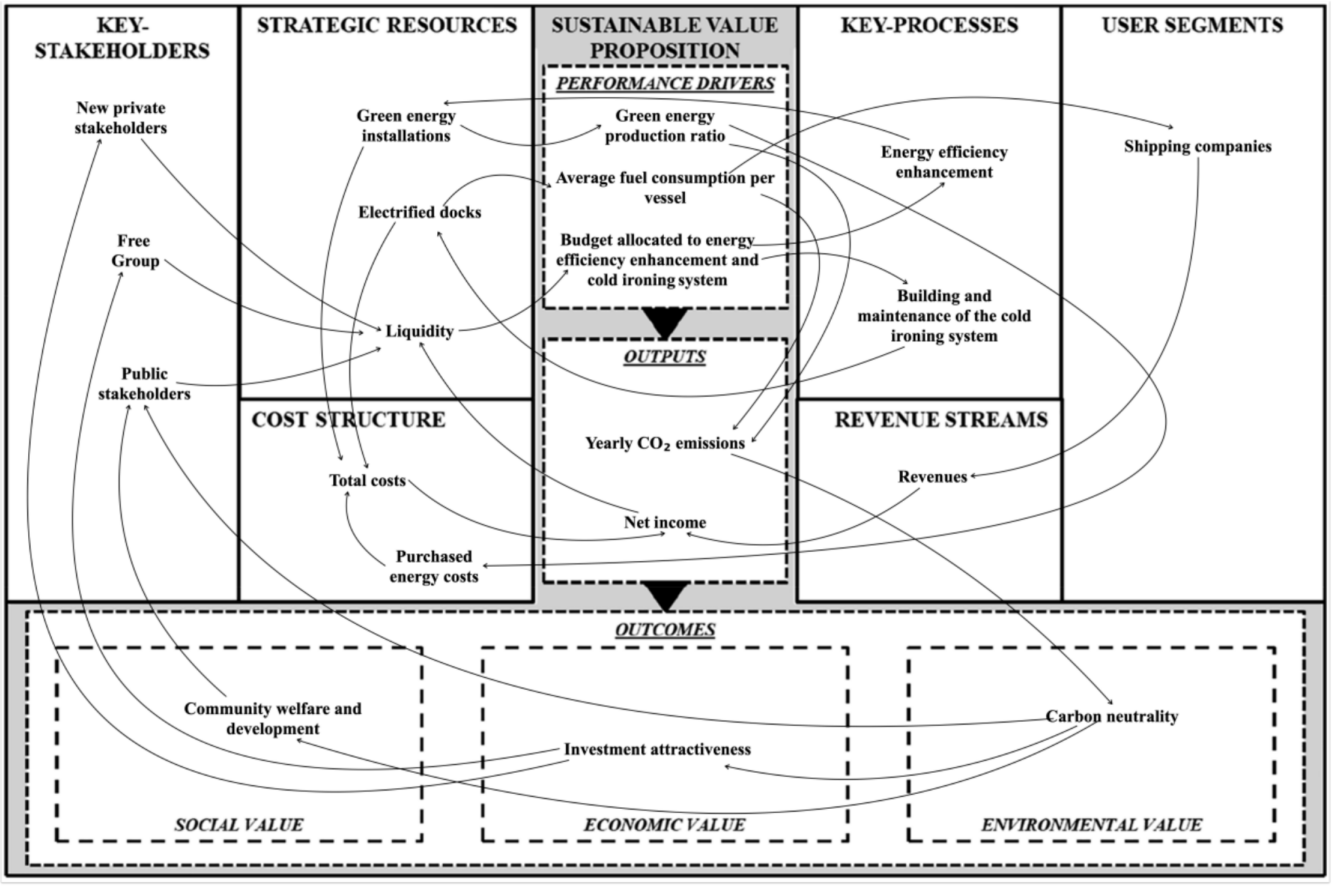

FIGURE 4 | The DBMfS canvas applied to the Western Sicily Port Authority: dock electrification and energy efficiency enhancement processes. *Source:* Author's elaboration.

The requalification of the pier in the Port of Palermo required an overall investment of approximately €25.5 million, funded through national public funds. Specifically, the resources were allocated by the Ministry of Infrastructure and Transport as part of a broader investment plan for port infrastructure development (Corte dei Conti 2024). In addition to this initial allocation, the Authority directly finances further works necessary for completing the redevelopment and bears the main operating and management costs of the regenerated area, including maintenance, personnel, energy consumption, and design activities.

Taken together, these investments have significantly increased the "Pier regeneration coverage," defined as the ratio between the area that has been regenerated and the total surface area of the pier. As regeneration progresses, a growing share of the pier is converted into pedestrian and green areas, measured through the indicator "Share of pedestrian and green areas." At the same time, the regenerated spaces are equipped with new commercial and leisure facilities (e.g., bars, restaurants, retail and service activities), enhancing the waterfront's usability and attractiveness and providing additional opportunities for local businesses. The physical transformation of the waterfront, in turn, enhances the "Relative waterfront image," a perception-based indicator that captures the attractiveness of the waterfront compared to predefined targets.

An improved waterfront image makes the area more appealing to businesses, increasing "Business density," measured as the square meters of regenerated space rented and used by firms over the total regenerated surface. As the waterfront becomes more vibrant and service-rich, "Tourism and foot traffic flows" rise, reflecting higher numbers of tourists and visitors and reinforcing the waterfront's role as a mixed-use port–city space. These dynamics contribute to the "Economic development of the port area" by generating additional income and employment opportunities for local businesses and communities, and by enhancing the Authority's "Investment attractiveness," as reflected in increased private investment in the regenerated zone.

From an environmental perspective, expanding pedestrian and green areas reduces annual CO_2 emissions from activities in the waterfront zone, contributing to the creation of a "Pollution-free pier area" in the long term. The environmental improvements feed back into the social dimension by enhancing "Community welfare and development," as better air quality and environmental conditions raise residents' perceived quality of life and support local employment.

Figure 4 maps the dynamics underlying sustainable value generation from dock electrification via cold ironing and energy-efficiency enhancements.

Dock electrification, achieved through a cold-ironing system, enables vessels to draw power from the port's electrical grid and shut down their engines while docked, thereby reducing fuel combustion during port stays. The investments required

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for designing, installing, and maintaining this infrastructure are captured by the indicator "Budget allocated to energy efficiency enhancement and the cold ironing system," which measures the share of financial resources devoted to energy transition measures over the total budget. These investments, together with ongoing operational costs (e.g., maintenance and personnel), constitute key components of the cost structure associated with the ecological transition.

Once the cold ironing system is operational, vessels can switch from onboard fuel combustion to shore-side electricity, thereby improving the "Average fuel consumption per vessel" by reducing fuel consumption during port stays. This performance driver directly contributes to reducing "Yearly CO_2 emissions", defined as the total tons of CO_2 generated per year by port-related activities. Over time, reductions in emissions, combined with the deployment of cleaner technologies in the port area, support progress towards "Carbon neutrality", as captured by the ratio of current CO_2 emissions to a predefined baseline year.

In parallel, the installation of renewable energy plants, such as photovoltaic panels, increases the "Green energy production ratio", which represents the share of the port's energy consumption from renewable sources relative to total energy consumed. Higher levels of green self-production reduce dependence on conventional energy sources and, in the medium to long term, lower the Authority's energy-related operating costs. These improvements strengthen the Authority's "Net income", reflecting its capacity, as a non-economic public entity, to reinvest surplus resources in infrastructure development, sustainability initiatives, and long-term financial stability.

Taken together, dock electrification and green energy generation translate into a coherent set of outputs that, in turn, feed into longer-term outcomes across the three dimensions of the Triple Bottom Line. Environmentally, the reduction in CO_2 emissions and the increased share of clean energy support progress towards carbon neutrality and improved air quality in the port–city interface. Socially, lower pollution and cleaner operations enhance community welfare and development, as residents benefit from better environmental conditions and a healthier urban waterfront. Economically, cost savings from energy efficiency and the signaling effect of advanced green infrastructure strengthen both the economic development of the port area and its investment attractiveness by positioning the AdSP MSO as a credible and forward-looking actor able to mobilize public and private capital for sustainable projects.

To operationalize the Sustainable Value Proposition, three complementary KPI sets were developed for (i) performance drivers as shown in Table 1, (ii) outputs as shown in Table 2, and (iii) outcomes as shown in Table 3. Together, these indicators support the monitoring and evaluation of the sustainable value-generation processes activated by the AdSP MSO.

Finally, the dynamic lens of the DBMfS enables explicit tracking of how the strategies implemented by the AdSP MSO contribute to the UN SDGs (Cosenz et al. 2024). In this regard, defining clear and relevant sustainability outcome indicators is crucial for analyzing, assessing, and monitoring both the progress of sustainability initiatives and their contribution to the SDG agenda (Di Vaio et al. 2018; UNCTAD 2023). Specifically, by improving local communities' quality of life and public health through cleaner operations and a more livable port–city interface, the AdSP MSO supports SDG 3 (Good health and well-being), SDG 8 (Decent work and economic growth), and SDG 11 (Sustainable cities and communities). Moreover, the economic development of the port area aligns with SDG 8 and SDG 9 (Industry, innovation and

TABLE 1 | KPIs related to performance drivers of the sustainable value generation processes in the AdSP MSO.

Variable name	Description	Measurement
Average fuel consumption per vessel	Measures the average fuel consumption — and thus the energy efficiency — of ships calling at the port.	Total fuel consumption/number of vessels
Budget allocated to energy efficiency and cold ironing	Indicates the share of financial resources devoted to energy transition measures (cold ironing and efficiency upgrades).	Budget allocated/total budget
Budget allocated to waterfront regeneration	Measures the proportion of investments aimed at waterfront regeneration.	Budget allocated/total budget
Business density	Measures the share of regenerated port space rented and used by businesses in the waterfront area, capturing the intensity of economic activity in the redeveloped zone.	m^2 rented by businesses in the waterfront/total m^2 regenerated
Green energy production ratio	Represents the share of port energy consumption covered by renewable sources.	Green energy produced/total energy consumed
Pier regeneration coverage	Measures the proportion of the total pier surface that has undergone physical redevelopment.	m^2 of regenerated pier area/total m^2 of pier area
Relative waterfront image	Perception-based indicator assessing the attractiveness of the waterfront against predefined objectives.	Actual waterfront image/target waterfront image (survey-based)

Source: Author's elaboration.

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TABLE 2 | KPIs related to outputs of the sustainable value generation processes in the AdSP MSO.

Variable name	Description	Measurement
Tourism and foot traffic flows	Captures the attractiveness of the waterfront by monitoring annual numbers of tourists and other visitors in the area.	(i) Number of tourists in the waterfront area/year; (ii) Number of visitors in the waterfront area/year
Share of pedestrian and green areas	Assesses the proportion of regenerated pier surface that has been converted into pedestrian zones and/or green spaces.	(i) m^2 of pedestrian areas/total m^2 of regenerated pier area; (ii) m^2 of green areas/total m^2 of regenerated pier area
Yearly CO_2 emissions	Provides the annual estimate of greenhouse gas emissions generated by port-related activities.	Total tons of CO_2 emissions/year
Net income	Represents the financial result of the Authority, reflecting its capacity, as a non-economic public entity, to generate a surplus that can be reinvested in infrastructure development and sustainability initiatives.	Revenues—costs

Source: Author's elaboration.

TABLE 3 | KPIs related to outcomes of the sustainable value generation processes in the AdSP MSO.

Variable name	Description	Measurement
Community welfare and development	Assesses the social impacts of port strategies by evaluating changes in residents' quality of life and in local employment opportunities within the waterfront area.	(i) Δ residents' perceived quality of life (survey-based); (ii) Δ employment in the waterfront area
Economic development of the port area	Measures the contribution of port activities to local and regional economic growth.	Δ total turnover of waterfront businesses
Investment attractiveness	Captures the port's ability to mobilize capital and attract private investors.	Δ value of private investments attracted
Pollution-free pier area	Assesses improvements in air quality, relating CO_2 emissions to regenerated surface area.	Tons of CO_2 emissions/m^2 of regenerated pier area
Carbon neutrality	Tracks progress towards net-zero emissions by comparing current CO_2 levels with a predefined baseline year.	Tons of CO_2 emitted in year t/tons of CO_2 emitted in baseline year

Source: Author's elaboration.

infrastructure), capturing the contribution of regenerated waterfront activities to local growth. Investment attractiveness is linked to SDG 8, SDG 9, and SDG 17 (Partnerships for the Goals), as it reflects the Authority's capacity to mobilize private capital and partnerships to support sustainable projects. From an environmental perspective, reducing CO_2 emissions in the regenerated area aligns with SDG 11 and SDG 13 (Climate action), while Carbon neutrality directly supports SDG 7 (Affordable and clean energy) and SDG 13 by tracking decarbonization progress relative to a baseline year. Through this explicit alignment, the DBMfS serves not only as a tool for managing sustainability performance but also as a coherent framework for positioning and communicating the contribution of port strategies to the UN 2030 Agenda for Sustainable Development.

6 | Discussion

The application of the DBMfS framework to the AdSP MSO case reveals how sustainability can be systematically embedded within the strategic planning and performance management of port organizations through a dynamic, integrative approach. The findings advance both theoretical understanding and the practical implementation of sustainability-oriented governance in complex port systems.

The case demonstrates that the DBMfS effectively operationalizes the Triple Bottom Line framework (Elkington 1998) by mapping the causal relationships linking economic, social, and environmental dimensions of port sustainability. This addresses a significant gap identified in the literature: sustainability initiatives in ports have traditionally been implemented in fragmented, ad hoc ways rather than systematically integrated into long-term strategic planning and control systems (Ashrafi et al. 2019; Gavalas 2024; Shabib et al. 2025). The framework's capacity to visualize interdependencies across sustainability dimensions responds to scholarly calls for holistic approaches that can capture trade-offs and synergies among the three pillars of sustainability (Acciaro 2015; Lam and Notteboom 2014; Puig et al. 2014).

The empirical evidence illustrates how the three core strategic processes analyzed—waterfront regeneration, dock

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electrification, and renewable energy deployment—generate cascading effects across multiple sustainability dimensions. Waterfront regeneration emerges not merely as an urban development initiative but as a multidimensional value-creation process that simultaneously enhances environmental quality through increased green spaces, stimulates economic activity by attracting businesses and tourism, and improves community welfare by enhancing residents' quality of life. This finding aligns with recent scholarship emphasizing the interconnected nature of sustainability dimensions in port contexts (Martins et al. 2024) and demonstrates how infrastructure interventions can function as strategic levers for integrated sustainable development.

Similarly, the analysis of dock electrification and renewable energy adoption reveals feedback mechanisms that challenge linear assumptions about sustainability investments. The installation of cold ironing systems reduces emissions and generates long-term cost savings through improved energy efficiency, thereby strengthening the Authority's financial capacity to reinvest in further sustainability initiatives. This dynamic reinforces the economic viability of environmental investments, contradicting traditional views that position environmental protection and economic performance as competing objectives (Di Vaio and Varriale 2018). The finding resonates with Langenus and Dooms' (2018) conceptualization of sustainability-oriented business models in ports, in which environmental innovations can simultaneously enhance competitiveness and operational efficiency.

The framework's contribution extends beyond static mapping by incorporating SD principles that capture temporal evolution and feedback dynamics. This temporal dimension proves particularly valuable in addressing the inherent complexity of port systems, characterized by multiple stakeholders, regulatory pressures, and interconnected operational processes (Notteboom et al. 2022; Parola and Maugeri 2013). Traditional business models and performance measurement systems, even sophisticated ones such as the Balanced Scorecard, typically provide snapshot evaluations rather than representing the dynamic trajectories and feedback effects that shape sustainability outcomes over time (Sislian and Jaegler 2018). The DBMfS overcomes this limitation by explicitly modeling how current decisions influence future resource stocks, performance drivers, and ultimately sustainability outcomes across extended time horizons.

The comprehensive set of key performance indicators developed within the DBMfS value proposition addresses another critical gap in the literature. Existing research has documented the predominance of environmental indicators in port sustainability assessment, with comparatively limited attention to social dimensions and weak integration with economic performance metrics (Di Vaio and Varriale 2018; Styliadis et al. 2022). The proposed KPI framework organizes indicators hierarchically across performance drivers, outputs, and outcomes, supporting structured performance monitoring while maintaining explicit linkages to strategic processes and resource allocations. This structured approach facilitates what Becker and Caldwell (2015) term "resilience through anticipation", enabling port authorities to detect performance gaps early and implement corrective actions before significant deviations occur.

Particularly noteworthy is the framework's capacity to support backward diagnostic analysis. When sustainability targets are not achieved, the causal mapping enables managers to trace performance gaps to their root causes—whether in insufficient resource allocation, suboptimal activity configuration, or inadequate management of performance drivers. This diagnostic capability transforms the framework from a mere planning tool into a dynamic governance instrument that supports adaptive management. The AdSP MSO case illustrates this through scenarios in which gaps in CO_2 emission reduction or in the economic development of the port area can be systematically traced to specific weaknesses in electrified dock coverage, renewable energy production, or the scope of waterfront regeneration. This analytical capability addresses concerns raised by Divandri and Yousefi (2011) regarding the complexity of port systems and the challenges of translating sustainability aspirations into actionable managerial responses.

Finally, the explicit alignment with the UN SDGs represents a further contribution. While several studies have discussed port contributions to the SDGs conceptually (Alamoush, Ballini, and Ölçer 2021; Caliskan 2022), fewer have provided operational frameworks for systematically tracking and communicating such contributions through structured performance indicators. By linking outcome indicators to specific SDG targets, the DBMfS creates a coherent bridge between organizational strategy and global sustainability agendas, enhancing both internal accountability and external legitimacy (Valenza and Damiano 2023).

6.1 | Theoretical Contribution

The study makes three explicit theoretical contributions. First, it extends the DBMfS framework—originally developed for private firms (Cosenz et al. 2020)—to public infrastructure organizations governed by hybrid public–private logics. While most research on sustainable business models has focused on private-sector organizations (Geissdoerfer et al. 2018; Schaltegger et al. 2016), this study shows how the DBMfS can guide non-economic public entities in designing and managing sustainable value-creation processes. This extension is significant given the unique characteristics of port authorities, which must balance commercial efficiency with public service mandates and regulatory compliance while serving diverse stakeholder groups with often conflicting interests. The research thus contributes to broader debates on the nature of value in public organizations and on how such value can be strategically designed and managed.

Second, the study advances the integration of System Dynamics with strategic management frameworks in the port domain. Existing SD applications in ports have primarily focused on isolated operational issues or specific sustainability subsystems (Li et al. 2019; Zhang et al. 2025; Zhong et al. 2023), while BSC adaptations have integrated sustainability KPIs but remained essentially static (Sislian and Jaegler 2018). By embedding SD within a sustainability-oriented Business Model Canvas, the DBMfS combines the multidimensional view of the Triple Bottom Line, the structural logic of the business model, and the temporal logic of feedback dynamics within a single coherent framework—an integration that, to the best of our knowledge, has not previously been demonstrated for port authorities. This methodological

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contribution is particularly relevant as organizations increasingly confront sustainability challenges requiring long-term, systemic perspectives that traditional management tools struggle to provide.

Third, the study contributes to operationalizing the Triple Bottom Line in port contexts. While the Triple Bottom Line framework enjoys widespread conceptual acceptance, its practical implementation remains problematic due to difficulties in balancing competing objectives and integrating diverse performance metrics (Di Vaio and Varriale 2018; Martins et al. 2024). The hierarchically organized KPI architecture (drivers, outputs, outcomes) developed in this study links operational levers to long-term outcomes and to specific UN SDGs, providing a structured approach for translating Triple Bottom Line principles into actionable strategies and measurable outcomes. It thereby addresses the implementation gap between sustainability aspirations and managerial practice that the literature has consistently identified.

6.2 | Practical Implications

From a practical standpoint, the framework offers port authorities a comprehensive tool for strategic sustainability planning and governance. The visual, intuitive representation of sustainability processes and their interdependencies facilitates strategic dialogue among diverse stakeholder groups, supporting collaborative decision-making in politically complex environments. Port managers can use the framework to communicate sustainability strategies more effectively, both internally—to align organizational units around common objectives—and externally, to build stakeholder support and legitimacy.

The structured KPI framework provides practical guidance for implementing sustainability-oriented performance measurement systems. Port authorities can adapt the proposed indicators to their specific contexts while maintaining the hierarchical organization across performance drivers, outputs, and outcomes. This structure supports both strategic planning through forward-looking scenario analysis and operational control through systematic monitoring and variance analysis. The backward diagnostic capability proves particularly valuable for adaptive management, enabling timely identification of strategic misalignments and the implementation of corrective actions before significant resource waste or opportunity loss occurs.

The framework also enhances sustainability reporting practices by providing a coherent narrative structure linking strategic processes to sustainability outcomes and SDG contributions. This strengthens accountability and transparency while positioning port authorities as credible partners in regional and national sustainability initiatives, potentially facilitating access to public funding and private investment for sustainability projects.

6.3 | Limitations

Despite these contributions, the study presents several limitations that warrant acknowledgment. First, the reliance on a single case study limits statistical generalizability across different port contexts. Port authorities operate under diverse governance structures, regulatory regimes, and stakeholder configurations that may influence the applicability of the framework and the relevance of the identified causal relationships. While the DBMfS methodology itself is transferable, the specific variable configurations and indicator specifications require adaptation to the context.

Second, the current implementation is a qualitative application that maps causal relationships and proposes indicators, but does not fully parameterize or simulate the model. This limitation stems partly from data availability constraints: many of the sustainability initiatives analyzed—cold ironing, photovoltaic plants, waterfront regeneration—are still in early implementation phases at the AdSP MSO and lack sufficient historical data for robust quantitative analysis. Future research incorporating quantitative modeling would enable more precise impact assessment, scenario testing, and predictive analysis to support evidence-based decision-making.

Third, the framework's complexity demands specialized expertise in both SD methodology and sustainability management, potentially creating implementation barriers for port authorities that lack these competencies. While the visual representation enhances accessibility, effective utilization requires training and sustained organizational commitment. Additionally, defining causal relationships involves an inherent degree of subjectivity that may introduce bias, though this was partially mitigated through document triangulation and validation with organizational members.

Fourth, data collection challenges pose another practical limitation, particularly for social sustainability indicators, which often require survey-based assessments of community perceptions and well-being. Many ports lack standardized sustainability reporting practices, limiting the availability of consistent, comparable data across time periods and organizations. Overcoming these data constraints requires investment in monitoring systems and stakeholder engagement processes that may exceed available resources in resource-constrained port authorities.

7 | Concluding Remarks

This study addresses a critical imperative in contemporary port governance by demonstrating how sustainability principles can be systematically embedded within strategic planning and performance management through dynamic business modeling. The research helps resolve the persistent tension between the conceptual acceptance of the Triple Bottom Line framework and its fragmented implementation in port authority practice (Di Vaio and Varriale 2018; Martins et al. 2024). By integrating SD methodology with business model logic, the DBMfS offers port authorities a structured approach to navigate the inherent complexity of sustainability governance while maintaining strategic coherence across economic, social, and environmental dimensions.

The framework's capacity to reveal causal interdependencies and feedback mechanisms represents a substantial advancement over the static performance measurement systems that have traditionally dominated port management practice (Lam and Notteboom 2014; Sislian and Jaegler 2018). This dynamic perspective

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proves particularly valuable given the temporal delays between strategic interventions and sustainability outcomes, enabling port managers to maintain a long-term strategic orientation despite short-term operational pressures. Moreover, the hierarchical organization of performance indicators across drivers, outputs, and outcomes provides port authorities with diagnostic capabilities essential for adaptive management in evolving regulatory and stakeholder environments (Becker and Caldwell 2015; Shabib et al. 2025).

Several directions for future research follow from the limitations discussed above. The most promising avenue is the quantitative operationalization of the framework through parameterized SD simulation models. Once sufficient longitudinal data on key variables—CO_2 emissions, fuel consumption per vessel, regenerated surface, business density, green energy share, and employment—become available, the causal structure mapped in this study can be translated into a stock-and-flow model and calibrated through historical data. This would enable: (i) ex ante scenario analysis under alternative investment, regulatory, and policy configurations; (ii) sensitivity analysis on key feedback loops; and (iii) ex post assessment of the impact of sustainability strategies on Triple Bottom Line outcomes. Comparative case studies across multiple port authorities operating under different governance and regulatory regimes would further test the analytical generalizability of the framework, while longitudinal investigations could illuminate its utility in guiding long-term sustainability transitions. Ultimately, the framework's promise lies not in providing definitive solutions but in fostering the systemic and dynamic thinking that ports require to fulfill their evolving role as catalysts of sustainable regional development.

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