A Modeling Approach for Strategic Fleet Sizing Under Maritime Sovereignty: Application to the Moroccan National Fleet

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***Abstract*—The disruptions experienced by global supply chains in recent years have reignited the importance of maritime sovereignty, particularly through the creation or reinforcement of national shipping fleets. In this context, the present study explores strategic approaches to national fleet sizing, drawing from recent policy directions and maritime planning models. The study is motivated by the need to design resilient and sovereign fleets that reduce dependency on foreign operators and strengthen autonomy in trade logistics. To complement this analysis, a mathematical model is developed in the form of a Mixed-Integer Nonlinear Programming (MINLP) formulation, where sovereignty is captured through the share of vessel operations under national control. In addition to sovereignty, the model integrates criteria of economic viability, environmental impact, and resilience, positioning Maritime Fleet Sizing within the broader scope of Strategic Transport Planning and Green Maritime Transport. Numerical experiments are carried out on a representative dataset of vessels and strategic routes, illustrating how sovereignty thresholds affect fleet composition and deployment. The results highlight a fundamental trade-off between sovereignty and profitability, emphasizing the need for strategic decision-making that carefully balances autonomy objectives with resilience and environmental considerations. Findings also show that moderate sovereignty thresholds support cost-efficient and diversified fleets, while maximalist sovereignty requirements lead to reduced coverage, higher unmet demand, and lower profitability. These insights underline the importance of calibrated strategies, where Sovereignty, Resilience in Maritime Logistics, and sustainability are treated as interconnected pillars of long-term fleet development.**

Keywords*—*Maritime fleet sizing; sovereignty and national ownership; strategic transport planning; resilience in maritime logistics; green maritime transport

I. Introduction

Africa's maritime domain represents a major strategic asset, essential for economic development and regional integration [1]. Nevertheless, this potential remains largely untapped due to structural vulnerabilities: inadequate port infrastructure, dependence on foreign shipping lines, weak logistical connectivity, and growing security threats. In this context, establishing sovereign national fleets appears as a critical lever to secure economic autonomy and strengthen the trade resilience of African states. Yet, recent studies reveal that the intersection between sustainability, resilience, and sovereignty in supply chain planning remains insufficiently explored, particularly when considering the role of local product promotion and national industrial strategies [2].

The experiences of Nigeria and Ghana during the 1960s to 1980s illustrate the difficulties associated with establishing national shipping companies. These initiatives aimed to reduce dependency on European maritime powers but largely failed due to poor governance, systemic corruption, and the inability to modernize fleets in the face of containerization [3] [4]. The primary lesson for developing countries is the need to avoid politicization in maritime management and to sustain continuous technological upgrading.

The major lesson to be learned by developing countries is that they should avoid politics in the management of the maritime industry and that they should ensure a consistent technological updating. Models of governance that have been the most effective in key worldwide ports have been those that are publicly-owned but privately managed (landlord model) [5] [6]. Excessive privatization makes the ports vulnerable to strategic losses, whereas inflexible governance restrains innovation. The model applicable in developing countries should be a hybrid model that favors the public-private partnerships and still maintains its sovereignty of strategic assets. In this context, Build-Operate-Transfer (BOT) schemes also represent a viable pathway, allowing private actors to finance and operate vessels under sovereign constraints before eventual transfer to public ownership.

The competitiveness of a national fleet is closely linked to the performance of port infrastructures. In [7], the authors demonstrate that improving connectivity and port quality significantly reduces freight costs, facilitating integration into global supply chains. For Morocco, strengthening Tanger Med, Nador West Med, and Casablanca is crucial to support the future sovereign fleet.

An integrated maritime security system, combining surveillance, environmental governance, and regional cooperation, is critical to sustain Morocco's ambitions in the blue economy, and it can only be achieved through the control of economic flows and the sovereignty of its maritime trade [8] [9].

The comparative analysis of African and international experiences shows that the success of a national maritime fleet depends on smart hybrid governance, high-performance infrastructure, integration into global supply chains, and comprehensive maritime security. Morocco's dual maritime façade (Atlantic-Mediterranean interface), its port assets (Tanger Med), and its proximity to the Strait of Gibraltar make it a natural maritime nation, assuming responsibilities as a coastal, port, and flag state [10]. Yet, strategic control over shipping remains fragile in the absence of a national fleet capable of withstanding foreign dependency. As of 2019, nearly 98 per cent of Morocco's external trade depended on maritime transport, while the potential collapse of national operators like IMTC was projected to result in complete reliance on foreign-owned fleets [11].

The key objective of this study is to make a contribution to the strategic planning of the maritime fleet through a structured modeling approach that puts the sovereignty parameter at its center. Indeed, this study will seek to offer a mathematical model applicable to the strategic development of a national commercial fleet, mainly adapted to developing countries such as Morocco.

This study is structured as follows: Section II draws a literature review that covers the approaches that have been taken in relation to the maritime fleet size and mix, typologies of methods used, and gaps that can be addressed through the strategies that are policy-oriented. Section III introduces the proposed optimization model, detailing its decision variables, parameters, and strategic criteria, including cost, sovereignty, environmental impact, and resilience. Section IV discusses the simulation framework, while Section V presents the model's results, and offers analysis and adequate interpretation, mainly regarding the sovereignty parameter, profitability, sustainability and resilience constraints. Section VI concludes and outlines future work.

II. Literature Review

The maritime fleet size and mix problem (MFSMP) constitutes a core research theme in operations research and maritime economics, addressing how to determine the optimal number and types of vessels needed to meet transportation demand under a variety of economic, operational, and regulatory constraints [12]. In the context of emerging economies such as Morocco, where maritime sovereignty, trade resilience, and infrastructure modernization are national priorities, this body of research offers valuable, yet incomplete, tools to guide long-term strategic planning.

Initial work in the area was based on deterministic and static formulations, such as [13]and [14], with optimization of fleet composition usually through linear programming approaches based on the assumption that demand is fixed and that ship types are uniform. Although such models were analytically tractable, they did not deal with long-term investment options, changing market circumstances or maritime lifecycle behavior.

A conceptual shift occurred with the development of multi-period models, commonly described as maritime fleet renewal problems (MFRP). These models are thoroughly discussed in [12], which differentiates between single-period static designs and long-horizon fleet strategies that consider aging of the ships, investment cycles, and changing operational demands. Their work also signals the significance of adaptability to fleet planning, in states wanting to undertake fleet renewal within the context of more general industrial and economic development. In relation to the case of Morocco, the national fleet has fallen from about 70 vessels in the 1980s to less than 20 in the 2020s, which has been seen as a problem of growing size in terms of structural and persistent decline [11]. New developments have focused on the inclusion of uncertainty in models used to size the fleet. Both [15] and [16] have suggested recourse to stochastic programming with regard to variability in charter rates, bunker costs, and demand. These models show the superiority of flexibility in investment and chartering decisions with volatile conditions. In addition to this, [17] presented a rule-based simulation framework to deal with uncertainty in the process of buying and selling and formed a solid foundation of practical application of adaptive maritime policy-making.

The literature has also seen the rise of heuristic and metaheuristic methods, such as genetic algorithms, particle swarm optimization [18], and tabu search, to handle complex routing and heterogeneous fleet structures. While effective in solving tactical-level problems, these approaches often lack a strategic orientation necessary for national-level fleet planning.

From a governance perspective, [19] proposed a typology distinguishing strategic, tactical, and operational fleet sizing decisions. Their classification is of some significance to states such as Morocco, which have to balance long-term capital intensity, infrastructural coordination and policy-driven maritime goals in their fleet-based decisions. Their work also describes structural differences in transportation planning between maritime and land transport planning. Despite these contributions, there are still a number of limitations. The majority of such existing models are oriented towards optimality in the case of firms and are unsuitable to reflect the particular needs of the public sector, which deals with maritime sovereignty, autonomy in trade or industrial capacity building. Also, lack of preset standards constrains cross-case comparisons and dampens the process of transferring modeling knowledge across borders or nationwide.

Table I, Table II and Table III support the fact that there is a need to contribute more to the modelling literature that puts the national policy applicability of results as a main criterion. In Morocco, whose port facilities are developing rapidly, maritime commerce is one of its main strategic platforms. Thus, fiscal investment limitations, dynamic demand, and nationwide governance of maritime logistics require an extensive adjustment of fleet size templates. Such models will be instrumental in informing the design of a resilient, efficient, and sovereign commercial fleet aligned with the country's long-term development trajectory. However, previous legislative reforms have been criticized for their lack of fiscal incentives and failure to embed the Moroccan economic interest, thereby weakening the strategic effectiveness of the national fleet [10].

TABLE I. MODELING-ORIENTED CONTRIBUTIONS

Reference	Transport Type	Modeling Method	Mathematical Approach	Time Horizon	Decision Level	Criteria Included	Geographic Scale	Relevance to Moroccan Case
[17]	Liner Shipping	Simulation + Scenario Analysis	Genetic Algorithms	Short to Mid-term	Tactical	Cost, Uncertainty	Regional (Japan)	Medium
[18]	Offshore / Arctic	Fleet Mix Optimization	Particle Swarm Optimization	Short to Mid-term	Tactical to Strategic	Cost, Uncertainty, Capacity	Arctic (Norway)	Medium
[20]	Industrial and Bulk shipping	Robust Integer Programming	MIP	Mid-term	Tactical	Cost, Capacity, Market	Global	High
[21]	Liner Shipping	System Dynamics	Qualitative + Simulation	Short- term	Tactical	Profit, Carbon emission	Global	High
[22]	Liner Shipping	Stochastic Optimization	Two-Stage SP + Scenario	Long-term	Strategic	Uncertainty, Cost	Global	High
[23]	Liner Shipping	Simulation Models	System Dynamics	Long-term	Strategic	Capacity, Sovereignty	National (Dev. Countries)	High
[16]	Liner Shipping	Scenario-based dynamic programming	MILP	Short to Mid-term	Tactical	Cost, Time	Global	High
[24]	Liner Shipping	Strategic routing problems	Linear Programming / MIP	Long-term	Strategic	Cost, Demand	Global	High
[14]	US Navy	Fleet Planning	Integer Programming	Long-term	Strategic	Cost, Port constraints	National (USA)	Low
[25]	Naval/Military	Strategic Lift Modeling/ AHP	MIP	Long-term	Strategic	Cost, Operational Constraints	National (USA)	Low
[26]	Ship Chartering	Strategic Deployment	Mathematical Optimization	Long-term	Strategic	Cost, Logistics	Global	Low
[27]	Offshore Supply	Routing and Scheduling	Integer Programming	Short-term	Tactical	Cost, Efficiency	National (Norway)	Medium
[28]	Large containerships	Costing Models	DEA	Mid-term	Tactical	Efficiency	Global	Low
[29]	Liner Shipping	Hub & Spoke scheduling	MIP	Short-term	Tactical	Cost, Time	South East Asia	Low
[30]	Liner Shipping	Routing + Fleet Sizing	Set Partitioning + Routing	Short-term	Tactical	Cost, Efficiency	Regional (Norway)	Medium
[31]	Liner Shipping	Network Design Problem	MIP + Heuristics	Long-term	Strategic	Cost, Competition	Global	Medium
[32]	Liner Shipping	Stochastic	Set Partitioning + Heuristics	Long-term	Strategic	Cost, Emission	Firm-level	Medium

TABLE II. POLICY AND STRATEGIC PLANNING CONTRIBUTIONS

Reference	Transport Type	Modeling Method	Mathematical Approach	Time Horizon	Decision Level	Criteria Included	Geographic Scale	Relevance to Moroccan Case
[1]	All types of maritime transportation	N/A	N/A	Long-term	Strategic	Sovereignty, Infrastructure	Regional (East & South Africa)	High
[33]	Coastal Shipping	Case Study + Policy Analysis	N/A	Mid to Long-term	Strategic	Sovereignty, Security	Regional (Sub-Saharan Africa)	High
[8]	All types of maritime transportation	N/A	N/A	Long-term	Strategic	Security, Sovereignty	Continental (Africa)	Medium
[34]	All types of maritime transportation	N/A	N/A	Long-term	Strategic	Sovereignty, Governance	Continental (Africa)	Medium
[4]	All types of maritime transportation	N/A	N/A	Long-term	Strategic	Sovereignty, Governance	Continental (Africa)	Medium
[35]	All types of maritime transportation	N/A	N/A	Long-term	Strategic	Policy & Infrastructure Review	National (Algeria)	Medium
[6]	All types of maritime transportation	N/A	N/A	Long-term	Strategic	Policy & Infrastructure Review	Global	Medium

[36]	All types of maritime transportation	N/A	N/A	Long-term	Strategic	Security, Resilience	Regional (Caribbean)	High
[37]	All types of maritime transportation	Discourse Analysis	N/A	Long-term	Strategic	GHG, Policy Framing	Regional (EU)	High
[38]	Naval/Defense	N/A	N/A	Long-term	Strategic	Resilience, Sovereignty	National (USA)	Medium
[23]	Liner Shipping	Simulation Models	System Dynamics	Long-term	Strategic	Capacity, Sovereignty	National (Dev. Countries)	High
[39]	All types of maritime transportation	N/A	N/A	Long-term	Strategic	Flagging, Sovereignty	National (Germany)	Low
[3]	Liner Shipping	N/A	N/A	Long-term	Strategic	Cost, Utilization	Regional (West Africa)	Medium
[7]	Liner Shipping	N/A	N/A	Long-term	Strategic	Policy & Infrastructure	Regional (Caribbean)	Low
[5]	All types of maritime transportation	N/A	N/A	Long-term	Strategic	Policy & Infrastructure Review	Global	Low
[40]	Naval/Defense	Agent-Based Modeling	Simulation	Mid to Long-term	Strategic	Behavioral, Capacity	National (Indonesia)	Low
[41]	Commercial Fleet	Empirical Performance Analysis	Panel Regression	Long-term	Strategic	Fleet Size, Profitability	National (Korea)	Medium

TABLE III. RESILIENCE, UNCERTAINTY, AND SUSTAINABILITY CONTRIBUTIONS

Reference	Transport Type	Modeling Method	Mathematical Approach	Time Horizon	Decision Level	Criteria Included	Geographic Scale	Relevance to Moroccan Case
[42]	Tramp and Industrial Shipping	Optimization and simulation	Monte Carlo Simulation	Long-term	Strategic	Cost, Uncertainty	National (Norway)	High
[17]	Liner Shipping	Simulation + Scenario Analysis	Genetic Algorithms	Short to Mid-term	Tactical	Cost, Uncertainty	Regional (Japan)	Medium
[43]	Container Shipping	N/A	N/A	N/A	N/A	Cost, Emissions	Atlantic Port cities	Medium
[18]	Offshore / Arctic	Fleet Mix Optimization	Particle Swarm Optimization	Short to Mid-term	Tactical to Strategic	Cost, Uncertainty, Capacity	Arctic (Norway)	Medium
[15]	Industrial /chemical Shipping	N/A	N/A	Mid to Long-term	Tactical to Strategic	Cost, Uncertainty	Arctic (Norway)	High
[44]	All types of maritime transportation	Futures Analysis	Foresight & System Dynamics	Long-term	Strategic	Resilience, Sustainability	Continental (Africa)	Medium
[37]	All types of maritime transportation	Discourse Analysis	N/A	Long-term	Strategic	GHG, Policy Framing	Regional (EU)	High
[45]	All types of maritime transportation	Resilience Index Analysis	N/A	Long-term	Strategic	Resilience, Emissions, security	National (China)	Low
[46]	Liner Shipping	Graph Theory	Non Linera Programming	Long-term	Strategic	Connectivity, Resilience	Global	High
[47]	Industrial /chemical Shipping	Stochastic Optimization	Two-stage Stochastic optimization	Long-term	Strategic	Ageing (retrofit), GHG emissions	Global	High
[22]	Liner Shipping	Stochastic Optimization	Two-Stage SP + Scenario	Long-term	Strategic	Uncertainty, Cost	Global	High
[38]	Naval/Defense	N/A	N/A	Long-term	Strategic	Resilience, Sovereignty	National (USA)	Medium
[40]	Naval/Defense	Agent-Based Modeling	Simulation	Mid to Long-term	Strategic	Behavioral, Capacity	National (Indonesia)	Low
[36]	All types of maritime transportation	N/A	N/A	Long-term	Strategic	Security, Resilience	Regional (Caribbean)	High
[32]	Liner Shipping	Stochastic	Set Partitioning + Heuristics	Long-term	Strategic	Cost, Emission	Firm-level	Medium

III. Modeling Formulation

This section presents the mathematical formulation of the model developed to support sovereign fleet planning. Built as a strategic decision-support tool, the model aims to reflect the multifaceted priorities of public authorities; balancing profitability with national interest, environmental compliance, and operational robustness. Unlike conventional formulations rooted in commercial fleet management [24][48][12], this approach is shaped by the realities of maritime policy in emerging economies, as the renewal of their national fleets requires a long-term framework that integrates logistical needs, industrial ambitions, and environmental constraints [10]. The model developed in this study is specifically tailored to the context of liner shipping operations, where vessels operate on fixed schedules and recurring routes. Other maritime segments, such as tramp shipping or industrial bulk transport, are outside the scope of this research. Indeed, the model simultaneously:

- maximizes the sovereign-adjusted profit generated by the fleet;
- penalizes unmet transport demand to enhance system resilience;
- and internalizes carbon taxation within the economic decision process.

Such an integrated approach responds to critical gaps identified in the literature: the lack of sovereign decision-making frameworks [8] [10] [35], the fragmented treatment of resilience [20][48][18], and the peripheral role of environmental concerns in traditional fleet models [16] [49] [37].

Thus, the model was built in layers, following the logic of national maritime planning. The priority was to simulate investment decisions under sovereign control, that is, to determine which types of vessels should be included in the national fleet, and in what configurations. This led to the formulation of the activation variable y_i, allowing each vessel i to be activated in the fleet, and when combined with the parameter A_{ik}, it reflects the possible configurations like feeder, regional, or deep-sea cargo capacity.

Once vessels were activated, the next layer addressed route assignment. Here, the binary variable x_{ir} determines whether vessel i is assigned to route r, reflecting the planning logic of matching vessel profiles to strategic corridors.

Finally, the third decision layer determines transport capacity deployed, with continuous variable q_{ir} representing the number of containers shipped by each vessel on each route. This variable is bounded by the technical capacity of the vessel, and its aggregation at the route level is compared against demand D_r.

Each of these layers is supported by constraints ensuring investment realism, operational feasibility, and policy compliance (e.g., emission limits). The result is a three-tiered model as illustrated in Fig. 1:

- Activation → strategic planning
- Assignment → operational deployment
- Transport → economic performance

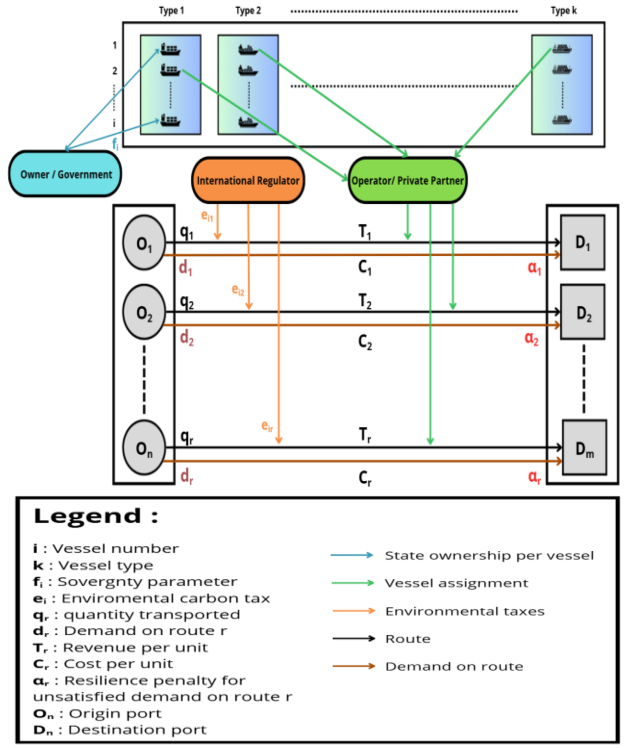

Fig. 1. The conceptual model of strategic fleet sovereignty model.

A. *Sets and Variables*

Let the following sets and parameters be defined:

Sets:

- I: Set of candidate vessels
- K: Set of vessel types (e.g., feeder, post-panamax)
- R: Set of strategic maritime routes

Parameters:

- T_{ir}: Revenue per TEU (Twenty-foot Equivalent Unit) for vessel i on route r
- C_{ir}: Operating cost per TEU for vessel i on route r
- e_{ir}: Carbon cost or penalty per TEU for vessel i on route r
- Q_k: Maximum transport capacity of vessel type k
- f_i : Sovereign ownership or financing ratio of vessel i
- θ : The minimum required average sovereignty ratio for the activated fleet
- α_r : Penalty for unsatisfied demand on route r
- Φ_i: Fixed operating cost for vessel i, incurred only if the vessel is activated.
- d_r : Transport demand on route r (TEUs)
- I_{ik}: Investment cost to activate vessel i as type k

- A_{ik}: A binary parameter equal to 1 if vessel i is from type k
- B : Total investment budget
- E^{max} : Maximum allowable CO_2 emissions

The model's decision variables include:

- $y_i \in \{0,1\}$: 1 if vessel i is activated
- $x_{ir} \in \{0,1\}$: 1 if vessel i is assigned to route r
- q_{ir}: Volume (in TEUs) transported by vessel i on route r

B. Justification of the Sovereignty Coefficient f_i by Vessel type

In order to reflect the importance of maritime sovereignty in the decision-making process of the fleet size and mix problem, the model presents a sovereignty coefficient to each vessel. This coefficient ranges from 0 to 1 and reflects the extent of governmental ownership for each vessel. Higher values indicate a stronger alignment with national sovereignty objectives. These values were determined based on typical ownership patterns, operational zones, and investment accessibility. Table IV summarizes the estimated sovereignty coefficients by vessel type.

TABLE IV. THE ESTIMATED SOVEREIGNTY COEFFICIENTS BY VESSEL TYPE

Vessel Type	f_i	Justification
Feeder	0.90	Frequently used in short-distance regional shipping; often owned or operated by local or national entities, enabling high sovereign control.
Small Handy	0.88	Small-scale vessels suitable for secondary routes, they are commonly accessible to domestic operators or public investment initiatives.
FeederMax	0.85	Larger than standard feeders, they are often deployed in extended regional services, typically still under partial or full national control
Panamax	0.70	Moderate capacity vessels able to transit the Panama Canal. Some national fleets operate them, though many are controlled by international shipping lines.
Medium Containership	0.65	Typical in mid-range logistics, they are widely deployed by global carriers but still present in some sovereign or mixed-ownership fleets
Post-Panamax	0.60	Larger vessels mostly integrated into the global fleet, they are generally inaccessible to smaller national actors.
Neo-Panamax	0.55	Designed for the expanded Panama Canal, their ownership and deployment are dominated by large international companies.
ULCV (Ultra Large Container Vessel)	0.40	Among the largest vessels globally (>20,000 TEUs), they are typically owned by a few multinational giants, making sovereign control highly unlikely

C. The Objective Function

This objective function captures the sovereignty-weighted profit, penalizes unmet demand to simulate resilience, and internalizes the investment cost of sovereign fleet expansion. The introduction of f_i as a decision-dependent parameter transforms the model from a cost-efficiency tool into a policy-aligned mechanism for state-led fleet control. This approach directly addresses gaps noted by [8] [21][44], who highlight the lack of sovereign metrics in operational maritime models. The objective function is defined as:

$$Max \sum_{i \in I} \sum_{r \in R} f_i \, . \, x_{ir} . (q_{ir} \, . (T_{ir} - C_{ir}) - \sum_{i \in I} \Phi_i \cdot y_i - \sum_{i \in I} \sum_{r \in R} e_{ir} . x_{ir} - \sum_{r \in R} \alpha_r \, . (d_r - \sum_{i \in I} q_{ir}) - \sum_{i \in I} \sum_{k \in K} f_i \, . \, \mathrm{I}_{ik} \, . A_{ik} . y_i$$

The objective function combines five components that consider the strategic, economic and environmental priorities of the model. The first term maximizes revenue on the transported volumes, weighted by the ratio of the sovereign ownership, hence encouraging national control over the maritime activities. This form of structural representation of sovereignty covers one of the key deficiencies of the traditional form of fleet sizing models under the assumption of neutrality in ownership structure [14][4][1]. The second term reflects the fixed costs of operation that are incurred when a vessel is activated, which is a consideration to make the fleet composition selective. The third term is about the carbon charges imposed on routes so as to discourage environmental externalities and make sure that environmental concerns are fulfilled based on deployment considerations. The fourth term will impose the demand unmet as a penalty, which aligns with recent findings highlighting how managing demand uncertainty through cooperative and sustainable sourcing strategies can strengthen resilience, especially in contexts aiming for national or regional autonomy [50]. Lastly, the fifth term, which is the sovereign investment costs, scaled by the ownership ratio, reflects the financial implications of an increase in capacity controlled by the government.

The objective function includes a bilinear term of the form:

$$\sum_{i \in I} \sum_{r \in R} f_i \, . \, x_{ir} . (q_{ir} \, . (T_{ir} - C_{ir})$$

This term contains the product of the binary decision variable x_{ir} and the continuous variable q_{ir}. This nonlinearity cannot be directly handled by linear optimization solvers. To address this, an auxiliary variable Z_{ir} is introduced to represent the product:

$$Z_{ir} = x_{ir} . q_{ir}$$

This variable is then linked to x_{ir} and q_{ir} through the following linear constraints, involving a sufficiently large constant M (Representing the upper bound of transported volume q_{ir}):

$$\begin{cases} Z_{ir} \le q_{ir}, \forall \, i \in I, r \in R \\ q_{ir} \le M . x_{ir}, \forall \, i \in I, r \in R \\ Z_{ir} \le M . x_{ir}, \forall \, i \in I, r \in R \\ Z_{ir} \ge q_{ir} - M(1 - x_{ir}), \forall \, i \in I, r \in R \end{cases}$$

The original bilinear expression in the objective function is then replaced by the linear term:

$$\sum_{i \in I} \sum_{r \in R} f_i \,.\, Z_{ir} \,.\, (T_{ir} - C_{ir})$$

D. Constraints

The model is subject to the following strategic and operational constraints:

1) Single Route Assignment per Vessel

$$\sum_{r \in R} x_{ir} \leq 1, \forall i \in I$$

This constraint ensures that a vessel is not assigned to more than one route, simultaneously.

2) Vessel activation condition

$$x_{ir} \leq y_i \;\; \forall\, i \in I, r \in R$$

Prevents deployment of vessels not activated [51].

3) Capacity Limit by Type

$$q_{ir} \leq \sum_{k \in K} Q_k . A_{ik} . y_i \;\; \forall\, i \in I, r \in R$$

Restricts capacity usage to actual vessel capability, as in [16] and [39].

4) Partial Demand Coverage (Resilience)

$$\sum_{i \in I} q_{ir} \leq d_r \;\; \forall\, r \in R$$

Allows under-supply, simulating strategic bottlenecks. This model's resilience is formalized by [20] and [48].

5) Investment Budget

$$\sum_{i \in I} \sum_{k \in K} f_i . \mathrm{I}_{ik} . A_{ik} . y_i \leq B \;\; \forall\, r \in R$$

Controls sovereign expenditure [22].

6) Environmental Emission Cap

$$\sum_{\boldsymbol{i \in I}} \sum_{\boldsymbol{r \in R}} \boldsymbol{e_{ir} . x_{ir}} \leq \boldsymbol{E^{max}}$$

Enables regulatory compliance and green planning strategies [37] and [36].

7) Sovereignty

$$\sum_{i \in I} f_i \, y_i \geq \theta \sum_{i \in I} y_i$$

8) Variable Domains

$$y_i \in \{0,1\}, x_{ik} \in \{0,1\}, q_{ir} \geq 0$$

E. Assumptions

The proposed model relies on a series of simplifying assumptions aimed at ensuring both analytical tractability and strategic relevance. These assumptions are consistent with the intended use of the model as a strategic planning tool for long-term maritime policy design. First, the model is developed as a deterministic, single-period formulation, representing a strategic decision snapshot over a long-term planning horizon (10 years or more). This choice reflects the irreversible and capital-intensive nature of fleet investment decisions, where vessel acquisition and sovereign activation are made on a long-term basis and are not subject to frequent revision. Similar simplifications are made in strategic logistics models dealing with infrastructure design or energy fleet mix [12] [44]. Second, transport demand on each route $d_r$is treated as known and deterministic. This is justified by the model's focus on national routes of strategic importance (e.g., connecting major ports or corridors), for which long-term projections are available from port authorities or national development plans. This assumption avoids the complexity of scenario modeling or stochastic programming, while still allowing partial satisfaction of demand via the resilience penalty. Third, the environmental taxation is modeled through a fixed carbon cost per TEU e_{ir} , which is not influenced by minor variations in vessel load. This simplification acknowledges that while actual emissions vary with loading conditions and speed profiles [49], policy-applied taxes and penalties often use standardized rates per unit transported, as recommended in IMO and EU carbon schemes. This assumption is reasonable for strategic planning where environmental constraints are treated as policy ceilings rather than engineering simulations [37] [36]. Then, we assume that each vessel can be assigned to at most one route, and its transport volume q_{ir} is dedicated entirely to that route. This assumption reflects the model's focus on permanent or seasonal deployment planning, rather than flexible daily scheduling. It is particularly relevant for state-led services (e.g., national supply corridors, food security logistics) where vessels are dedicated based on geopolitical or regional priorities [8] [18]. Also, the model does not assume any preferential match between vessel types and demand profiles. Instead, vessel type selection (via y_{ik}) and route assignment (via x_{ir}) are endogenously determined by the optimization process. This allows for flexibility in configuring the fleet to meet evolving transport and policy requirements. Finally, all costs (investment, operational, and environmental) and revenues are either modeled linearly or linearized using linearization techniques. This allows the use of mixed-integer linear programming (MILP) techniques, which are well-established in fleet sizing literature and offer reasonable solvability even for large-scale problems [48] [12].

IV. Simulation Framework

The simulations were carried out on a typical desktop personal computer with Intel core i7 1.9 GHz and 16 GB of RAM. Pyomo modeling framework was used to write the optimization model in Python, and used SCIP 9.2.2, an open-source high performance solver for mixed-integer linear programs developed by the Zuse Institute Berlin (ZIB). It is a compilation of the solver added in optimized mode, 8-byte precision and based on SoPlex 7.1.4 as its LP backend.

Importantly, the Branch & Cut algorithm was employed to ensure the derivation of exact optimal solutions, reinforcing the model's credibility for strategic-level decision-making.

The computational tests were based on a realistic configuration involving 100 candidate vessels, 230 strategic maritime routes, and 8 vessel types, as per Table IV. The choice of 100 vessels and 230 routes is justified by the ambition of Morocco, as an example of an emerging country, to rebuild its national maritime fleet by 2040. The full model formulation resulted in a total of 69,100 variables, of which 23,100 are binary and 46,000 continuous, underlining the combinatorial complexity of the problem. To evaluate the model's behaviour under different sovereignty priorities, four simulations were performed by varying the minimum average sovereignty threshold parameter θ:

- Low requirement ($\theta = 0.25$)
- Moderate requirement ($\theta = 0.50$)
- High requirement ($\theta = 0.75$)
- Sovereignty-maximalist ($\theta = 0.88$)

During every run, the model produced the most favorable sizes of the fleet, the composition of the vessels, route assignments, and volumes transported. Randomly generated values of inputs and in calibrated bounds based on real maritime benchmarks have been considered without violation of investment, capacity, emission and policy constraints. An observation of the computational performance was made in every scenario. The calculation time was between: 330.61 seconds ($\theta = 0.25$), 401.49 seconds ($\theta = 0.50$), 402.91 seconds ($\theta = 0.75$) and 549.99 seconds ($\theta = 0.88$), denoting increases in time needed to solve based on severe sovereignty constraints.

V. RESULTS

In order to evaluate the model's response to real-life problems, different scenarios were examined to highlight the trade-offs between cost and fleet sovereignty, environmental influences and resilience. The analysis reveals the way in which changes of strategic priorities alter the optimal structure and utilization of the fleet. It also sheds light on how the transport demand and environmental aspects are impacted.

A. Fleet Mix, Size and Activation Patterns

The optimization outcomes indicate a similar pattern in the vessel activation decisions in all scenarios, as shown in Table V. At best, the model prefers a smaller, more effective fleet mix that is mainly composed of mid-sized vessels: Feeder, Medium CS, and Small Handy under a smaller threshold of sovereignty ($\theta = 0.25$ and $\theta = 0.50$). As θ increases, reflecting higher sovereignty constraints, the diversity of activated vessels drops drastically, and total activation volume declines, particularly on high-volume routes.

When $\theta = 0.88$, the model heavily prioritizes vessels with the highest sovereignty scores, even at the cost of reduced transport capacity and higher unmet demand. Notably, the vessels of type ULCV and Panamax family (Panamax, Post-Panamax and Neo-Panamax) are consistently excluded across all scenarios.

Regarding the fleet size, Table VI illustrates the evolution of total fleet size per scenario. When $\theta = 0.25$ or $\theta = 0.50$, the model result is respectively a fleet of 17 vessels that are cost-efficient and sovereignty sensitive. The number of activated vessels increases significantly to 53 when $\theta = 0.75$, suggesting a diversification strategy that covers a wider range of demand. However, the number of activated vessels decreases to 18 once more when the sovereignty constraint reaches $\theta = 0.88$.

TABLE V. ACTIVATED VESSEL TYPES PER SOVEREIGNTY SCENARIO

Vessel Type		Sovereignty Score (f_i)	θ = 0.25	θ = 0.50	θ = 0.75	θ = 0.88
Feeder		0.90	Yes	Yes	Yes	No
Feedermax		0.85	No	No	No	No
Small Handy		0.88	Yes	Yes	Yes	Yes
edium CS		0.65	Yes	Yes	Yes	No
Panamax		0.70	No	No	No	No
Post-Panamax		0.60	No	No	No	No
Neo-Panamax		0.55	No	No	No	No
ULCV		0.40	No	No	No	No

TABLE VI. TOTAL NUMBER OF ACTIVATED VESSELS PER SCENARIO

Sovereignty Threshold (θ)	Number of Activated Vessels	Comments
0.25	17	The fleet remains compact
0.50	17	The fleet is almost as per the scenario θ = 0.25
0.75	53	High increase in fleet size
0.88	18	Many high-capacity ships excluded

B. Economic Viability and Profitability

The objective value, representing the sovereignty-adjusted fleet profit, steadily decreases as the sovereignty requirement intensifies. At $\theta = 0.25$ and $\theta = 0.50$, the model yields high optimal values of respectively 8.67 and 8.63 million units. At $\theta = 0.88$, the profit collapses to just 62.8k units due to strict filtering of eligible vessels. Fig. 2 presents the evolution of optimal objective value by sovereignty threshold.

C. Environmental Factor

Table VII and Table VIII presents the top ten most carbon-efficient vessel-route pairings across the four sovereignty scenarios, ranked by the lowest carbon penalty per TEU transported. A consistent trend emerges: vessels with lower emission coefficients (e_{ir}) are consistently allocated to high-volume corridors, regardless of the sovereignty constraint level θ. When the sovereignty threshold is low or moderate ($\theta = 0.25$, $\theta = 0.50$, $\theta = 0.75$), the allocation tends towards vessels with the best criteria in terms of cost, emissions, and sovereignty. The pool of eligible vessels, however, drastically shrinks when $\theta = 0.88$. Consequently, the model's capacity to sustain environmentally optimal decisions is weakened.

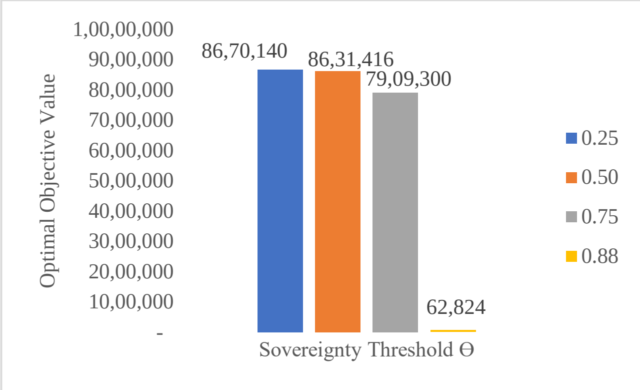

Fig. 2. Evolution of optimal objective value by sovereignty threshold.

TABLE VII. TOP TEN CARBON EFFICIENT PAIRING PER θ

$\theta = 0.25, \theta = 0.50, \theta = 0.75$				
Vessel Id	***Route ID***	***Vessel Route pair***	q_{ir}***value***	e_{ir}
v82	route187	v82route187	120	0,668
v15	route21	v15route21	120	0,668
v18	route66	v18route66	120	0,672
v51	route15	v51route15	120	0,674
v49	route156	v49route156	120	0,678
v1	route187	v1route187	120	0,68
v58	route180	v58route180	120	0,683
v14	route12	v14route12	120	0,683
v76	route56	v76route56	180	1,003
v64	route67	v64route67	180	1,029

TABLE VIII. TOP TEN CARBON EFFICIENT PAIRING PER $\theta = 0.88$

$\theta = 0.88$				
Vessel Id	***Route ID***	***Vessel Route pair***	q_{ir}***value***	e_{ir}
v86	route125	v86route125	15	0,223
v72	route75	v72route75	15	0,234
v92	route37	v92route37	15	0,256
v11	route145	v11route145	15	0,3
v33	route19	v33route19	15	0,435
v94	route68	v94route68	15	0,437
v35	route44	v35route44	15	0,52
v93	route77	v93route77	15	0,56
v8	route114	v8route114	15	0,561
v71	route90	v71route90	120	2,256

D. Resilience and Demand Satisfaction

Resilience, interpreted here through transport demand coverage and unmet demand penalties α_r, exhibits a clear decline when $\theta = 0.88$. For $\theta = 0.25$, $\theta = 0.50$ and $\theta = 0.75$, almost all routes are served, with over 95 per cent of demand satisfied, as shown in Table VII and Table VIII. When $\theta = 0.88$, only a fraction of strategic routes are covered, and small-capacity vessels are unable to absorb large volumes, triggering unmet demand costs.

VI. DISCUSSION

Besides the numerical results, special consideration must be paid to the realization of policy aspects emerging from each scenario. These insights are essential for decision-makers, who must balance short-term financial constraints with the long-term goals of maritime sovereignty and sustainable fleet development.

The analysis highlights that strategic trade-offs become visible through the activation patterns of the fleet. At lower sovereignty thresholds, the solutions consistently point towards compact and efficient fleet structures, largely composed of mid-sized vessels such as Feeders, Medium Containerships, and Small Handies. These vessel types have moderate purchase prices, viable carbon footprints and strong national ownership ratings, making them well-aligned with economic viability and sovereignty objectives. When sovereignty requirements are raised, a marked contraction of fleet diversity is observed, with significant reductions in activation volumes, especially on high-demand routes. Comparable patterns are observed in recent models of oligopolistic 3PL competition, where environmental and digital imperatives, such as IoT adoption, directly affect pricing and deployment strategies [52], confirming the central role of sovereignty and sustainability in nowadays logistics network design. Indeed, the exclusion of vessels of type ULCV and Panamax family (Panamax, Post-Panamax and Neo-Panamax) confirms their incompatibility with a sovereign-oriented national fleet due to their high acquisition cost, foreign dominance, and operational scale requirements. This evolution highlights a fundamental trade-off that underlies the nature of strategic fleet planning: the higher maritime sovereignty becomes a central goal, the more the model leans toward limited vessel options. As a matter of fact, these results justify the choice of several developing maritime nations of the cabotage or the Short-Sea Shipping (SSS) as a strategic choice, leaving the long routes and corridors to international firms.

The discussion of activation patterns must also be complemented by the evolution of the fleet size. When $\theta = 0.25$ or $\theta = 0.50$, the model result is respectively a fleet of 17 vessels that are cost-efficient and sovereignty sensitive. Consequently, the profitability is maintained without overextending the fleet thanks to this controlled activation, which follows the logic of economic viability. The number of activated vessels increases significantly to 53, when $\theta = 0.75$, suggesting a diversification strategy that covers a wider range of demand. However, the number of activated vessels decreases to 18 once more when the sovereignty constraint reaches $\theta = 0.88$. Because of the model's stringent national control, which prevents many large-capacity vessels from activating, this represents a strategic narrowing. The trade-off between autonomy and scale is highlighted by this fluctuation in fleet size: operational breadth is given up in order to preserve political and financial control over maritime assets as sovereignty is maximized.

From an economic perspective, the steady reduction in profit with increasing sovereignty thresholds highlights the measurable financial cost of sovereignty. This degradation, as shown in Fig. 2 , reflects the inherent cost of sovereignty prioritization: limiting access to high-capacity, cost-efficient ships translates into suboptimal network coverage and inflated operational expenses. Moreover, investment costs rise with the number of activated vessels needed to meet coverage requirements under constrained types.

Moderate thresholds preserve profitability, whereas maximalist sovereignty requirements collapse economic performance by excluding cost-efficient, large-capacity vessels. From a policymaking perspective, this analysis helps quantify the economic sacrifices associated with asserting maritime sovereignty, a pivotal trade-off at the core of strategic fleet planning.

The analysis further reveals how sovereignty constraints shape environmental outcomes and carbon efficiency. The results in Table VII and Table VIII show that the optimization algorithm favors vessels with strong environmental performance, especially on high-demand routes. At a lower or moderate sovereignty threshold, the model benefits from greater flexibility in vessel selection. Consequently, a balance is set between minimizing environmental impact and maximizing capacity utilization. At a higher sovereignty threshold, the model still finds a core set of ships that meet national ownership requirements and environmental standards, pointing to the potential for a foundational "sovereign-green" fleet. Similar findings are reported in recent stochastic ship design models, which show that LNG and methanol configurations are relatively robust initial choices because of their retrofit potential towards ammonia or hydrogen, providing flexibility under uncertain fuel and carbon prices [53]. One noteworthy finding is that, when this restriction is rigorously enforced, vessels with low sovereignty ratings but high environmental scores are left out of the solution, underscoring the dominating influence of sovereignty. This highlights a significant obstacle in sustainable fleet planning: if national control goals are involved, carbon efficiency alone is insufficient. In fact, recent studies underline that decarbonization policies will require more than technological improvements, as carbon pricing and alternative fuels are expected to significantly reshape fleet economics [54].

When combined, these results highlight the necessity of well-thought-out investment plans. Consequently, for countries such as Morocco, the government must encourage the retrofitting or local purchase of mid-sized ships that combine acceptable emissions profiles with significant national ownership potential, if it hopes to build a fleet that is both sovereign and environmentally conscious.

These insights may guide targeted green fleet development, especially for routes with high transport demand and strict environmental thresholds.

As per the resilience analysis, captured through demand coverage, the simulation underscores the systemic fragility introduced by overly restrictive sovereignty rules. The simulation highlights a resilience paradox: while sovereign fleets may be politically desirable, they may also struggle to absorb operational shocks or meet rising freight demand, unless complemented by supportive policy instruments or hybrid strategies (e.g., public-private joint ventures).

To validate the consistency of the proposed model, the sovereignty coefficient f_i was neutralized (set to 1 for all vessels), so that the formulation approximates a standard fleet sizing problem. The model's results in this sovereignty-free form are in line with two well-known studies [46] and [16]. The model emphasizes how operational costs and vessel capacity shape fleet composition. While smaller units offer flexibility, larger ships dominate when demand is high and costs are crucial. Thus; it concentrates on strategic fleet composition and environmental penalties, while [46] prioritized sailing speed and detailed routing. Despite this, both models converge toward a similar balance between cost effectiveness, emissions, and fleet diversity. Moreover,[16] who investigated multi-period fleet deployment under demand uncertainty, show also a similar alignment. The model's sovereignty-free version demonstrates that, in the absence of policy restrictions, demand satisfaction and profitability naturally determine the best fleet composition. The main difference is temporal: the current model is single-period and strategic, whereas [16] consider multi-period stochastic dynamics, but the fundamental economic reasoning is the same.

Importantly, only sovereignty was neutralized for this validation. Other parameters, such as resilience penalties and environmental constraints, were preserved because they form an integral part of the model's originality and are not explicitly treated in [16] and [46]. By incorporating sovereignty as a new strategic criterion, the suggested model not only replicates the insights of [46] and [16] but also builds upon them, ensuring that the comparison is both equitable and methodologically sound.

When combined, these results highlight how sovereignty-maximalist methods diminish resilience, flexibility, profitability, and environmental performance, making them insufficient to maintain strategic autonomy on their own. The implications for policymakers are clear: calibrated strategies that balance national control with operational and economic viability are essential. As a result, the model offers a decision-support tool that highlights the risks to resilience and measures the financial and environmental costs of sovereignty.

The limitations of this study must also be acknowledged. Long-term dynamics and uncertainty are simplified by the single-period, deterministic formulation. To improve realism, extensions should include geopolitical risk factors, stochastic trade flows, and multi-period horizons. In order to scale the model to larger problem instances, future research could also investigate heuristic or hybrid solution approaches. As a matter of fact, recent studies emphasize that near-zero emission fleet transitions depend on integrated strategies that jointly address renewal, deployment, and alternative fuel adoption under multiple sources of uncertainty [55]. Notwithstanding these drawbacks, the model already provides valuable information for building autonomous, robust, and sustainable fleets in developing maritime countries.

VII. Conclusion

This study introduces a strategic fleet sizing model tailored for public maritime authorities operating under sovereignty, environmental, demand coverage, and budgetary constraints. Through a sovereignty coefficient, the model directly incorporates national interest into the objective function, in contrast to traditional firm-level optimization techniques. It uses a mixed-integer formulation based on liner shipping dynamics and public policy considerations to capture decision-making at three levels: vessel activation, route assignment, and deployment of transport volumes.

The trade-offs brought about by sovereignty constraints are demonstrated by computational experiments conducted on a medium-scale dataset (100 vessels, 230 routes). The model gives cost-effectiveness and environmental performance priority at lower thresholds. However, the solution space shrinks as sovereignty requirements increase: the fleet is more vulnerable to resilience threats, flexibility decreases, and demand coverage deteriorates. Although a sovereignty-maximalist approach supports the goals of national control, it significantly reduces the network's overall capacity and economic viability.

These results highlight the significance of calibrated policymaking. Rigid constraints alone cannot sustain sovereignty and strategic autonomy. Indeed, a delicate balance between operability and control is needed. For maritime nations like Morocco, the suggested model provides a useful tool for decision-making that helps in resolving the delicate conflict between sovereign imperatives and economic rationality. Subsequent extensions might investigate dynamic, multi-period formulations or add uncertainty by incorporating geopolitical risks and stochastic trade flows. Nevertheless, the model already offers important information for building robust national managed fleets.

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Declaration of Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

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