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Towards Maritime Network Transition Scenarios for 2050 in the Ligurian Sea

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Abstract. Maritime transport and port systems are facing major transformations driven by decarbonisation, vessel automation, and the growing digitalisation of navigation and port logistics. These changes are likely to affect shipping routes, service organisation, the expected skillset of workers, and port hierarchies within regional maritime systems. This paper presents a methodological framework to investigate possible maritime network transitions in the Ligurian Sea up to 2050 within the Interreg Marittimo JASON project. The study area is treated as a cross-border navigation system linking the French and Italian Riviera and Monaco, with strong interactions between dense traffic corridors, major and secondary ports, supervision systems, and environmentally sensitive zones such as PELAGOS. We intend to use Automatic Identification System (AIS) trajectories with complementary data on vessel characteristics, port infrastructure, weather and operational hazards, and environmental constraints. On this basis, General Morphological Analysis (GMA) will be used to structure a scenario space and to compare three tentative illustrative transition archetypes for 2050. The proposed framework is intended to specify the data used for the case study, and show how contrasting maritime futures can support the discussion of network evolution, port adaptation, and reskilling needs.

1 Introduction

Maritime transport is currently undergoing major transformations driven by environmental constraints, technological innovation, and the reorganisation of global and regional logistics systems. The pressure to reduce greenhouse gas emissions is fostering changes in vessel propulsion [1], energy needs and operational practices [2], while advances in automation and digital navigation are opening new perspectives for traffic management and service coordination. These developments are not confined to ships alone. They are also likely to affect ports, service networks and the spatial organisation of maritime flows. In this context, maritime transition must be understood not only as a technological shift, but also as a broader reconfiguration of transport systems and port-related territorial dynamics.

From the perspective of maritime transportation, these changes raise questions about the future organisation of shipping routes [3], the distribution of maritime services, and the

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evolving role of ports within regional and international networks [4]. Decarbonisation may reinforce some ports as strategic refuelling and service nodes, while marginalising others that are less able to adapt their infrastructure [5]. At the same time, increasing automation and smart navigation [6] may alter routing practices, operational efficiency, and the relationship between major hubs, feeder services, and secondary ports. The issue is therefore not simply whether maritime transport will become greener or more technologically advanced, but how these transitions will reshape the geography of maritime circulation and redefine port hierarchies. Because such changes depend on interacting technical, economic, regulatory, and spatial factors, they cannot be reduced to a single linear trajectory.

The Ligurian Sea offers a particularly relevant case study for examining these issues. As a dense cross-border maritime space structured by major traffic flows, the central role of Genoa as a regional hub for maritime traffic, and strong coastal interfaces between Italy, France, and Monaco, it provides an appropriate setting for observing how route structures, port functions, and territorial organisation interact. Within the Interreg Marittimo JASON project, the issue is not only to describe future traffic, but also to determine what adaptation and reskilling strategies may be required to preserve maritime performance as technologies, fuels, and operating constraints evolve towards 2050. JASON addresses three contexts, namely navigation, port activities, and cybersecurity, although in this paper we mainly focus on navigation. This focus leads us to analyse the Ligurian Sea as a socio-technical navigation system composed of routes, vessel movements, ports, supervisory entities and environmental constraints. The presence of an ecologically sensitive sub-area such as PELAGOS strengthens the relevance of the case study for discussing trade-offs between traffic performance, safety, and environmental protection.

Against this background, this paper proposes a methodological framework and a first set of tentative illustrative scenarios to explore possible future transformations of maritime transport and port organisation in the Ligurian Sea up to 2050. The approach combines a reconstruction of the current maritime network with a morphological analysis designed to generate a structured set of coherent transition scenarios. More specifically, this paper clarifies the operational framing of the JASON project for the navigation theme, specifies the data used to reconstruct the current maritime network, and tentatively shows how different combinations of decarbonisation pathways, levels of vessel autonomy, navigation-system evolution, infrastructure adaptation, and operational constraints can be grouped into different scenario archetypes. The remainder of the paper presents the case-study design, the data model, the GMA procedure, and three tentative illustrative scenarios, before discussing their implications for maritime transport systems, port adaptation, and reskilling needs.

2 Research Design

2.1 Case-study perimeter and project context

Within the JASON project, the operational question discussed with partners can be formulated as follows: what adaptation strategy for skills and organisations is required to preserve maritime performance in the face of technological change in maritime transport by 2050? In the full project this question is to be studied through three complementary approaches: navigation, port systems, and cybersecurity, although in this paper we focus mainly on navigation. The performance criteria retained at this stage are environmental performance, maritime safety and security, and, more selectively, the economic robustness of transport and port operations. This framing is important because it determines both the data to be mobilised and the dimensions to be retained in the scenario-building process.

The case-study perimeter is the Ligurian maritime region (within the Interreg Marittimo area that encompasses the French administrative subdivisions of Var, Alpes-Maritimes and Corsica, and the Italian administrative subdivisions of Liguria, Sardinia, and the coastal provinces of Tuscany), understood as a cross-border navigation area. The unit of analysis is therefore the navigation system that connects routes, vessel movements, port calls, onboard systems, supervision frameworks, and exposed marine environments. Particular attention is paid to high-density routes, to the relationship between the dominant hub of Genoa and secondary coastal nodes (such as Toulon, Savona, La Spezia, Leghorn, Sassari and Cagliari), and to environmentally sensitive areas that may constrain routing or speed management. In this sense, the Ligurian Sea is used both as a transport network and as an operational space in which environmental and safety requirements may reshape circulation patterns.

2.2 Data used and baseline reconstruction

The empirical baseline combines several complementary families of maritime data. AIS trajectories constitute the core data because they provide time-stamped information on vessel positions, speed, and course, and therefore allow the reconstruction of traffic densities, main corridors, and port-to-port connections. These trajectories are complemented by vessel descriptors (type of ship, size, cargo or service profile, and, when available, propulsion/fuel characteristics), by port and supervision information, and by contextual layers describing weather, hazards, and sensitive marine environments. The purpose is not to isolate AIS as a self-sufficient source, but to embed traffic traces in the broader socio-technical system of navigation emphasised during the JASON workshops.

Table 1: Data families used to reconstruct the Ligurian baseline

Data family	Examples of variables	Role in the baseline
AIS trajectories	Positions, speed, course, port-call sequences	Reconstruct route density, corridors, and port links
Vessel descriptors	Ship type, size class, cargo or service profile, propulsion/fuel information	Differentiate traffic segments and adaptation capacity
Port and supervision data	Port functions, support infrastructures, traffic-management and supervision arrangements	Relate flows to nodes, control capacities, and organisation
Environmental and hazard data	Weather, marine hazards, sensitive ecosystems such as PELAGOS	Identify constraints on routing, speed management, and ecosystems

In analytical terms, the baseline is built in three steps. First, AIS tracks need to be cleaned and aggregated to identify recurrent route segments, traffic-density zones, and port calls. Second, these movements are related to vessel categories and port functions so that the regional network can be described not only as a set of lines, but as a structured system of operational services. Third, environmental and supervision layers are superimposed on the traffic network in order to highlight where future transformations may occur, driven by ecological constraints, weather exposure, or changes in traffic management. This baseline is not exhaustive in terms of maritime operations, but it provides a sufficiently explicit reference configuration for comparing future scenarios.

3 Scenario-building method

3.1 The General Morphological Analysis

Given the multiplicity of drivers involved in maritime transition and the absence of predictive models that are able to integrate technological, organisational, environmental, and regulatory changes, a scenario-building approach is particularly appropriate for exploring possible future configurations of transport and port systems. The chosen method is General Morphological Analysis (GMA), first developed by Fritz Zwicky in the 1940s and later adapted to strategic and policy problems. We take as an example the case study developed by Johansen in [8], with a focus on Norwegian defence. For the JASON project, GMA is especially relevant because it can handle many heterogeneous parameters, including qualitative variables, uncertain relations, and limited (or uncertain) data availability. The evolution of maritime networks cannot be inferred from a single determinant, since it depends on the interaction between technological change, environmental regulation, infrastructure adaptation, operational constraints, and institutional choices. In such a context, GMA offers a useful framework for structuring prospective reasoning without reducing future developments to a linear forecasting exercise. The method, whose steps are shown in Figure 1, is used here to organise a space of plausible futures within which the possible reconfiguration of shipping routes, port functions, and regional maritime organisation can be examined in a comparative way.

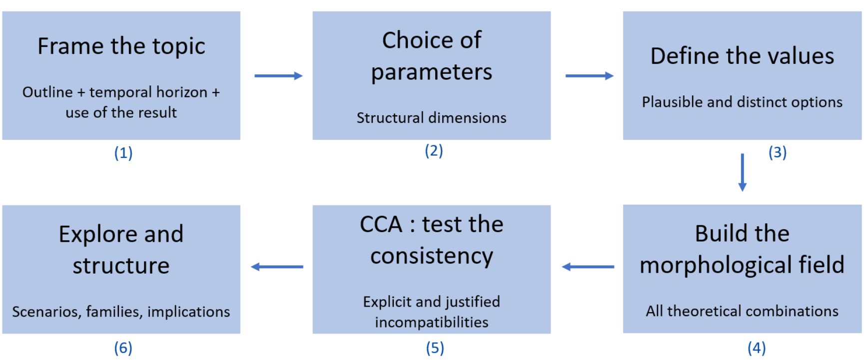

Figure 1: The six steps of the General Morphological Analysis

In the JASON navigation case, the preliminary morphological field is organised around a limited number of structuring parameters that are to be identified during the workshop phase: and tentatively those parameters will revolve around the concepts of vessel profile, propulsion and fuel pathway, level of autonomy, traffic density, route organisation, intensity of environmental and climatic constraints, and the degree of digital supervision and coordination. For each of the identified parameters within those concepts, several distinct values are defined so as to include both gradual transitions and rupture options by 2050. Taken together, these parameters and values form a morphological field that captures both the technical evolution of vessels and the territorial reorganisation of maritime circulation.

Because not all theoretical combinations of parameter values are meaningful, the morphological field is then subjected to a cross-consistency assessment (CCA). Following the classical GMA logic, pairs of values are examined and discussed as compatible, incompatible, or context-dependent. This step is particularly useful in the Ligurian case because some combinations that are technically possible in abstract terms become weak once port equipment, ecological constraints, traffic density, or governance arrangements are considered together. CCA therefore reduces the initial combinatorial space and makes the underlying assumptions explicit, which is essential both to the scientific approach and to the collective validation within the framework of the JASON project.

At this stage, the coherent configurations retained after consistency assessment are grouped into a limited number of representative archetypes. The purpose is not to forecast a single future, but to compare contrasted classes of transition and to use them as supports for subsequent discussion on resilience and reskilling. Three tentative archetypes, presented here only for the sake of illustration, are shown below as tentative examples of how the scenario space can be interpreted for the Ligurian Sea.

3.2 Exemplification with tentative scenario archetypes

In this subsection, we present an example of what the scenario archetypes could look like. They are still hypothetical, and presented here for the sake of the example.

Scenario 1: Green corridor concentration. In this configuration, decarbonisation is driven by a relatively small number of highly equipped ports able to supply alternative fuels and support advanced digital coordination. Major hubs capture most innovation and traffic growth, while secondary ports remain connected through feeder or specialised services. Route structures become more selective and corridor-based, and reskilling needs concentrate on new propulsion systems and digitally assisted traffic coordination.

Scenario 2: Distributed regional adaptation. In this scenario, the energy transition is more gradual and its benefits are spread across several ports and vessel categories. Automation progresses, but remains partial and heterogeneous, allowing conventional and low-emission fleets of vessels to coexist for a long transition period. The maritime network remains relatively dense and polycentric, with several coastal nodes adapting incrementally. Reskilling is therefore distributed across ship operators, port services, and supervision actors rather than concentrated in a few major hubs.

Scenario 3: Eco-constrained supervised navigation. In this configuration, environmental protection and exposure to operational hazards become dominant structuring constraints. Sensitive zones such as PELAGOS, weather variability, and tighter safety requirements lead to stronger routing, speed-management, and monitoring measures. Port hierarchy is redefined less by fuel supply alone than by the ability to integrate compliance and environmental performance. The main reskilling needs concern monitoring, risk interpretation, incident management, and the handling of increasingly data-fed supervision systems.

4 Discussion and conclusions

The comparison of these illustrative tentative archetypes raises various issues in the analysis of maritime transition in the Ligurian Sea. We have to consider that the future of maritime traffic is likely not to depend only on vessel technology, but also on ports and their capacity to accommodate the new energy requirements and other issues such as cybersecurity. Also, some constraints such as the environmental constraints are expected to be drivers of change rather than simple constraints. From this perspective, the interest of the proposed framework lies in its ability to connect route structures, port functions, environmental constraints, and reskilling questions within the same analytical device.

This paper has therefore presented our proposed approach through GMA, leading to the introduction of illustrative tentative scenario archetypes by specifying the families of data mobilised in our framework. In this respect, this framework can support further work on resilience, governance, environmental performance, and the territorial implications of maritime transition, while also preparing the subsequent analysis of proper GMA and scenario archetypes, leading to the formulation of reskilling strategies within the JASON project.

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