

Article

A Framework-Based Evaluation of Open Data Platforms in European Ports: A Comparative Study of Barcelona and Antwerp–Bruges

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Abstract

Open data platforms (ODPs) are emerging as strategic infrastructures for smart port development within the European Union, yet there is limited research offering integrated approaches to evaluate their performance across technical, operational, and regulatory dimensions. To address this gap, this study develops an analytical framework combining four complementary perspectives: open data platform design, FAIR (Findability, Accessibility, Interoperability, and Reusability) principles, smart port enablement, and EU regulatory alignment. The framework is applied through a qualitative comparative case study of the Ports of Barcelona and Antwerp–Bruges, based exclusively on secondary data sources, including the academic literature, policy documents, and publicly accessible platform data. The analysis is structured around three analytical dimensions—FAIR and interface features and accessibility, smart port enablement, and EU regulatory alignment—applied consistently across both cases. The findings reveal two distinct models: Barcelona adopts an open-by-default approach prioritising accessibility, transparency, and integration with public data ecosystems, while Antwerp–Bruges follows a controlled-access model focused on operational integration, system reliability, and business-to-business data exchange. Both approaches align with EU policy frameworks but involve different trade-offs between openness and operational control. The study contributes a structured, transferable framework for evaluating port ODPs and identifies practices for their design and governance in smart port and maritime logistics contexts.



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Keywords: open data platforms; smart ports; port digitalization; FAIR principles; open data; data governance; maritime logistics; European ports

1. Introduction

Open data has become a key component of digital governance within the European Union (EU), where it is recognised as a strategic resource for enhancing transparency, innovation, and interoperability across sectors. Defined as data that can be freely used, reused, and redistributed, open data is increasingly positioned as a driver of digital transformation and value creation. In the maritime domain, this paradigm has gained relevance in seaports,

where open data platforms (ODPs) are emerging as enabling infrastructures for smart port development and data-driven logistics [1,2].

European ports operate as critical nodes within global and regional supply chains and are under increasing pressure to align with the EU's twin transition agenda, combining digitalisation and sustainability. In this context, ODPs support the publication of structured, machine-readable datasets through interoperable interfaces, providing the technical basis for real-time coordination, operational visibility, and innovation. However, the implementation of such platforms remains heterogeneous. While some port authorities adopt open-by-default approaches that prioritise accessibility and transparency, others favour controlled data-sharing models that emphasise system integration and operational reliability.

The existing literature highlights the importance of data accessibility, interoperability, and usability for smart port transformation [3,4], as well as the challenges associated with governance, standardisation, and adoption of open data initiatives [5,6]. Nevertheless, there is limited research providing a structured comparison of port ODPs, particularly in relation to platform design, stakeholder orientation, and compliance with European regulatory frameworks. Furthermore, current approaches tend to address key dimensions—such as data quality, usability, operational relevance, and regulatory alignment—separately, without integrating them into a unified evaluative framework.

This gap reflects the absence of a comprehensive analytical instrument capable of simultaneously addressing technical, operational, and regulatory aspects of open data platforms in port environments. As discussed in the framework development, existing models focus either on data characteristics, such as the FAIR principles, or on broader digitalisation indicators, without capturing platform-level design and governance in an integrated manner. Consequently, port authorities lack structured methodologies to evaluate platform performance, benchmark implementations, and identify transferable practices.

To address this limitation, this study pursues three main objectives. First, it develops an analytical framework for evaluating port ODPs, based on the integration of four complementary dimensions: open data platform design, FAIR principles, smart port enablement, and the European regulatory framework. This framework adapts established theoretical and policy-based concepts into a structured and context-specific evaluative approach suitable for European ports. Second, the framework is applied to a comparative case study of the Ports of Barcelona and Antwerp–Bruges, selected for their strategic relevance and contrasting approaches to open data governance. Third, the study aims to derive transferable insights to support the design and implementation of ODPs in other European port contexts.

The research adopts a qualitative comparative case study methodology based on secondary data sources, including academic literature, policy documents, and publicly accessible platform data. The analysis is structured around three analytical dimensions—FAIR principles and interface features and accessibility, smart port enablement, and EU regulatory alignment—operationalised through a consistent evaluation structure applied to both cases.

By combining technical, operational, and regulatory perspectives, this study contributes to the understanding of how open data platforms function within maritime logistics systems. It provides a structured framework for platform evaluation, offers empirical insights into different governance models, and supports evidence-based decision-making for port authorities. In this context, ODPs are not only instruments of transparency but also strategic infrastructures designed to support coordination, innovation, and regulatory compliance within the European port ecosystem.

2. Literature Review

2.1. Open Data Platforms in Port Contexts

Open data has become a central component of digital governance, particularly within the European Union (EU), where it is recognised as a strategic resource for transparency, innovation, and economic development. Broadly defined as data that can be freely used, reused, and redistributed, open data supports interoperability and value creation across sectors [7]. In operational terms, it is characterised by attributes such as accessibility, timeliness, and freedom from restrictive licensing conditions [8].

Within this context, open data platforms (ODPs) function as centralised infrastructures for publishing, discovering, and reusing datasets. They typically provide machine-readable formats, metadata, and access mechanisms such as application programming interfaces (APIs), enabling both human and system-level interaction [9,10]. Beyond their role as repositories, ODPs are increasingly understood as enablers of innovation ecosystems, supporting the development of digital services and data-driven applications [11].

In port environments, ODPs play a particularly important role due to the complexity of logistics systems and the need for coordination among multiple stakeholders. Ports operate as critical nodes within global supply chains, where the availability of structured and interoperable data has been identified as a key enabler of operational efficiency and more informed decision-making, though its practical realisation depends on governance conditions and data quality [2]. However, the implementation of ODPs varies significantly across port authorities, reflecting differences in governance models, institutional priorities, and technological maturity.

2.2. FAIR Principles and Interface Features and Accessibility

The FAIR principles—Findability, Accessibility, Interoperability, and Reusability—provide a widely recognised framework for improving the quality and usability of data [12]. These principles establish that datasets should be easily discoverable through metadata and identifiers, accessible via standardised protocols, interoperable across systems, and reusable under clear licensing conditions.

In European policy contexts, FAIR principles are embedded in open data strategies and maturity assessments, reinforcing their role as benchmarks for improving data quality and reuse potential. In parallel, European maturity assessments evaluate how these principles are operationalised at the platform level, including portal functionalities, service provision, and governance structures [13]. Their practical implementation involves processes such as metadata enrichment, adoption of standard formats, and clarification of licensing conditions, often referred to as “FAIRification” [14].

However, compliance with FAIR principles alone does not guarantee effective platform use. Studies emphasise that technical quality must be complemented by observable interface features and accessibility design, including intuitive navigation structures, clear dataset presentation, and access mechanisms that allow different user profiles to discover and retrieve data [15], as well as feedback channels and participatory features that support platform improvement [16]. As noted by Molodtsov and Nikiforova and by O’Grady and Mangina [15,16], in port contexts, where users range from logistics operators to policymakers and developers, the design of interface features and access pathways shapes the practical accessibility of published data—an aspect that can be assessed through platform documentation and publicly observable design choices, even in the absence of direct user testing.

2.3. Open Data and Smart Port Transformation

The concept of the smart port reflects the integration of digital technologies and data-driven processes to improve operational efficiency, sustainability, and stakeholder

coordination [5]. Technologies such as the Internet of Things (IoT), artificial intelligence, and data analytics enable ports to optimise cargo handling, infrastructure use, and logistics flows [17].

Within this transformation, open data plays a key enabling role. By providing structured, accessible, and interoperable datasets, ODPs are positioned to support real-time coordination and the development of digital applications across port ecosystems [2]. Data such as vessel arrival times, terminal status, and environmental conditions provide the information inputs that smart port applications require for situational awareness and operational decision support, though their actual contribution depends on adoption, integration, and data quality conditions.

Despite these opportunities, several barriers remain. These include issues related to data quality, incomplete metadata, and challenges in linking organisational data to interoperable structures such as knowledge graphs, which can limit effective data integration and reuse [18], and institutional resistance to data sharing [2]. As a result, the effectiveness of ODPs in supporting smart port transformation depends not only on data availability but also on how platforms are designed and governed to meet operational needs.

2.4. EU Regulatory Framework for Port Data

The development and operation of ODPs in European ports are shaped by a multi-layered regulatory framework. The Open Data Directive (Directive (EU) 2019/1024) establishes the principle that public sector information should be made available for reuse in machine-readable formats and under transparent licensing conditions [19]. It also identifies high-value datasets, including transport data, which must be accessible via APIs and free of charge [19].

Complementary instruments further define the governance of data sharing. The Data Governance Act (Regulation (EU) 2022/868) introduces mechanisms for trusted data exchange through intermediaries [20], while the Data Act (Regulation (EU) 2023/2854) establishes rights to access and use data generated by connected devices [21]. Transport-specific regulations, such as the eFTI Regulation and the European Maritime Single Window environment (EMSW), impose additional requirements for the digital exchange of freight and maritime information [22,23].

These instruments collectively promote interoperability, accessibility, and secure data sharing, while also imposing constraints related to privacy, security, and governance. For port authorities, compliance with this framework requires balancing openness with operational control and data protection considerations.

2.5. Research Gap and Conceptual Positioning

Although the literature provides substantial insights into open data, platform design, smart port transformation, and regulatory frameworks, these perspectives are typically addressed in isolation. ODP design studies focus on technical functionalities without offering structured evaluation tools; FAIR principles provide benchmarks for data quality but do not fully address governance or operational contexts [12]; smart port frameworks examine digital transformation broadly without targeting platform-level assessment [5]; and regulatory analyses focus on compliance rather than platform design.

As a result, there is a lack of integrated approaches capable of evaluating ODPs across technical, operational, and regulatory dimensions simultaneously. This gap is particularly relevant in port environments, where data platforms must support complex logistics operations while complying with evolving European policy frameworks.

To address this limitation, this study proposes an integrated evaluation framework that combines FAIR principles, interface features and accessibility, smart port enablement,

and EU regulatory alignment into a unified analytical structure. This framework provides a basis for systematically assessing ODPs and identifying strategic trade-offs in their design and governance.

3. Materials and Methods

This study adopts a qualitative research design combining framework development with a comparative case study approach. The methodological strategy is structured in two sequential stages: (i) the development of an analytical evaluation framework grounded in existing literature and policy instruments, and (ii) its application to two European port open data platforms (ODPs) through a structured comparative analysis.

3.1. Framework Development

The evaluation framework was developed through an integrative approach, combining multiple strands of literature and policy guidance relevant to open data platforms in port environments. Rather than proposing an entirely new theoretical model, the framework builds on the synthesis and contextual adaptation of four established bodies of knowledge: (i) conceptual foundations of open data and ODP design, (ii) the FAIR principles and observable interface features and accessibility design, (iii) smart port transformation literature, and (iv) the European Union regulatory framework governing data publication and reuse.

This integrative logic responds to a gap identified in the literature, where existing approaches address these dimensions separately but do not provide a unified evaluative instrument suitable for port contexts. ODP design literature focuses on platform functionalities without offering structured evaluation tools; FAIR principles emphasise data quality and reuse but do not fully capture governance and regulatory dimensions [12]; smart port frameworks address digital transformation broadly without targeting platform-level assessment [24]; and open data maturity models provide benchmarking indicators but do not account for operational relevance in complex logistics environments [13].

The resulting framework is structured around three analytical dimensions: (i) FAIR principles and interface features and accessibility, (ii) smart port enablement, and (iii) EU regulatory alignment. These dimensions are operationalised through a four-part evaluation structure, which includes a final synthesis of platform-specific strengths and limitations. The framework is designed to support qualitative comparison rather than quantitative scoring, enabling context-sensitive analysis of platform design, governance, and operational relevance.

3.2. Case Study Design

To validate and apply the framework, the study employs a comparative case study design focusing on the Ports of Barcelona and Antwerp–Bruges. Case study methodology is particularly suitable for analysing complex socio-technical systems within real-world contexts, where institutional arrangements, technological infrastructures, and governance mechanisms interact dynamically [25,26].

The selection of cases follows a purposive sampling strategy based on two criteria: strategic relevance and contrastive potential. Both ports are core nodes within the Trans-European Transport Network (TEN-T) and are recognised for their advanced digitalisation strategies. At the same time, they exhibit contrasting approaches to open data governance, with Barcelona adopting a transparency-oriented model and Antwerp–Bruges implementing a more controlled, operations-driven model. This contrast enables a structured comparison of how the framework dimensions are operationalised under different institutional conditions.

3.3. Data Collection and Sources

The study relies exclusively on secondary data sources. These include publicly accessible materials from the official open data platforms of both ports, such as dataset catalogues, metadata records, API documentation, licencing conditions, and technical specifications. These sources are complemented by port authority reports, strategic documents, European policy instruments, and peer-reviewed academic literature.

The use of secondary data ensures transparency and replicability, allowing all observations to be verified through publicly available information. This approach is consistent with established qualitative research practices in digital governance and institutional analysis [27].

3.4. Analytical Procedure

The analysis is conducted using a structured evaluation protocol derived from the framework. Each case is assessed across the three analytical dimensions—FAIR principles and interface features and accessibility, smart port enablement, and EU regulatory alignment—using a consistent set of criteria. This ensures comparability while allowing for context-specific interpretation.

Findings are organised into a four-part structure for each case, corresponding to the framework dimensions and concluding with a synthesis of strengths and limitations. The results are then compared across cases to identify patterns, differences, and strategic trade-offs in platform design and governance.

3.5. Methodological Limitations

The methodological approach is subject to certain limitations. First, the reliance on secondary data does not allow for direct insight into internal decision-making processes, user experiences, or platform usage metrics. In particular, the first analytical dimension, FAIR principles and interface features and accessibility, is necessarily bounded to observable platform characteristics, such as interface structure, metadata presentation, access mechanisms, and documentation quality. It does not assess actual user experience, adoption rates, or usability as understood in empirical human–computer interaction research, which would require primary data collection through user surveys, interviews, or platform usage analytics. Second, the analysis is limited to publicly accessible open data platforms and does not include proprietary systems or restricted-access data infrastructures used within port operations.

Finally, the comparative case study design, while providing depth and contextual insight, does not support statistical generalisation. However, the study aims to achieve analytical generalisation by developing and applying a transferable evaluation framework grounded in the literature and policy benchmarks [25].

4. Results and Discussion

4.1. Development of the Evaluation Framework

The analytical framework developed in this study is designed to support a structured and comparative evaluation of open data platforms (ODPs) within European port ecosystems. Rather than proposing an entirely new model, the framework results from the deliberate integration and contextual adaptation of established conceptual foundations, ensuring both academic robustness and practical applicability.

4.1.1. Conceptual Foundations and Integrative Logic

As established in the literature review, four bodies of knowledge collectively define what constitutes a well-functioning ODP in the European port context. The first concerns the conceptual foundations of open data and ODP design, which frame the platform as

both a repository and a strategic infrastructure for innovation, coordination, and transparency [2]. The second encompasses the FAIR principles, which provide internationally recognised benchmarks for data quality and reuse potential, gaining practical relevance when combined with observable interface features and accessible design that support adoption across diverse stakeholder groups [12]. The third draws on the smart port transformation literature, which positions ODPs as central enablers of operational coordination, real-time data use, and digital ecosystem development [24]. The fourth relates to the European Union regulatory framework, which defines binding and enabling conditions for data publication, interoperability, and governance, further contextualised through maturity assessments such as the EU Open Data Maturity framework [13].

Taken individually, however, each of these bodies of knowledge addresses only part of the analytical challenge. The ODP design literature does not provide a structured evaluative instrument; FAIR remains focused on data characteristics and does not fully address organisational governance or regulatory compliance [12]; smart port frameworks assess digitalisation more broadly without offering a dedicated instrument for platform evaluation [24]; and maturity frameworks do not capture platform-level design choices or the operational role of data within complex logistics environments [13]. No single model therefore integrates technical data quality, platform usability, operational relevance, and regulatory alignment into a unified evaluative instrument suited to port environments. This gap provides the justification for the integrated framework developed in this study.

4.1.2. Framework Structure

The framework is organised around three complementary analytical dimensions, each addressing a distinct aspect of ODP performance. Rather than assessing these dimensions in isolation, the framework treats them as mutually reinforcing: technical quality enables operational utility, operational utility gains legitimacy through regulatory alignment, and regulatory alignment is only meaningful when platforms are usable and accessible in practice.

The first dimension, FAIR Principles and Interface Features and Accessibility, evaluates the technical quality and observable accessibility design of each platform. It draws on the FAIR sub-principles established by Wilkinson et al. [12] and incorporates portal and quality indicators from the EU Open Data Maturity assessment [13]. This dimension examines the extent to which each ODP enables dataset discovery, access, integration, and reuse across different user profiles, based on publicly observable platform characteristics such as interface structure, metadata presentation, access mechanisms, and documentation quality. It is explicitly bounded to features that can be assessed through secondary sources, and does not claim to evaluate actual user experience or adoption outcomes.

The second dimension, Smart Port Enablement, evaluates the extent to which each platform is designed and configured to support the operational and innovation objectives of smart port development. Drawing on González-Cancelas et al. [5] and Inkinen et al. [2], it focuses on the availability and timeliness of operational datasets, the coverage of multi-modal and infrastructure data, and the accessibility of application programming interfaces (APIs) for third-party use. It also considers automation readiness and the capacity to support informed decision-making through reliable, timely, and interoperable data.

The third dimension, EU Regulatory Alignment, assesses the extent to which each ODP reflects the obligations and opportunities defined by European data governance frameworks. Rather than treating compliance as a binary condition, this dimension evaluates how regulatory instruments are interpreted and operationalised within platform design and governance structures, recognising that EU legislation functions both as a constraint and as an enabling framework for innovation.

As illustrated in Figure 1, the three analytical dimensions are mapped onto a set of operational criteria, forming a coherent structure for evaluating ODP performance. The figure highlights how the dimensions interact, linking technical, operational, and regulatory aspects into a unified evaluative approach.

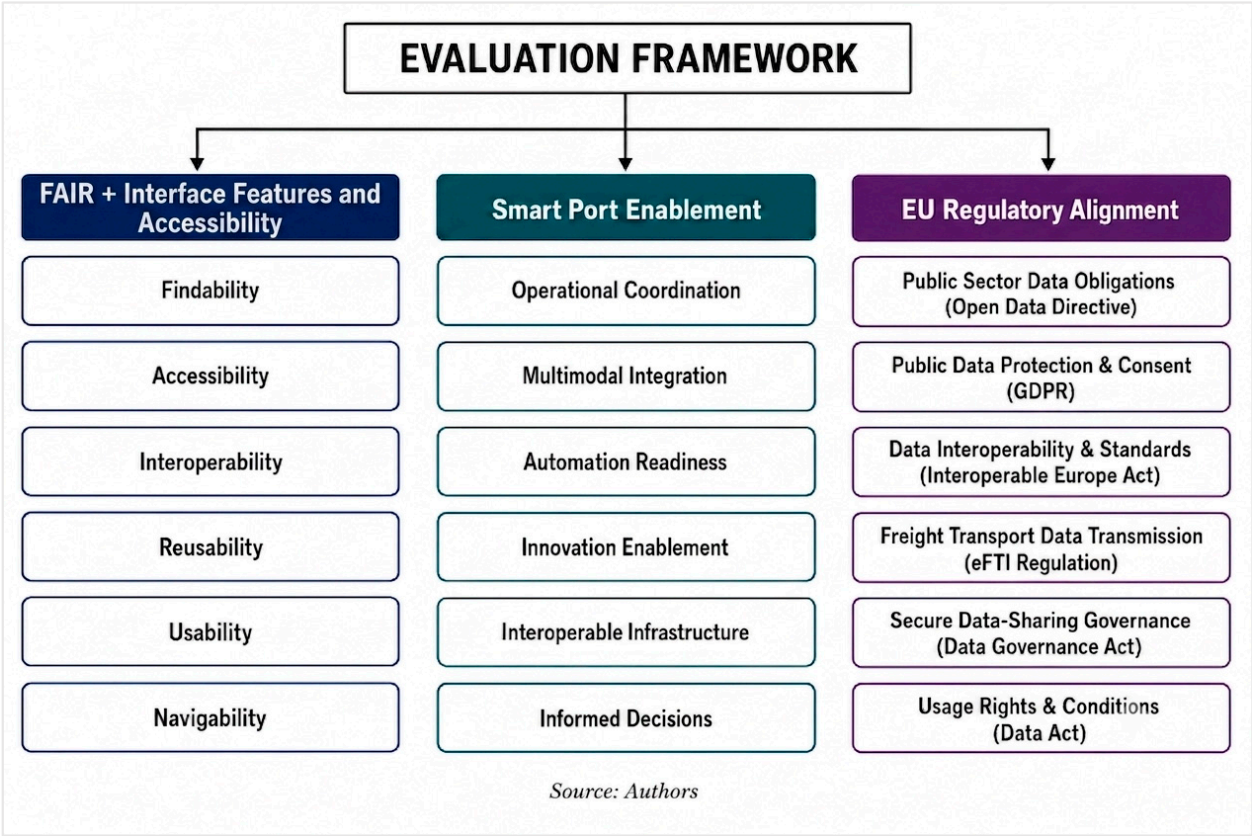


Figure 1. Evaluation framework for Open Data Platforms (ODPs). Source: Authors’ elaboration.

4.1.3. Operationalisation and Evaluation Structure

The three dimensions are operationalised through a four-part evaluation structure applied consistently across case studies. The first three components correspond directly to the analytical dimensions described above, while the fourth synthesises findings into an overall assessment of each platform’s strengths and limitations. This final component is particularly relevant for identifying trade-offs between openness, operational control, and regulatory compliance, as well as for deriving transferable insights for other port contexts.

Each component of the framework is assessed using publicly accessible secondary sources, including platform documentation, dataset catalogues, metadata records, port authority reports, EU regulatory texts, and academic literature. The exclusive reliance on secondary data ensures transparency and replicability, in line with established qualitative research approaches in institutional and digital governance studies [25].

4.1.4. Scope and Transferability

The framework is designed for ports operating within the European Union regulatory context and should be understood as transferable within this environment rather than universally applicable. The selected case studies, the Ports of Barcelona and Antwerp–Bruges, represent contrasting models of open data governance within TEN-T core ports, enabling the identification of strategic trade-offs and transferable practices.

The framework does not aim to produce quantitative scores or rankings. Instead, it supports structured qualitative comparison and the identification of context-sensitive

practices for ODP design and governance. Ports operating outside the EU context, or at earlier stages of digital maturity, may require adaptation of the regulatory dimension before applying the framework.

4.2. Application of the Framework to Case Studies

The evaluation framework was applied to two European port open data platforms (ODPs): the Port of Barcelona and the Port of Antwerp–Bruges. These cases were selected due to their strategic relevance as core nodes within the Trans-European Transport Network (TEN-T), as well as their contrasting approaches to open data governance, providing an analytically robust basis for comparative evaluation.

The application follows the three analytical dimensions defined in the framework: (i) FAIR principles and interface features and accessibility, (ii) smart port enablement, and (iii) EU regulatory alignment. Each case is assessed using a consistent structure, ensuring comparability while allowing for context-specific interpretation of platform design and governance choices.

Table 1 provides a structured overview of the observable platform characteristics documented for each case, organised by analytical dimension and drawn exclusively from publicly accessible secondary sources as listed in the reference list. All qualitative assessments reflect observable platform design features and do not constitute formal legal compliance determinations or verified operational usage outcomes.

Table 1. Evidence matrix: comparative overview of observable platform characteristics. Source: Author’s own elaboration.

Indicator	Port of Barcelona	Port of Antwerp–Bruges	Primary Source
Fair Principles, Interface Features, and Accessibility			
Platform infrastructure	CKAN open-source data management system	NxtPort API gateway (neutral data intermediary)	[28–30]
Access model	Open-by-default; no registration required	Registration and authentication required	[29–31]
Data formats	CSV, JSON	JSON (via RESTful APIs)	[29,31,32]
API availability	RESTful API; publicly accessible	RESTful API; access-controlled	[29–32]
Metadata provision	Descriptive tags, persistent URLs, thematic grouping	Thematic categorisation; publicly available service documentation	[29,30,32]
Persistent identifiers	IMO and MMSI codes for maritime cross-referencing	Consistent naming conventions per API technical standards	[29,31,32]
Licencing conditions	Creative Commons Attribution 4.0 (CC BY 4.0)	Contractual agreements; no standardised open licence	[29,30]
Interface for non-specialist users	Multilingual interface; browsable catalogue	Developer-oriented documentation; no public browsing interface	[28–30,32]
Feedback/participatory features	Absent	Structured onboarding and support; no public feedback channel	[29,30,32]

Table 1. Cont.

Indicator	Port of Barcelona	Port of Antwerp–Bruges	Primary Source
Smart Port Enablement			
Number of publicly documented datasets	79 datasets across 7 thematic groups (Port Operations, Statistics, Geography and Location, among others)	Five freely accessible APIs: ETA Terminal, Meteo, Bridges and Locks, Bathymetric Survey, and PortStays	[30,32–37]
Dataset types	Operational, statistical, geospatial, multimodal	Operational and infrastructural (vessel scheduling, environmental, navigational)	[32–37]
Update frequency	Regular intervals (near-real-time for terminal access datasets)	Frequent; real-time delivery via APIs	[29,30,32–34]
Multimodal coverage	Yes (railway services, routes, frequencies, transit times)	No multimodal coverage documented	[30,32–37]
Third-party integration potential	Machine-readable formats and public API support external application development	API architecture supports machine-to-machine integration within the registered ecosystem	[29,30,32,37]
Automation readiness	Partial (public API available; not linked to internal operational systems)	High (API design oriented toward operational system integration)	[29–32]
EU Regulatory Alignment			
Open Data Directive alignment	High: machine-readable formats, free of charge, open licence, API access	Partial: machine-readable and API access, but registration required and no open licence	[19,29,30,32]
Integration into public data ecosystems	Yes: linked to Barcelona Datastore and datos.gob.es	No: not documented as linked to national or European catalogues	[29,30]
Data Governance Act relevance	Not applicable (no data intermediary in use)	Structural alignment: NxtPort operates as a neutral data intermediary	[20,29,30]
Data Act relevance	Partial: open-by-default approach consistent with access principles	Partial: API-based access to machine-generated data consistent with access provisions	[21,29,30]
GDPR compliance	Sensitive and personal data excluded from the platform	Access-controlled model limits exposure of sensitive data	[29,30]
Transport-specific regulations (EMSWe, eFTI)	Not directly addressed through the ODP	Addressed through separate operational systems, not the ODP	[22,23]

4.2.1. Port of Barcelona

FAIR Principles, Interface Features, and Accessibility in the Port of Barcelona

The Port of Barcelona’s ODP demonstrates a comprehensive implementation of the FAIR principles, supported by a clearly defined user-centred design. The platform is built on CKAN, an open-source data management system that facilitates structured data cataloguing and retrieval [28]. Datasets are organised into thematic groups such as “Port

Operations,” “Statistics,” and “Geography and Location,” which enhances discoverability by enabling both human users and automated systems to navigate the catalogue efficiently.

Findability is further reinforced through the use of metadata, descriptive tags, and persistent URLs, which allow datasets to be consistently identified and accessed. In addition, the inclusion of internationally recognised identifiers, such as IMO and MMSI codes, supports cross-referencing with global maritime databases and enhances interoperability across systems. These features contribute to a structured data environment aligned with recognised best practices for open data platforms.

Accessibility is ensured through an open-by-default model, whereby users can access datasets without registration or authentication. This reduces administrative barriers and supports engagement by a wide range of stakeholders, including researchers, developers, and logistics operators. Data is provided in machine-readable formats such as CSV and JSON, and is complemented by a RESTful API, enabling both manual and programmatic access.

Interoperability is supported by the use of open formats and standardised identifiers, facilitating integration with external systems such as port community systems, customs platforms, and maritime data networks. Reusability is strengthened through the adoption of Creative Commons Attribution 4.0 licensing, which provides explicit legal permission for redistribution and adaptation of data, provided appropriate attribution is given [29]. This licensing clarity addresses a commonly identified barrier to open data adoption, namely uncertainty regarding reuse conditions.

From an interface design and accessibility perspective, the platform includes multilingual options and a structured navigation layout observable through the publicly accessible CKAN interface, which lowers the threshold for non-specialist users. Metadata is generally presented in accessible language, supporting comprehension across diverse user groups. However, the absence of interactive features, such as feedback mechanisms or dataset request channels, limits opportunities for user engagement. It should be noted that these observations are based on publicly accessible platform documentation and direct inspection of the interface; they describe observable design features rather than empirically verified user experience outcomes.

Smart Port Enablement in the Port of Barcelona

The Port of Barcelona’s ODP is configured to support smart port objectives by providing datasets intended to improve the informational basis for operational visibility and data-driven decision-making. The platform includes real-time datasets on terminal access times, updated at regular intervals, which are designed to provide logistics actors with near-real-time information on landside operations, with the potential to support congestion monitoring and scheduling. These datasets are particularly relevant for hauliers and terminal operators.

In addition, the platform provides structured information on railway services connecting the port to inland logistics hubs. This dataset includes details such as service operators, routes, frequencies, and transit times, supporting multimodal logistics planning and improving transparency regarding hinterland connectivity. By making such information publicly available, the platform provides a transparency infrastructure that could support coordination across transport modes and more informed supply chain planning.

These design features are consistent with the role attributed to open data in the smart port literature, particularly in relation to operational coordination, multimodal integration, and situational awareness [3]. The availability of machine-readable and regularly updated datasets is technically compatible with integration into third-party applications and decision-support tools, though actual adoption depends on factors beyond platform design.

However, the platform does not provide access to the full range of operational data used within the port, nor does it include advanced features such as predictive analytics

or automated decision-support systems. As such, its design orientation toward smart port objectives can be characterised as enabling but not fully integrative. It provides the technical foundation for data-driven operations but remains partially decoupled from internal operational systems.

EU Regulatory Alignment in the Port of Barcelona

The Port of Barcelona's ODP demonstrates a high degree of alignment with the European Union regulatory framework governing open data and digital infrastructures. The platform complies with the Open Data Directive (Directive (EU) 2019/1024) by providing transport-related datasets in machine-readable formats, free of charge, and under open licences. The inclusion of API access and high-frequency updates further supports compliance with the Directive's requirements for high-value datasets [19].

Interoperability requirements, as promoted by the Interoperable Europe Act [38], are addressed through the use of standard formats, persistent identifiers, and structured metadata. The platform's integration into broader data ecosystems, including municipal and national portals such as the Barcelona Datastore and datos.gob.es, enhances discoverability and supports alignment with European data-sharing objectives.

The platform also reflects principles associated with the Data Governance Act and the Data Act, particularly in terms of transparency, legal clarity, and interoperability. Although it does not implement advanced data-sharing mechanisms such as data intermediaries, its open-by-default approach facilitates potential integration into broader European data spaces.

Compliance with the General Data Protection Regulation (GDPR) is ensured through the exclusion of sensitive or personal data from the platform. Overall, the Port of Barcelona's ODP represents a transparency-oriented model that closely aligns with both the formal requirements and the broader objectives of EU open data policy.

Open Data Platform Architecture in the Port of Barcelona

Figure 2 summarises the architecture of the Port of Barcelona's open data platform, illustrating the flow from data sources through the CKAN infrastructure to end users. The diagram highlights the platform's open-by-default design, in which data collected across operational, statistical, geospatial, environmental, and multimodal domains is published through a single centralised management system and made available to all user categories without registration, via both a public RESTful API and direct file download. The platform's integration with external public ecosystems, including the Barcelona Datastore and datos.gob.es, further extends its reach beyond the port community.

4.2.2. Port of Antwerp–Bruges

FAIR Principles, Interface Features, and Accessibility in the Port of Antwerp–Bruges

The Port of Antwerp–Bruges' ODP adopts a technically robust but access-controlled approach to implementing the FAIR principles. Data is provided through APIs managed by NxtPort, a neutral data intermediary that handles user registration, authentication, and access control. In this context, accessibility is achieved through structured procedures rather than unrestricted public access, reflecting the FAIR principle that data may be accessible under well-defined conditions [12].

Findability is supported through thematic categorisation of datasets and publicly available documentation describing available data services. However, direct access to datasets requires prior registration, which introduces a barrier to discovery for casual users. Interoperability is a key strength of the platform, with datasets delivered through RESTful APIs in JSON format, following consistent technical standards and naming conventions [31]. These features facilitate integration with operational systems and support machine-to-machine communication.

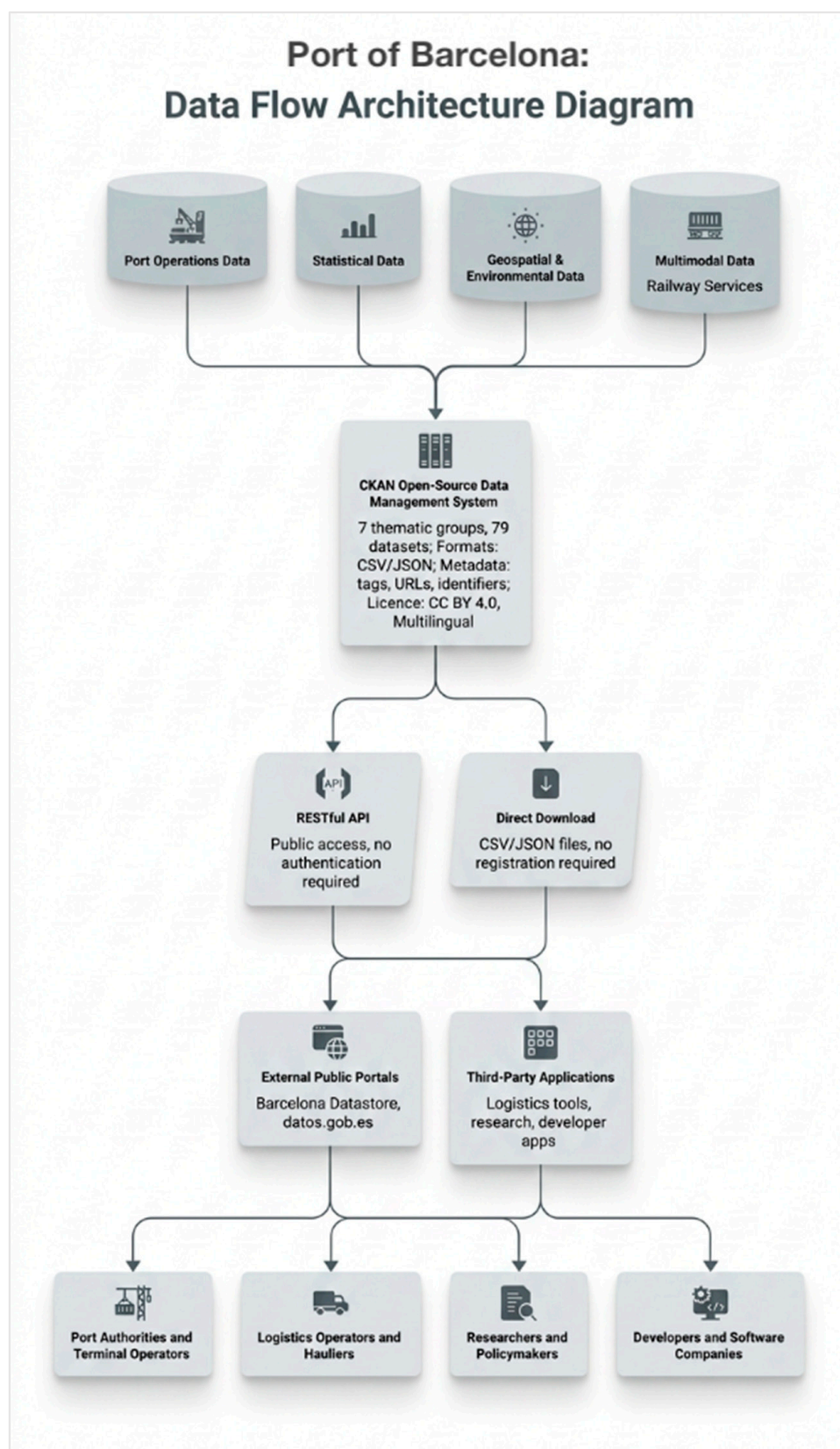


Figure 2. Port of Barcelona: Open Data Platform architecture. Source: Authors' own elaboration based on case study.

Reusability is enabled through detailed technical documentation and reliable API access, allowing users to integrate data into their workflows. However, reuse conditions

are governed by contractual agreements rather than standardised open licences, which may reduce transparency for external users evaluating potential use cases.

From an interface design and accessibility perspective, the platform's publicly available documentation and onboarding materials indicate a design orientation towards technically proficient users. Observable features include structured API documentation and registration-based access workflows, while no simplified browsing interface or dataset catalogue for non-specialist users is publicly available. These observations, derived exclusively from publicly accessible platform materials, describe design and access features rather than verified user experience outcomes.

Smart Port Enablement in the Port of Antwerp-Bruges

The Port of Antwerp-Bruges' ODP is designed with a strong orientation toward smart port objectives, particularly in terms of operational integration and real-time data provision through API-based access. The platform offers a focused set of datasets, including ETA Terminal, Meteo, Bridges and Locks, and Bathymetric Survey data, each serving specific operational functions.

These datasets are designed to support critical activities such as vessel scheduling, infrastructure coordination, navigational safety, and environmental monitoring. Data is updated frequently and delivered through APIs, making real-time integration into operational systems technically feasible. This design is oriented toward supporting automation and operational responsiveness within the port ecosystem.

Although the number of datasets is relatively limited, their operational focus and documented technical specifications reflect a targeted design approach to smart port enablement. The platform prioritises depth and integration over breadth of data availability, focusing on datasets that are documented as serving logistics and infrastructure management functions.

EU Regulatory Alignment in the Port of Antwerp-Bruges

The Port of Antwerp-Bruges' ODP demonstrates selective alignment with the European Union regulatory framework. While datasets are provided in machine-readable formats and via APIs, the requirement for user registration limits full compliance with the open-by-default principles of the Open Data Directive. In addition, the absence of standardised open licences and limited integration into European data catalogues constrain discoverability and reuse.

However, the platform aligns closely with other regulatory instruments. The use of NxtPort as a data intermediary reflects the principles of the Data Governance Act, supporting secure and trusted data sharing. The platform's emphasis on interoperability and API-based access is consistent with the Data Act, which promotes access to machine-generated data and system interoperability [20,21].

Compliance with transport-specific regulations, such as EMSWe and the eFTI Regulation, is achieved through separate digital systems rather than the open data platform itself. This reflects a dual approach to regulatory alignment, in which open data and operational systems serve complementary but distinct roles.

Overall, the platform represents an operationally driven interpretation of EU regulation, prioritising secure data exchange and system integration over broad public accessibility.

Open Data Platform Architecture in the Port of Antwerp-Bruges

Figure 3 illustrates the data flow and access architecture of the Port of Antwerp-Bruges open data platform. In contrast to Barcelona's open-by-default model, data from the five freely accessible APIs (ETA Terminal, Meteo Data, Bridges and Locks, Bathymetric Survey, and PortStays) is channelled through the NxtPort API Gateway, which functions as a neutral data intermediary. Access is governed by a multi-step process encompassing API

specifications, OAuth2 authentication, technical standards compliance, and contractual acceptance, resulting in a controlled-access model oriented toward registered professional users rather than the general public.

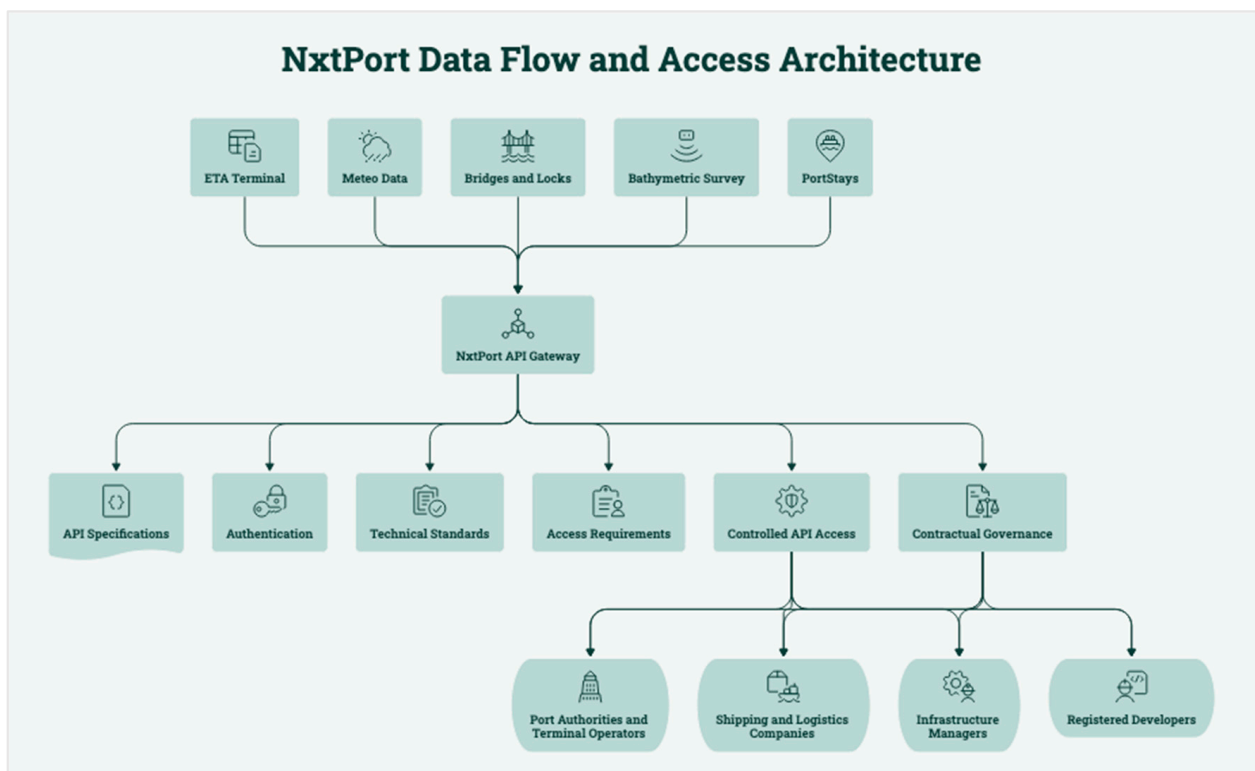


Figure 3. Port of Antwerp–Bruges: data flow and access architecture. Source: Author’s own elaboration based on case study.

4.3. Cross-Case Insights and Operational Implications

The comparative application of the evaluation framework to the Ports of Barcelona and Antwerp–Bruges reveals two distinct approaches to the design and governance of open data platforms (ODPs) within European port ecosystems. While both platforms operate under the same European Union (EU) regulatory framework, they differ in how they prioritise openness, operational integration, and governance structures. These differences highlight the analytical value of the framework in capturing not only compliance with technical and regulatory criteria but also strategic orientation and institutional choices.

Figure 4 presents a structured comparison of the two platforms across three analytical layers: data sensing, data management, and data application. This comparison provides a consolidated visual basis for the cross-case discussion that follows. At the data sensing layer, Barcelona offers a broader and more diverse dataset portfolio, while Antwerp–Bruges provides a smaller set of operationally focused APIs with real-time delivery. At the data management layer, the two platforms reflect fundamentally different governance philosophies: Barcelona’s CKAN-based open-by-default model contrasts with Antwerp–Bruges’ NxtPort-mediated controlled-access approach. At the data application layer, Barcelona supports unrestricted third-party development and public ecosystem integration, whereas Antwerp–Bruges is oriented toward machine-to-machine integration within a registered professional ecosystem. These distinctions are explored in detail in the sub-sections below.

Port Comparison: Barcelona vs. Antwerp-Bruges			
Characteristic	Data Sensing	Data Management	Data Application
Barcelona	79 datasets, near-real-time updates	CKAN open-source, open-by-default	Public API, direct download
Antwerp-Bruges	5 free APIs, real-time delivery	NxtPort API gateway, OAuth2 access	Machine-to-machine integration, operational focus

Figure 4. Comparative overview of port Open Data Platforms by data sensing, data management, and data application layer. Source: Authors’ own elaboration.

4.3.1. Comparative Analysis Across Framework Dimensions

Across the three analytical dimensions, both ports demonstrate alignment with the core principles of open data and digital transformation, yet they operationalise these principles in contrasting ways.

In terms of FAIR principles, interface features, and accessibility, the Port of Barcelona adopts an open-by-default model, characterised by unrestricted access, multilingual interfaces, and standardised metadata. This approach enhances discoverability and inclusiveness, supporting a wide range of users, including non-specialist stakeholders. By contrast, the Port of Antwerp–Bruges implements a controlled-access model, where data is accessed through authenticated APIs managed by NxtPort. While this model introduces barriers to entry, it ensures traceability, system integrity, and a structured user environment, particularly suited to professional and technical users [12].

Regarding smart port enablement, both platforms are designed to support operational objectives, but through different mechanisms. Barcelona provides a broader range of publicly accessible datasets, including real-time information on terminal access and multimodal connections, providing the informational basis for situational awareness and logistics planning across the logistics chain. Antwerp–Bruges offers a more limited but operationally focused dataset portfolio, centred on real-time APIs for vessel scheduling, infrastructure management, and environmental monitoring. This reflects a distinction between breadth of accessibility and depth of operational integration, as discussed in smart port literature [3].

In terms of EU regulatory alignment, Barcelona closely follows the open-by-default principles of the Open Data Directive, providing datasets in machine-readable formats under open licences and integrating them into national and municipal data portals. Antwerp–Bruges demonstrates a more selective alignment, complying with technical requirements such as interoperability and API-based access, while relying on controlled access mechanisms and contractual governance structures. This approach aligns more closely with the Data Governance Act and Data Act, which emphasise trusted data sharing and interoperability [20,21].

As illustrated in Table 2, the two ports occupy distinct positions across the evaluation dimensions. The Port of Barcelona is positioned towards openness, accessibility, and public reuse, whereas the Port of Antwerp–Bruges is oriented towards controlled access, operational integration, and system reliability. The figure visually summarises how each

platform balances the three dimensions, reinforcing the analytical distinction between transparency-driven and operations-driven models.

Table 2. Comparative overview of the Port of Barcelona and the Port of Antwerp–Bruges across the three analytical dimensions. Source: Author’s own elaboration.

Dimension	Port of Barcelona	Port of Antwerp–Bruges
Fair and Interface Features and Accessibility	Open-by-default CKAN portal; multilingual access; public API; persistent identifiers.	Controlled access via NxtPort; developer-oriented documentation; registration required; limited public data.
Smart Port Enablement	Real-time datasets on truck gate access and rail logistics; transparent and multimodal-friendly.	High-frequency APIs (e.g., ETA, Meteo); tightly integrated with operational workflows; Business-oriented data integration and compliance.
EU Regulatory Alignment	Aligned with the Open Data Directive; publicly shared transport datasets; linked to national data catalogues.	Trusted data intermediary; controlled access; focuses on structured compliance and secure interoperability.

4.3.2. Strategic Trade-Offs in ODP Design

The comparison reveals that ODP design involves a series of strategic trade-offs between openness and operational control. These trade-offs are not merely technical choices but reflect broader governance priorities and institutional contexts.

Barcelona’s model prioritises openness and inclusiveness, facilitating broad access to data and supporting cross-sector reuse. This approach enhances transparency and aligns closely with EU open data policy objectives. However, it may limit the integration of sensitive or high-value operational data, which remains outside the scope of the platform.

In contrast, Antwerp–Bruges prioritises control, security, and operational relevance. By restricting access through authentication and contractual agreements, the platform ensures data reliability and supports integration with operational systems. This approach is particularly suited to complex logistics environments where data accuracy and system integrity are critical, but it reduces accessibility for external users and limits broader reuse.

Table 3 presents these trade-offs in a structured manner, comparing key design considerations such as accessibility, discoverability, reuse potential, and security. The figure highlights how Barcelona and Antwerp–Bruges represent two contrasting positions along these dimensions, illustrating the inherent tensions between public openness and controlled data exchange.

Table 3. Strategic trade-offs between openness and operational control in open data platform design.

Design Consideration	Favouring Openness	Favouring Operational Control
User Accessibility	Public access without login.	Access gated by registration and verification.
Discoverability	Integrated into open government catalogues; rich metadata.	Limited discoverability: accessed mainly by ecosystem members.
Compliance Model	Open publication meets transparency requirements.	Compliance achieved via trusted intermediaries and access control.
Reuse Potential	High: datasets reusable across sectors.	Moderate: focused on system-to-system use by logistics stakeholders
Secure and Accountability	Lower risk mitigation: trust placed in openness.	Higher control: ensures traceability and secure integration.

4.3.3. Operational Implications for Smart Ports

The findings have several implications for the development of ODPs in European ports. First, the analysis demonstrates that there is no single optimal model for open data platform design. Instead, effectiveness depends on aligning platform architecture with institutional priorities, stakeholder needs, and operational requirements.

Second, the analysis suggests that technical compliance with FAIR principles and EU regulation is necessary but not sufficient. Platforms must also address accessible interface design and operational relevance to support effective data use. As the two cases illustrate, data availability alone does not guarantee adoption or integration; rather, the potential for value creation depends on the alignment of platform design with the workflows and technical capacities of intended users.

Third, the study highlights the importance of governance structures in shaping ODP performance. Barcelona's integration into public data ecosystems enhances visibility and reuse, while Antwerp–Bruges' use of a data intermediary supports trust and system integration. These approaches reflect different interpretations of how open data should function within port ecosystems.

Overall, the framework provides a structured basis for analysing how ODPs are designed to support smart port transformation by balancing openness, interoperability, and operational control. By identifying these trade-offs and their observable characteristics, the analysis offers structured insights for port authorities seeking to design or refine their own open data platforms, while acknowledging that the operational effects of such platforms require further investigation through primary data.

It is important to note that this study evaluates smart port enablement on the basis of publicly observable platform design features, including dataset types, update frequency, API availability, and documentation quality. It does not assess actual adoption rates, usage volumes, or verified operational outcomes such as reductions in gate congestion or improvements in vessel turnaround times. The distinction between data availability and demonstrated operational impact is a recognised limitation of secondary data approaches in this domain and represents a priority area for future empirical investigation.

5. Conclusions

This study examined the design, implementation, and strategic orientation of open data platforms (ODPs) in two leading European ports, Barcelona and Antwerp–Bruges, within the broader context of digital transformation and European data governance. By developing and applying an analytical framework grounded in FAIR principles, interface features and accessibility, smart port enablement, and EU regulatory alignment, the research provides a structured basis for analysing how open data platforms are designed and governed in complex maritime environments.

The findings highlight that ODPs can follow distinct yet equally valid strategic pathways. The Port of Barcelona adopts an open-by-default model that prioritises transparency, accessibility, and integration with public data ecosystems. This approach supports broad data reuse and aligns closely with the principles of the Open Data Directive. In contrast, the Port of Antwerp–Bruges implements a controlled-access model, where data is delivered through structured APIs within a secured, business-oriented environment. This model emphasises operational reliability, system integration, and trusted data exchange among logistics stakeholders.

These contrasting approaches reveal that the effectiveness of an ODP is not determined by the degree of openness alone but by the alignment between platform design, stakeholder needs, and institutional context. While open access enhances discoverability and cross-sector innovation, controlled architectures can strengthen system integrity and operational

performance. As such, port authorities must navigate trade-offs between accessibility, security, interoperability, and governance when designing their data platforms.

From an academic perspective, this study contributes by advancing a multidimensional framework that integrates technical, operational, and regulatory considerations into a single evaluative structure. This framework addresses a gap in the literature by enabling systematic comparison of ODPs and by linking data governance principles with real-world port applications. From a practical standpoint, the findings provide actionable insights for port authorities seeking to develop or refine their open data strategies, particularly in aligning platform design with both regulatory requirements and operational priorities.

The study is subject to limitations. The reliance on secondary data sources restricts insight into internal decision-making processes and user behaviour, and the focus on two case studies limits generalisability. Future research should incorporate primary data collection, such as stakeholder interviews and usage analytics, and extend the analysis to a broader range of ports, including those with different levels of digital maturity. Further work is also needed to explore the integration of ODPs with emerging digital infrastructures, such as European data spaces, digital twins, and AI-driven analytics.

In conclusion, open data platforms should be understood not merely as tools for transparency but as strategic infrastructures designed to support coordination, innovation, and regulatory compliance in maritime logistics. When designed with a balanced consideration of openness, accessible design, and governance, ODPs have the potential to play a central role in advancing the digital transformation of European ports and strengthening the resilience and efficiency of port ecosystems.

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Data Availability Statement: The data supporting the reported results are derived exclusively from publicly accessible secondary sources. These include the official open data platforms of the Port of Barcelona (<https://opendata.portdebarcelona.cat>), the Port of Antwerp–Bruges (<https://www.portofantwerpbruges.com>), and NxtPort, the neutral data intermediary managing API-based data access for the Port of Antwerp–Bruges (<https://nxtport.com>), as well as European Union legislative instruments available via EUR-Lex (<https://eur-lex.europa.eu>) and the peer-reviewed academic literature. No new datasets were created or deposited in external repositories. All sources consulted are identified in the reference list.

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Abbreviations

The following abbreviations are used in this manuscript:

ODP	Open Data Platform
CC BY 4.0	Creative Commons Attribution 4.0 International
EU	European Union
FAIR	Findability, Accessibility, Interoperability, and Reusability
API	Application Programming Interface
IOT	Internet of Things
eFTI	Electronic Freight Transport Information
EMSW	European Maritime Single Window environment
TEN-T	Trans-European Transport Network
CKAN	Comprehensive Knowledge Archive Network
URL	Uniform Resource Locators
IMO	International Maritime Organisation
MMSI	Maritime Mobile Service Identity
CSV	Comma-Separated Values
JSON	JavaScript Object Notation
GDPR	General Data Protection Regulation
ETA	Estimated Time of Arrival
AI	Artificial Intelligence

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