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## D7 - Baseline Technical Requirements for Smart Port Digital Infrastructure and System-of-Systems Architecture

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| 0.2     | 2026-03-10 | C. Orfanidis                                     | Revised draft after coordinator feedback.   |
| 0.3     | 2026-04-19 | P. Pop / C. Orfanidis / P. Pappinisseri Puluckul | Rescoped as a preliminary baseline derived via MBSE; requirements restructured into per-requirement engineering blocks; representative reference scenario added; evaluation metrics removed (moved to D9 and D10) |

## Abbreviations

Only non-obvious and project-specific acronyms are listed. Widely known terms such as ISO, IEC, IMO, EU, IoT, and IT are used without an entry.

**Consortium and funders.** AEI (Agencia Estatal de Investigación, Spain); CBS (Copenhagen Business School); CETP (Clean Energy Transition Partnership); CMP (Copenhagen-Malmö Port); CTH (Chalmers University of Technology); DTU (Technical University of Denmark); PoA (Port of Aalborg); SWEA (Swedish Energy Agency); USEV (Universidad de Sevilla); WMU (World Maritime University).

**Project-internal.** WP (Work Package); LLN (Living Lab Network); SoS (System of Systems); MBSE (Model-Based Systems Engineering). Requirement domains: INT (Interoperability middleware and protocols); EDG (Edge computing and field IoT); DAT (Data platform and data fabric); DT (Digital Twin); EMG (Energy integration); OPS (Operational monitoring and optimization); SEC (Cybersecurity and IT/OT convergence); GOV (Governance and trust).

**Port operations and energy.** AIS (Automatic Identification System); BESS (Battery Energy Storage System); DER (Distributed Energy Resources); DSO (Distribution System Operator); EMS (Energy Management System); EMSWe (European Maritime Single Window environment, EU 2019/1239); EV (Electric Vehicle); HDV (Heavy-Duty Vehicle); MSW (Maritime Single Window); OPS (Onshore Power Supply); OT (Operational Technology); PCS (Port Community System); PtX (Power-to-X); PV (Photovoltaic); RoRo (Roll-on/Roll-off); SCADA (Supervisory Control and Data Acquisition); STS (Ship-to-Shore crane); TOS (Terminal Operating System); VTS (Vessel Traffic Service).

**Standards, frameworks, and modelling.** AADL (Architecture Analysis and Design Language, SAE AS5506); AAS (Asset Administration Shell, IEC 63278); FIWARE (open reference-platform ecosystem); IIRA (Industrial Internet Reference Architecture); IDS-RAM (International Data Spaces Reference Architecture Model); NGSI-LD (context information management API, ETSI); OPC UA (IEC 62541); PortCDM (Port Collaborative Decision Making); SGAM (Smart Grid Architecture Model); SWOT (strengths, weaknesses, opportunities, threats analysis).

**Regulation and policy.** AFIR (Alternative Fuels Infrastructure Regulation, EU 2023/1804); CRA (Cyber Resilience Act, EU 2024/2847); ENISA (European Union Agency for Cybersecurity); FuelEU Maritime (EU 2023/1805); NIS2 (Directive EU 2022/2555 on network and information security).

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## Executive summary

This deliverable reports a preliminary baseline of technical requirements for the digital infrastructure of smart ports, treated as a System of Systems (SoS), under task T3.1 of POTENT-X. The requirements are derived through Model-Based Systems Engineering. Three inputs are used for the derivation of requirements: the standards applicable in the port areas (e.g., ISO/IEC/IEEE 15288 and 21839, IEC 62443, ISO 23247 with the IEC 63278 Asset Administration Shell, and the European maritime-policy instruments); the scientific literature on smart ports and port digital twins; and the authors' domain expertise in digitalization, SoS embedded IoT communication for port environments. A questionnaire reached approximately 94 contacts across port authorities, terminal operators, energy utilities, technology vendors, public agencies, and research organizations, and returned five valid responses. Those responses are used as practitioner grounding, not as statistical evidence.

The deliverable has identified 30 requirements over eight technical domains and one cross-cutting category. They are based on a representative mid-size European port scenario, which we have identified. Each requirement is mapped to a candidate architecture component in the POTENTX: : "namespace". The formal reference architecture and the associated risk-analysis framework are in deliverable D9 (task T3.3); the performance indicators and the SWOT analysis are in deliverable D10 (task T3.4).

## Use of generative AI tools

No generative AI was used for the conceptualization, design, or technical development of the requirements baseline reported in this deliverable. The reference scenario, the elicitation methodology, the requirements, the rationales, and the mapping to architectural components were produced without the use of generative AI tools.

During drafting, the authors used generative AI tools for editorial tasks and for consistency checks, operating on text, requirements, and rationales authored entirely by the authors. Gemini 3.1 Pro was used to correct grammar and spelling, to verify that acronyms are defined before first use, to combine inputs from several authors, and to condense text. ChatGPT 5.4 (Extended Thinking) was used to cross-check internal consistency, for example, that the requirement identifiers referenced in Section 5 match the requirement blocks defined in Section 4. Any issues identified by these checks were resolved manually.

The authors are aware of the risks associated with generative AI tools, in particular hallucinations, most critically in bibliographic references, and bias. Generative AI was not used to generate or reformat references. Every citation in the References section was compiled and verified by the authors against the original source, and the authors have checked that the meaning of the source material has not been altered. A critical review of all AI-processed text was performed by the lead author. No confidential or personal data was provided to public AI tools. The authors retain full responsibility for the content of this deliverable.

## 1. Introduction

Maritime ports no longer fit the single-purpose cargo-node model. A modern mid-size European port runs cargo and passenger operations, hinterland transport chains, a busy interface with the surrounding city, and a growing portfolio of energy services. The energy portfolio alone drives much of the added complexity: European ports now operate OPS to decarbonize vessels at berth, host battery energy storage systems (BESS) and renewable generation, support EV and HDV charging, and act as landing points for emerging PtX fuel chains<sup>1 2</sup>. Each of these services imposes new digital obligations (metering, forecasting, coordination with distribution system operators (DSOs), vessel arrival synchronization, regulated data sharing with city and customs actors). Most European ports have to absorb these obligations on top of a fragmented ownership environment, in which the port authority, terminal operators, utilities, and city agencies each run their own systems and assets.

The CETPartnership project POTENT-X, *Ports as Energy Transition Hubs*, addresses four inter-related challenges in that setting: governance (work package WP1), policy and supply-chain transition (WP2), digitalization and energy resilience (WP3), and socio-economic integration (WP4). WP3, led by the Technical University of Denmark (DTU), treats the port as a SoS: a set of operationally and managerially independent subsystems (terminals, energy assets, port community systems, vessel interfaces, city services) that collaborate to deliver port-level functions without a single controlling authority<sup>3 4</sup>.

D7 is the requirements baseline that drives the WP3 digitalization work. Task T3.1 is formally scoped as the development of a SoS reference architecture for smart ports, anchored on MBSE principles; D7 captures the technical requirements that the reference architecture must satisfy, and leaves the architecture itself to D9. The requirements will be provided as inputs to three artifacts inside WP3:

- **D8: Digital Twin Prototype** (task T3.2, lead University of Seville (USEV) and SEAPort Solutions, due M30): a concrete digital twin for port operations and port–city relations. D8 consumes the DT-domain and data-platform requirements from Section 4.
- **D9: SoS-Based Reference Architecture and Risk Analysis Framework** (task T3.3, lead DTU, due M32): an analyzable reference-architecture model of the port SoS, together with the associated risk-analysis methodology. The modelling language for D9 is not yet fixed. One candidate under active consideration is the Architecture Analysis and Design Language (AADL), a formal description language standardized by the

<sup>1</sup> Autorità di Sistema Portuale del Mar Tirreno Settentrionale. *Allegato Statistico 2024* (Livorno statistical annex). 2025. [https://www.portaltotirreno.it/wp-content/uploads/2025/02/LIVORNO\\_Allegato\\_Statistico\\_2024.pdf](https://www.portaltotirreno.it/wp-content/uploads/2025/02/LIVORNO_Allegato_Statistico_2024.pdf)

<sup>2</sup> Göteborgs Hamn AB. *Årsredovisning 2024* (Port of Gothenburg Annual Report 2024). 2025. <https://www.goteborgshamn.se/globalassets/dokument/publikationer/arsredovisning-2024—goteborgs-hamn-ab.pdf>

<sup>3</sup> ISO/IEC/IEEE 15288:2023, *Systems and software engineering, System life cycle processes*. International Organization for Standardization, 2023. <https://www.iso.org/standard/81702.html>

<sup>4</sup> ISO/IEC/IEEE 21839:2019, *Systems and software engineering, System of systems (SoS) considerations in life cycle stages of a system*. International Organization for Standardization, 2019. <https://www.iso.org/standard/71955.html>

Society of Automotive Engineers as SAE AS5506 that supports analyzable description of software, hardware, communication links, and deployment bindings within a single model<sup>5</sup>. The Systems Modeling Language (SysML) version 2, standardized by the Object Management Group<sup>6</sup>, and the Arcadia method with its open-source Capella tooling<sup>7</sup> are alternative candidates. The choice among them is scoped to the start of task T3.3 and will be reported in D9 itself. Regardless of the modelling language that D9 selects, every requirement defined in this document is to be mapped to one or more architectural components in D9, together with the associated verification strategy.

- **D10: Performance Indicators and SWOT analysis** (task T3.4, lead Chalmers University of Technology (CTH), due M32): resilience performance indicators and a SWOT (strengths–weaknesses–opportunities–threats) analysis for sectoral coupling. Project-level key performance indicators for port resilience and energy transition belong to D10, not to D7.

D7 also has a link to WP2. D3 (assessment of future energy utilization, task T2.1, World Maritime University (WMU)), D5 (mathematical toolkit for the grid impacts of port electrification, task T2.3, CTH), and D6 (supply-chain model for hydrogen and e-fuels, task T2.4, CTH) cover the energy-analysis work in WP2. The energy-integration requirements in Section 4.5 are on the architectural level, and do not re-derive those analyses.

We follow published standards on requirements documentation. The requirements style (engineering “shall” statements, each paired with a rationale and a linked architectural component) is the style used in analyzable MBSE deliverables of comparable prior EU research. For architecture description, we commit to ISO/IEC/IEEE 42010 as the viewpoint and concern framework for D9<sup>8</sup>, with ISO/IEC/IEEE 15288, 21839, 21840, and 21841 as the systems- and SoS-engineering process baseline<sup>9 10 11 12</sup>. Operational-technology cybersecurity is related to the IEC 62443 standards series<sup>13</sup>. The digital-twin perspective relies on ISO 23247 and the

<sup>5</sup> SAE International. SAE AS5506D, *Architecture Analysis and Design Language (AADL)*. 2022. <https://saemobilus.sae.org/standards/as5506d-architecture-analysis-design-language-aadl>

<sup>6</sup> Object Management Group. *Systems Modeling Language (SysML) version 2*. OMG, 2025. <https://www.omg.org/sysml/sysmlv2/>

<sup>7</sup> Eclipse Foundation / Thales. *Arcadia method and Capella modelling tool*. <https://mbse-capella.org/arcadia.html>

<sup>8</sup> ISO/IEC/IEEE 42010:2022, *Software, systems and enterprise, Architecture description*. International Organization for Standardization, 2022. <https://www.iso.org/standard/74393.html>

<sup>9</sup> ISO/IEC/IEEE 15288:2023, *Systems and software engineering, System life cycle processes*. International Organization for Standardization, 2023. <https://www.iso.org/standard/81702.html>

<sup>10</sup> ISO/IEC/IEEE 21839:2019, *Systems and software engineering, System of systems (SoS) considerations in life cycle stages of a system*. International Organization for Standardization, 2019. <https://www.iso.org/standard/71955.html>

<sup>11</sup> ISO/IEC/IEEE 21840:2019, *Systems and software engineering, Guidelines for the utilization of ISO/IEC/IEEE 15288 in the context of system of systems (SoS)*. International Organization for Standardization, 2019. <https://www.iso.org/standard/71956.html>

<sup>12</sup> ISO/IEC/IEEE 21841:2019, *Systems and software engineering, Taxonomy of systems of systems*. International Organization for Standardization, 2019. <https://www.iso.org/standard/71957.html>

<sup>13</sup> IEC 62443 series (parts 2-1, 2-4, 3-2, 3-3, 4-1, 4-2), *Security for industrial automation and control systems*. International Electrotechnical Commission. <https://www.iso.org/standard/78744.html>

Asset Administration Shell c.f. IEC 63278 <sup>14 15</sup>. The European maritime policy context, EU Port Services Regulation 2017/352 <sup>16</sup>, the NIS2 Directive <sup>17</sup>, the Cyber Resilience Act <sup>18</sup>, the AFIR / FuelEU Maritime / EU ETS Maritime legislative triplet <sup>19</sup>, and the IMO Maritime Single Window obligation in force from 1 January 2024 <sup>20</sup>, frames the governance assumptions under which the SoS operates.

The rest of this document is structured as follows. Section 2 documents the methodology and the honest limitations of the evidence base. Section 3 defines a representative mid-size European port as the reference scenario, built from published characteristics of real European ports. Section 4 lists the requirements baseline in eight technical domains and a cross-cutting category. Section 5 gives a preliminary mapping of each requirement to a candidate architecture component, to be formalized in D9. Section 6 states the limitations of the present baseline. Section 7 previews the reference architecture that D9 will develop.

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<sup>14</sup> ISO 23247 series (parts 1–4), *Automation systems and integration, Digital twin framework for manufacturing*. International Organization for Standardization, 2021. <https://www.iso.org/standard/75066.html>

<sup>15</sup> IEC 63278-1:2023, *Asset Administration Shell for industrial applications, Part 1: Asset Administration Shell structure*. International Electrotechnical Commission, 2023. <https://webstore.iec.ch/en/publication/65628>

<sup>16</sup> Regulation (EU) 2017/352 of the European Parliament and of the Council of 15 February 2017 establishing a framework for the provision of port services and common rules on the financial transparency of ports. <https://eur-lex.europa.eu/legal-content/EN/LSU/?uri=CELEX%3A32017R0352>

<sup>17</sup> Directive (EU) 2022/2555 on measures for a high common level of cybersecurity across the Union (NIS2 Directive). 14 December 2022. <https://eur-lex.europa.eu/eli/dir/2022/2555/2022-12-27/eng>

<sup>18</sup> Regulation (EU) 2024/2847 on horizontal cybersecurity requirements for products with digital elements (Cyber Resilience Act). 23 October 2024. <https://eur-lex.europa.eu/eli/reg/2024/2847/oj/eng>

<sup>19</sup> Regulation (EU) 2023/1804 on the deployment of alternative fuels infrastructure (AFIR); Regulation (EU) 2023/1805 on the use of renewable and low-carbon fuels in maritime transport (FuelEU Maritime); Directive (EU) 2023/959 amending Directive 2003/87/EC as regards maritime transport (EU ETS Maritime extension). <https://eur-lex.europa.eu/eli/reg/2023/1804/oj/eng>

<sup>20</sup> International Maritime Organization. Maritime Single Window, *Free flow of trade by ship*. FAL.5/Circ.42/Rev.3, mandatory from 1 January 2024. <https://www.imo.org/en/mediacentre/hottopics/pages/free-flow-of-trade-by-ship.aspx>

## 2. Methodology

The requirements baseline is derived via Model-Based Systems Engineering, organized as a five-step process aligned with the system life-cycle activities of ISO/IEC/IEEE 15288<sup>21</sup> and specialized for SoS settings per ISO/IEC/IEEE 21839, 21840, and 21841<sup>22 23 24</sup>.

**Step 1. Reference scenario construction.** We synthesize a representative mid-size European port from published characteristics of real ports and from the scientific literature on smart ports (Section 3). The scenario fixes the class of system that the requirements target (approximately 0.5–1.5 M TEU/year throughput, multipurpose cargo mix, fragmented governance, mixed energy portfolio, and close interaction with a surrounding city) and supplies a consistent set of assumptions for reasoning about subsystem boundaries, interfaces, and stakeholder roles.

**Step 2. Requirement elicitation.** Candidate requirements are derived from three sources. Standards and regulations supply the normative baseline for systems engineering, architecture description, OT cybersecurity, digital twin and Asset Administration Shell modelling, industrial communication (OPC UA, MQTT, and IEC 61850 at the field level, with IEC/IEEE 80005 at the shore-connection interface), and EU maritime policy. The scientific literature on smart ports, port digital twins, port cybersecurity, and port-energy integration supplies the state-of-the-art perspective and identifies recurring engineering concerns not yet standardized. The authors’ domain expertise (MBSE for SoS in earlier EU research and current DTU work on IoT communication for port environments) provides the translation from the state of the art into explicit “shall” engineering statements bound to architectural components.

**Step 3. Practitioner grounding.** A grounding questionnaire was distributed to approximately 94 contacts spanning port authorities, terminal operators, energy utilities, technology vendors and integrators, public agencies, and research organizations. Five valid responses were returned, four from academic organizations and one from the public sector, with most respondents located in Europe. The response rate, estimated at roughly 5%, is too low to support a representative baseline of practitioner views. The responses are therefore used for *practitioner grounding* only, a qualitative check that the requirements derived in Step 2 align with how existing organizations describe their digital-infrastructure priorities and pain points. The questionnaire structure, the anonymized response set, and the derived themes are reported in Annex A and Annex B.

<sup>21</sup> ISO/IEC/IEEE 15288:2023, *Systems and software engineering, System life cycle processes*. International Organization for Standardization, 2023. <https://www.iso.org/standard/81702.html>

<sup>22</sup> ISO/IEC/IEEE 21839:2019, *Systems and software engineering, System of systems (SoS) considerations in life cycle stages of a system*. International Organization for Standardization, 2019. <https://www.iso.org/standard/71955.html>

<sup>23</sup> ISO/IEC/IEEE 21840:2019, *Systems and software engineering, Guidelines for the utilization of ISO/IEC/IEEE 15288 in the context of system of systems (SoS)*. International Organization for Standardization, 2019. <https://www.iso.org/standard/71956.html>

<sup>24</sup> ISO/IEC/IEEE 21841:2019, *Systems and software engineering, Taxonomy of systems of systems*. International Organization for Standardization, 2019. <https://www.iso.org/standard/71957.html>

**Step 4. Synthesis.** The candidates from Step 2, checked against Step 3, are merged into a single baseline, organized in eight technical domains: interoperability middleware and protocols (INT), edge computing and field IoT (EDG), data platform and data fabric (DAT), digital twin (DT), energy integration (EMG), operational monitoring and optimization (OPS), cybersecurity and IT/OT convergence (SEC), and governance and trust (GOV); plus a cross-cutting category (X). Each requirement uses a five-field block template: identifier, description in “shall” form, rationale, abstraction level (High or Low), and the architectural component that it most directly constrains. Architectural components are written in a POTENTX: : namespace that D9 will populate with concrete elements once a modelling language is selected at the start of task T3.3. Standards, EU projects, and academic sources that frame each domain are cited in the domain introduction paragraphs of Section 4 and in the narrative sections of this document, not on individual requirement blocks. Metrics and dependencies are not part of the block template either: project-level performance indicators belong to D10 (task T3.4), verification metrics to D9 (task T3.3), and dependencies are represented through the architecture mapping.

**Step 5. Preliminary component mapping.** Each requirement is then mapped to a candidate architecture-component name in the POTENTX: : namespace, grouped by the preview layer sketched in Section 7 (*Bridge to D9*). The mapping is preliminary: D9 will refine it into a formal reference architecture. Unresolved questions and acknowledged gaps are recorded in Section 6.

**Scope.** Verification of the requirements against an instantiated reference architecture, and risk-based evaluation of the resulting digital infrastructure, are addressed in D9 (task T3.3). Project-level performance indicators for port energy transition and resilience, including resilience KPIs and the SWOT analysis, are defined in D10 (task T3.4, led by CTH). D7 therefore limits itself to the requirements baseline and its preliminary mapping to candidate architecture components.

### 3. Representative smart port reference scenario

This section defines a representative mid-size European container and multipurpose port as the reference scenario against which the requirements in Section 4 are derived. The scenario is synthesized from published characteristics of real European ports. No single real port is the subject of D7: the scenario is deliberately abstracted so that the requirements remain portable across the POTENT-X consortium and beyond. Claims that rest on the authors' judgement rather than on a single primary source are flagged as.

#### 3.1 Port profile

The reference port handles roughly **0.5–1.5 million TEU per year** and **20–35 million tones of total annual cargo**, with a mixed portfolio of container, RoRo/ferry, dry and liquid bulk, project and general cargo, cruise, and offshore or service calls. The port estate covers approximately **400–1,200 ha**, and the port is embedded in, or immediately adjacent to, an urban area rather than sited in a separated industrial zone. Commercial quay inventory is approximately **15–35 berths and quay faces**, of which 2–6 are container berths, together with additional RoRo, bulk, passenger, and service berths. Rail connectivity is the baseline hinterland interface; inland waterway connectivity is common but not universal. City interaction is high and spans air quality, noise, traffic, employment, cruise and ferry acceptance, and emergency response.<sup>25</sup>

The composite is consistent with ports such as Livorno (663,622 TEU and 29.4 Mt in 2024)<sup>26</sup>, the Port of Gothenburg (largest port in Scandinavia; 49 berth positions; approximately 70 trains per day and 25+ inland terminals)<sup>27 28</sup>, Copenhagen Malmö Port (container, RoRo, cruise/ferry, bulk and rail in a single operating group)<sup>29</sup>, and the Port of Tyne (container, bulk, automotive and offshore-wind support near Newcastle)<sup>30</sup>. Upper-tier European hubs such as Hamburg, Antwerp-Bruges, and Rotterdam are not used for sizing, because their absolute scale places them outside the mid-size class; they are cited in this section only as sources of digital-programme evidence.

A specific engineering assumption follows: the reference port is **not a single-operator environment**. The port authority owns or regulates common infrastructure, while terminal operators, energy utilities, city agencies, customs, pilots, tug companies, shipping lines, and digital-platform operators each run their own systems and assets. Governance fragmentation is

<sup>25</sup> Autorità di Sistema Portuale del Mar Tirreno Settentrionale. *Allegato Statistico 2024* (Livorno statistical annex). 2025. [https://www.portialtotirreno.it/wp-content/uploads/2025/02/LIVORNO\\_Allegato\\_Statistico\\_2024.pdf](https://www.portialtotirreno.it/wp-content/uploads/2025/02/LIVORNO_Allegato_Statistico_2024.pdf)

<sup>26</sup> Autorità di Sistema Portuale del Mar Tirreno Settentrionale. *Allegato Statistico 2024* (Livorno statistical annex). 2025. [https://www.portialtotirreno.it/wp-content/uploads/2025/02/LIVORNO\\_Allegato\\_Statistico\\_2024.pdf](https://www.portialtotirreno.it/wp-content/uploads/2025/02/LIVORNO_Allegato_Statistico_2024.pdf)

<sup>27</sup> Port of Gothenburg (Göteborgs Hamn AB). *Hamnen i siffror* (The port in figures). <https://portgot.maglr.com/hamnenisiffror>

<sup>28</sup> Göteborgs Hamn AB. *Årsredovisning 2024* (Port of Gothenburg Annual Report 2024). 2025. <https://www.goteborgshamn.se/globalassets/dokument/publikationer/arsredovisning-2024—goteborgs-hamn-ab.pdf>

<sup>29</sup> Copenhagen Malmö Port. *Container services*. <https://www.cmport.com/services/containers/>

<sup>30</sup> Port of Tyne. *The sustainable smart port*. <https://www.portoftyne.co.uk/news-and-media/news/the-sustainable-smart-port>

therefore a first-class architectural constraint, not a deployment accident, and the requirements in Section 4 are written on that assumption <sup>31</sup>.

### 3.2 Energy assets

The energy portfolio that the reference port must digitally integrate is summarized in Table 1. Typical capacity ranges are synthesized from published values at representative European ports. Integration protocols are stated at the boundary between the asset and the port energy-management layer; they are not prescriptive for the asset-internal automation.

**Table 1. Energy assets in the reference scenario, with typical capacity ranges and integration protocols.**

| Asset              | Typical capacity / scale  | Integration protocols  | Typical operator  |
|--------------------|---|--|---|
| OPS / cold ironing | Ferry/RoRo 1–5 MVA per berth; cruise 8–16 MVA per berth; container 4–10 MVA per berth; port programme 5–30+ MVA           | Energy meters at berth and substation; SCADA/BMS integration via OPC UA <sup>32</sup> , Modbus <sup>33</sup> , and IEC 61850 <sup>34</sup> at MV/HV interfaces | Port authority or city-port infrastructure company; operation may be delegated to port operator or energy partner <sup>35</sup> |
| Solar PV           | Building to estate scale; hundreds of kWp to low single-digit MWp, occasionally higher where roof and land stock is large | Generation telemetry into EMS/BMS/SCADA; inverter and meter data typically exposed over Modbus or OPC UA <sup>36</sup>   | Port authority, tenant, logistics real-estate owner, or utility JV <sup>37</sup>  |
| Onshore wind       | One to a few turbines; low tens of MW where siting allows; often off-estate but electrically relevant                     | Turbine SCADA plus substation metering; IEC 61850 or utility-specific telemetry <sup>38</sup>  | Independent power producer, municipal utility, or port-energy JV  |
| BESS               | 0.5–20 MWh at port-authority or logistics-cluster scale   | EMS/SCADA links; meter and state-of-charge data via OPC UA or Modbus; DSO/market   | Port authority, utility, local flexibility-market   |

<sup>31</sup> Göteborgs Hamn AB. *Årsredovisning 2024* (Port of Gothenburg Annual Report 2024). 2025. <https://www.goteborgshamn.se/globalassets/dokument/publikationer/arsredovisning-2024—goteborgs-hamn-ab.pdf>

<sup>32</sup> IEC 62541-1:2020, *OPC Unified Architecture, Part 1: Overview and Concepts*. International Electrotechnical Commission, 2020. <https://webstore.iec.ch/publication/61109>

<sup>33</sup> Modbus Organization. *Introduction to Modbus*. <https://modbus.org/introduction-to-modbus>

<sup>34</sup> IEC 61850, *Communication networks and systems for power utility automation*. International Electrotechnical Commission. <https://iec61850.dvl.iec.ch/>

<sup>35</sup> Copenhagen Malmö Port. *Shore power information*. 2025. <https://www.cmport.com/wp-content/uploads/2025/12/Shore-power-information.pdf>

<sup>36</sup> Modbus Organization. *Introduction to Modbus*. <https://modbus.org/introduction-to-modbus>

<sup>37</sup> Port of Tyne. *Ground officially broken on operations and maintenance base for the world's biggest offshore wind farm*. Press release. <https://www.portoftyne.co.uk/news-and-media/news/ground-officially-broken-on-operations-and-maintenance-base-for-worlds-biggest-offshore-wind-farm>

<sup>38</sup> IEC 61850, *Communication networks and systems for power utility automation*. International Electrotechnical Commission. <https://iec61850.dvl.iec.ch/>

| Asset                    | Typical capacity / scale   | Integration protocols  | Typical operator  |
|--------------------------|--|--|---|
|                          |  | interfaces through enterprise platforms  | operator, or tenant consortium <sup>39</sup>  |
| EV and HDV charging      | AC 11–22 kW, DC 50–350 kW; Megawatt Charging System (MCS) scale and depot charging as programmes mature; staged rollout typical                          | Open Charge Point Protocol (OCPP) for charger-backend communication <sup>40</sup> ; meter data integrated to EMS | Port authority fleet, terminal operator, logistics tenant, charge-point operator, DSO/utility             |
| Hydrogen / PtX           | Pilot or early-commercial integration point; larger hubs are external network connections rather than core on-port assets in the mid-size reference case | Process control via PLC/SCADA and historians; pipeline/storage metering; safety instrumentation                  | University lab, industrial tenant, energy developer, utility, or port authority as landlord <sup>41</sup> |
| LNG / bio-LNG bunkering  | None to active niche service; when active, tens of thousands to hundreds of thousands of m <sup>3</sup> /year  | Bunkering notifications, safety checklists, berth planning, mass/volume metering, hazardous-goods workflows      | Bunker suppliers and terminal operators under port-authority rules <sup>42</sup>                          |
| Building energy systems  | Hundreds of kW to low MW aggregated loads  | BMS/EMS, submeters, historians; Modbus/OPC UA common integration layers <sup>43</sup>                            | Port authority and terminal operators   |
| Cargo-handling equipment | Electrified STS cranes nearly universal; yard fleet mixed diesel-electric, hybrid, battery-electric in mid-size ports                                    | OEM telemetry, PLC/SCADA, maintenance CMMS, meter and fuel data  | Terminal operators <sup>44</sup>  |

### 3.3 Operational assets

The operational side of the reference port is summarized in Table 2. The set of operational assets drives a large share of the data flows that the SoS digital infrastructure must carry, and therefore directly shapes requirements on the data platform, the PCS interface, the gate and OCR systems, the VTS layer, and the asset telemetry pipeline.

<sup>39</sup> Port of Rotterdam Authority. *Successful trial, Port of Rotterdam electricity platform*. News release. <https://www.portofrotterdam.com/en/news-and-press-releases/successful-trial-port-rotterdam-electricity-platform>

<sup>40</sup> Open Charge Alliance. *Open Charge Point Protocol (OCPP)*. <https://openchargealliance.org/protocols/open-charge-point-protocol/>

<sup>41</sup> Port of Aalborg. *Green transition, Power-to-X*. <https://portofaalborg.dk/en/green-transition-power-to-x/>

<sup>42</sup> Autoridad Portuaria de la Bahía de Algeciras (APBA). *Green Energy Hub, el Puerto de Algeciras lidera el suministro de GNL y bioGNL*. <https://www.apba.es/noticias/green-energy-hub-el-puerto-de-algeciras-lidera-el-suministro-de-gnl-y-biognl>

<sup>43</sup> Modbus Organization. *Introduction to Modbus*. <https://modbus.org/introduction-to-modbus>

<sup>44</sup> Copenhagen Malmö Port. *STS cranes*. <https://www.cmport.com/projects/sts-cranes-2/>

**Table 2. Operational assets, typical scale, and data interfaces.**

| Asset class                       | Typical scale  | Data interfaces  | Main operator  |
|-----------------------------------|--|--|--|
| Container terminal                | One main terminal plus a smaller feeder facility; 2–6 STS cranes; yard blocks with reachstackers, straddles or rubber-tyred gantry cranes (RTGs); reefer monitoring; customs holds | TOS, Optical Character Recognition (OCR) and Automatic Number Plate Recognition (ANPR) at autogates, asset telemetry, maintenance systems, PCS links | Terminal operator <sup>45</sup>  |
| RoRo / ferry                      | Dedicated ramps, marshalling yards, booking and slotting, security, passenger segregation  | Booking APIs, gate systems, PCS, passenger information systems   | Ferry operators and terminal operator; port authority regulates access             |
| Bulk / general cargo              | Liquid and dry bulk berths, warehouses, conveyors, weighbridges, hazardous-goods controls  | Terminal systems, weighbridge data, dangerous-goods reporting, environmental monitoring  | Specialized terminal concessionaires   |
| Landside gates                    | 2–8 truck lanes with OCR/ANPR/autogate, pre-booking, exception handling, customs holds   | OCR/ANPR, appointment systems, release and booking data (e.g., Certified Pick up, Secure Chain, SUMC patterns), PCS/TOS integration                  | Terminal operator together with port authority, customs, and haulers <sup>46</sup> |
| Yard logistics and berth planning | Planning horizon from minutes to several days  | Berth planners, digital port-call tools, TOS and PCS messages  | Port control / harbor master and terminal operators <sup>47</sup>                  |
| Inter-modal rail and inland links | Port rail terminal(s), siding capacity, train slot planning; rail is a major differentiator for European mid-size ports  | Rail planning tools, PCS hinterland modules, customs declarations, cargo-document links  | Port railway, rail operators, terminal operators <sup>48</sup>                     |
| VTS, pilotage, tugs               | Continuous monitoring, pilot ordering, tug dispatch, incident handling   | AIS, radar, hydro-met data, radio, call reporting, PCS messages  | Harbor master / VTS authority, pilotage and tug operators                          |
| Dry dock / repair /               | Workshops, permit-to-work, utility hooks, hazardous maintenance operations   | Port security, work permits, maintenance and energy data   | Shipyard and service operators   |

<sup>45</sup> Copenhagen Malmö Port. *Container services*. <https://www.cmport.com/services/containers/>

<sup>46</sup> Adriaports. *Port of Trieste: tender launched to expand and speed up truck access*. <https://www.adriaports.com/en/shipping-en/port-of-trieste-tender-launched-to-expand-and-speed-up-truck-access/>

<sup>47</sup> Port of Gothenburg. *Digital Port Call (DPC)*. <https://www.goteborgshamn.se/operations/hubb-e-tjanster/dpc/>

<sup>48</sup> Port of Gothenburg (Göteborgs Hamn AB). *Hamnen i siffror (The port in figures)*. <https://portgot.maglr.com/hamnenisiffror>

| Asset class      | Typical scale | Data interfaces | Main operator |
|------------------|---------------|-----------------|---------------|
| offshore support |               |                 |               |

### 3.4 Data and systems inventory

The reference port runs, at a minimum, the set of information systems shown in Table 3. Integration between these systems is the main architectural problem that D9 must address: public sources describe the flagship applications well, while the integration fabric between PCS, TOS, SCADA, historians, and cloud analytics usually remains undisclosed <sup>49</sup>.

**Table 3. Digital systems in the reference port.**

| System                             | Role  | Typical vendors or operator pattern                         | Examples   |
|------------------------------------|---|---|--|
| Port Community System (PCS)        | Neutral transaction fabric for port calls, cargo events, customs, and hinterland exchange | Public-private or port-community operators                  | Portbase (Rotterdam/Amsterdam) <sup>50</sup> , DAKOSY (Hamburg) <sup>51</sup> , NxtPort (Antwerp), Portic (Barcelona), ValenciaportPCS |
| Maritime Single Window (MSW)       | Statutory reporting for arrival, stay, and departure                                      | National or public systems interfacing with PCS and customs | EMSWe-aligned national implementations <sup>52</sup>   |
| Terminal-local systems (TOS, gate) | Yard, berth, equipment, and gate execution  | Terminal-operator managed; product names rarely public      | Terminal-specific  |
| VTS / port-traffic management      | Nautical safety, sequencing, situational awareness  | Port authority / harbor master platforms                    | Hamburg Traffic Tower, Antwerp APICA, Algeciras VTS/STM <sup>53</sup>  |
| PLC/SCADA and OT historians        | Control of substations, OPS, gates, pumps, lighting, buildings, and energy assets         | Operator- or utility-owned OT                               | Modbus, OPC UA, IEC 61850 integration layers <sup>54</sup>   |

<sup>49</sup> DAKOSY. *Cargo communications, Port of Hamburg*. <https://www.dakosy.de/en/cargo-communications/portofhamburg>

<sup>50</sup> Portbase. *About us, Port Community System for Rotterdam and Amsterdam*. <https://www.portbase.com/en/about-us/>

<sup>51</sup> DAKOSY. *Import, Port Community System for the Port of Hamburg*. <https://www.dakosy.de/en/portofhamburg/import>

<sup>52</sup> Regulation (EU) 2019/1239 establishing a European Maritime Single Window environment (consolidated version, 15 August 2025). <https://eur-lex.europa.eu/eli/reg/2019/1239/2025-08-15/eng>

<sup>53</sup> Port of Antwerp-Bruges. *Smart port*. <https://www.portofantwerpbruges.com/en/our-port/port-future/smart-port>

<sup>54</sup> IEC 62541-1:2020, *OPC Unified Architecture, Part 1: Overview and Concepts*. International Electrotechnical Commission, 2020. <https://webstore.iec.ch/publication/61109>

| System                              | Role   | Typical vendors or operator pattern                            | Examples   |
|-------------------------------------|--|--|--|
| IoT / environmental sensing         | Air, water, noise, odour, occupancy, parking, and infrastructure monitoring                              | Sensor specialists and city-platform partners                  | Algeciras environmental platform with FIWARE data models and Thinking Cities <sup>55</sup>       |
| Edge / 5G / communications backbone | Low-latency connectivity for video, IoT, autonomous aids, operational applications                       | Private 5G and telecom upgrades are increasingly port-specific | Valencia port private 5G for 25,000+ devices <sup>56</sup>                                       |
| Port-city / digital-twin platform   | Cross-domain situational awareness and simulation  | Port-authority or city-port initiatives                        | Antwerp APICA, Rotterdam digital twin, Algeciras NextPort <sup>57</sup>                          |
| Enterprise IT / billing / identity  | Dues, invoicing, billing, access control, Authorized Economic Operator (AEO) and security administration | ERP and identity stacks integrated with port portals           | CMP finance and access-card workflows <sup>58</sup> ; Rotterdam Secure Chain authorization model |

### 3.5 Stakeholder ecosystem

Table 4 is the stakeholder set against which the requirements in Section 4 are scoped. Two features of the set matter for the architecture. The set spans public and private entities with very different operational cadences and data-protection expectations. No stakeholder has full authority over the SoS: the port authority holds the strongest regulatory position, but it does not own most of the data flows.

**Table 4. Stakeholder concerns, data interests, and regulatory obligations.**

| Stakeholder        | Primary concerns   | Data interests  | Regulatory exposure  |
|--------------------|--|---|--|
| Port authority     | Safety, capacity, compliance, concession oversight, decarbonization, port-city legitimacy              | VTS picture, berth occupancy, energy use, environmental KPIs, dues, incidents | Port services and transparency; MSW/EMSW interfaces; NIS2 where designated essential; AFIR/FuelEU/ETS exposure                         |
| Terminal operators | Throughput, labor and equipment productivity, gate fluidity, energy cost, cybersecurity, customer SLAs | TOS, yard inventory, gate OCR, asset telemetry, OPS and charging demand       | FuelEU/ETS indirectly through vessel and terminal operations; NIS2/CRA where digital products or essential infrastructure are operated |

<sup>55</sup> APBA Innovation. *Advanced platform for environmental sustainability management in the Port of Algeciras*. <https://innovation.apba.es/en/advanced-platform-for-environmental-sustainability-management-in-the-port-of-algeciras-2/>

<sup>56</sup> Port Authority of Valencia. *Orange awarded the deployment of the port's private 5G network*. Press release. <https://www.valenciaport.com/en/the-port-authority-of-valencia-awards-orange-the-deployment-of-its-private-5g-network/>

<sup>57</sup> Port of Antwerp-Bruges. *Smart port*. <https://www.portofantwerpbruges.com/en/our-port/port-future/smart-port>

<sup>58</sup> Copenhagen Malmö Port. *Finance*. <https://www.cmpport.com/about-cmp/finance/>

| Stakeholder  | Primary concerns   | Data interests  | Regulatory exposure   |
|--|--|---|---|
| Shipping lines and agents                                    | Predictable turnaround, berth certainty, safe data exchange, release integrity, cost   | ETA/ETD, berth windows, pilot and tug status, MSW declarations, electronic Bill of Lading (eBL) events            | IMO FAL/MSW, EMSWe, FuelEU, EU ETS Maritime   |
| Haulers and inland operators                                 | Fast pickup and drop-off, secure release, slot reliability, border clearance           | Gate slots, release authorizations, rail slots, terminal status   | Customs and security rules; port police rules; digital-release compliance                         |
| Customs, border, sanitary authorities                        | Risk-based inspection, lawful reporting, throughput without control loss               | Cargo declarations, manifests, release status, inspection schedules   | EMSWe/MSW <sup>59</sup> ; customs law; national border and sanitary controls                      |
| Utility / DSO / energy-market actors                         | Grid capacity, connection queues, flexibility, settlement-quality metering, safety     | 15-minute and real-time meter data, charging and OPS load forecasts, BESS state, curtailment and flexibility bids | AFIR, grid codes, cyber obligations, product compliance <sup>60</sup>                             |
| Municipality / city agencies                                 | Air quality, noise, traffic, emergency response, cruise acceptance, jobs               | Environmental sensor feeds, traffic counts, cruise and ferry schedules, road-gate congestion                      | European Green Deal targets reflected in local plans; public-health and environmental obligations |
| Technology vendors / integrators                             | Interoperability, service levels, cyber resilience, access to operational data         | API events, device telemetry, GIS and context layers, maintenance and audit logs                                  | CRA product-security obligations; NIS2-derived contractual security                               |
| Environmental authorities, harbor police, emergency services | Monitoring, incident prevention, evidentiary records, hazardous goods, spill detection | Camera and drone feeds, air/water/noise data, dangerous-goods declarations, VTS data                              | Environmental law, port-police regulations, hazardous-goods and incident-reporting rules          |

### 3.6 External interfaces and data flows

The reference port exchanges data across seven principal interface classes, each of which imposes different latency, throughput, integrity, and regulatory-reporting requirements on the SoS.

<sup>59</sup> Regulation (EU) 2019/1239 establishing a European Maritime Single Window environment (consolidated version, 15 August 2025). <https://eur-lex.europa.eu/eli/reg/2019/1239/2025-08-15/eng>

<sup>60</sup> IEC 61850, *Communication networks and systems for power utility automation*. International Electrotechnical Commission. <https://iec61850.dvl.iec.ch/>

1. **Port–vessel and port-call coordination.** Ship, master, agent, harbour master, pilots, tug operators, and terminal. Data: AIS position, ETA/ETD, berth readiness, pilot and tug orders, declared arrival and departure information, weather and hydro data. Protocols: AIS, ECDIS context on board, PCS and port-call APIs, IMO FAL and EMSWe reporting. Frequency: AIS at seconds-to-minutes scale; administrative messages event-based per call. Regulatory driver: SOLAS/AIS, ECDIS carriage rules, IMO FAL<sup>61</sup>, EMSWe<sup>62</sup>.
2. **Port–city environment and mobility.** Port authority, municipality, environmental agencies, residents, and public open-data users. Data: air quality, water quality, noise, odor and light pollution, cruise schedules, truck traffic and closures. Protocols: IoT platforms, open APIs, FIWARE-style data models, open-data catalogue software such as CKAN, a widely used open-data portal platform. Frequency: sub-minute telemetry to daily planning and reporting. Regulatory driver: local environmental permits and Green Deal programmes<sup>63</sup>.
3. **Port–DSO, flexibility, and grid balancing.** Port energy manager, DSO, supplier or aggregator, utility, and large tenants. Data: connection status, substation and berth metering, charging demand, BESS state, flexibility offers, settlement values. Protocols: IEC 61850<sup>64</sup>, OPC UA<sup>65</sup>, Modbus<sup>66</sup>, charger backends via OCPP<sup>67</sup>. Frequency: real-time telemetry plus quarter-hourly or settlement-interval data. Regulatory driver: AFIR<sup>68</sup>, local grid-congestion management, cyber obligations for digital equipment<sup>69</sup>.
4. **Port–customs and maritime single window.** Ship or agent, port authority, customs, health and border authorities. Data: FAL declarations, crew and passenger lists, cargo declarations, waste and security notifications, inspection status. Protocols: EMSWe and IMO MSW guidance. Frequency: event-based around arrival, stay, and departure. Regulatory driver: EU Regulation 2019/1239<sup>70</sup> and IMO FAL guidance<sup>71</sup>.

<sup>61</sup> International Maritime Organization. Maritime Single Window, *Free flow of trade by ship*. FAL.5/Circ.42/Rev.3, mandatory from 1 January 2024. <https://www.imo.org/en/mediacentre/hottopics/pages/free-flow-of-trade-by-ship.aspx>

<sup>62</sup> Regulation (EU) 2019/1239 establishing a European Maritime Single Window environment (consolidated version, 15 August 2025). <https://eur-lex.europa.eu/eli/reg/2019/1239/2025-08-15/eng>

<sup>63</sup> APBA Innovation. *Advanced platform for environmental sustainability management in the Port of Algeciras*. <https://innovacion.apba.es/en/advanced-platform-for-environmental-sustainability-management-in-the-port-of-algeciras-2/>

<sup>64</sup> IEC 61850, *Communication networks and systems for power utility automation*. International Electrotechnical Commission. <https://iec61850.dvl.iec.ch/>

<sup>65</sup> IEC 62541-1:2020, *OPC Unified Architecture, Part 1: Overview and Concepts*. International Electrotechnical Commission, 2020. <https://webstore.iec.ch/publication/61109>

<sup>66</sup> Modbus Organization. *Introduction to Modbus*. <https://modbus.org/introduction-to-modbus>

<sup>67</sup> Open Charge Alliance. *Open Charge Point Protocol (OCPP)*. <https://openchargealliance.org/protocols/open-charge-point-protocol/>

<sup>68</sup> Regulation (EU) 2023/1804 on the deployment of alternative fuels infrastructure (AFIR); Regulation (EU) 2023/1805 on the use of renewable and low-carbon fuels in maritime transport (FuelEU Maritime); Directive (EU) 2023/959 amending Directive 2003/87/EC as regards maritime transport (EU ETS Maritime extension). <https://eur-lex.europa.eu/eli/reg/2023/1804/oj/eng>

<sup>69</sup> IEC 61850, *Communication networks and systems for power utility automation*. International Electrotechnical Commission. <https://iec61850.dvl.iec.ch/>

<sup>70</sup> Regulation (EU) 2019/1239 establishing a European Maritime Single Window environment (consolidated version, 15 August 2025). <https://eur-lex.europa.eu/eli/reg/2019/1239/2025-08-15/eng>

<sup>71</sup> International Maritime Organization. Maritime Single Window, *Free flow of trade by ship*. FAL.5/Circ.42/Rev.3, mandatory from 1 January 2024. <https://www.imo.org/en/mediacentre/hottopics/pages/free-flow-of-trade-by-ship.aspx>

5. **Port-shipper, track-and-trace, and documentation.** Carriers, shippers, forwarders, PCS providers, and terminals. Data: milestone events, eBL issuance/amendment/surrender, container status, and release authorization. Protocols: DCSA eBL and Track-and-Trace standards, PCS APIs. Frequency: event-driven throughout pre-shipment, ocean, post-ocean, and post-shipment phases. Regulatory driver: trade facilitation, customs digitalization, fraud reduction.
6. **Port-financial and billing.** Port authority, customers, utilities, and terminal operators. Data: port dues, berth and time charges, energy/OPS consumption, gate service charges, invoices, and payment status. Protocols: ERP, API, web-portal flows, metering data imports, customer identity services. Frequency: per call, per service event, daily and monthly settlement. Regulatory driver: Port Regulation transparency <sup>72</sup>.
7. **Port-inland logistics chain.** Terminals, rail operators, depots, truckers, inland terminals, and customs. Data: cargo documents, release status, slot bookings, train schedules, inland arrivals, and exceptions. Protocols: PCS hinterland modules, Secure Chain / Certified Pick up style authorization, digital gate systems. Frequency: continuous, event-driven, often near real time. Regulatory driver: supply-chain security, customs, and intermodal efficiency <sup>73</sup>.

### 3.7 Policy context

The reference scenario operates under an EU regulatory stack that is already committed and partly in force. The most directly load-bearing instruments for the requirements in Section 4 are the Port Services Regulation (EU) 2017/352 <sup>74</sup>; the European Maritime Single Window Environment Regulation 2019/1239 <sup>75</sup>; the NIS2 Directive <sup>76</sup>; the Cyber Resilience Act <sup>77</sup>; the AFIR, FuelEU Maritime, and EU ETS Maritime legislative triplet <sup>78</sup>; and the IMO Maritime Single Window obligation in force from 1 January 2024 <sup>79</sup>. The European Green Deal and the 2023 IMO GHG Strategy shape the long-range decarbonization objectives behind the port-energy and digital-efficiency programmes discussed above. National implementation detail, in particular

<sup>72</sup> Regulation (EU) 2017/352, full text on EUR-Lex. <https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX%3A32017R0352>

<sup>73</sup> DAKOSY. *Import, Port Community System for the Port of Hamburg*. <https://www.dakosy.de/en/portofhamburg/import>

<sup>74</sup> Regulation (EU) 2017/352 of the European Parliament and of the Council of 15 February 2017 establishing a framework for the provision of port services and common rules on the financial transparency of ports. <https://eur-lex.europa.eu/legal-content/EN/LSU/?uri=CELEX%3A32017R0352>

<sup>75</sup> Regulation (EU) 2019/1239 establishing a European Maritime Single Window environment (consolidated version, 15 August 2025). <https://eur-lex.europa.eu/eli/reg/2019/1239/2025-08-15/eng>

<sup>76</sup> Directive (EU) 2022/2555 on measures for a high common level of cybersecurity across the Union (NIS2 Directive). 14 December 2022. <https://eur-lex.europa.eu/eli/dir/2022/2555/2022-12-27/eng>

<sup>77</sup> Regulation (EU) 2024/2847 on horizontal cybersecurity requirements for products with digital elements (Cyber Resilience Act). 23 October 2024. <https://eur-lex.europa.eu/eli/reg/2024/2847/oj/eng>

<sup>78</sup> Regulation (EU) 2023/1804 on the deployment of alternative fuels infrastructure (AFIR); Regulation (EU) 2023/1805 on the use of renewable and low-carbon fuels in maritime transport (FuelEU Maritime); Directive (EU) 2023/959 amending Directive 2003/87/EC as regards maritime transport (EU ETS Maritime extension). <https://eur-lex.europa.eu/eli/reg/2023/1804/oj/eng>

<sup>79</sup> International Maritime Organization. Maritime Single Window, *Free flow of trade by ship*. FAL.5/Circ.42/Rev.3, mandatory from 1 January 2024. <https://www.imo.org/en/mediacentre/hottopics/pages/free-flow-of-trade-by-ship.aspx>

for EMSWe, NIS2, and AFIR, varies across Member States; Section 4 therefore treats EU law as the common denominator and models national specifics as deployment variants <sup>80</sup>.

### 3.8 Implication for POTENT-X

A credible mid-size European reference port is digitally heterogeneous. It typically operates a functioning PCS or equivalent community fabric, at least one serious port-call or gate digitalization programme, and increasing OT/IT coupling through energy and environmental assets; cybersecurity pressure is rising because operational decisions that were formerly local are becoming data-mediated and externally connected. <sup>81</sup> That combination is the context against which the requirements in Section 4 are written.

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<sup>80</sup> Regulation (EU) 2019/1239 establishing a European Maritime Single Window environment (consolidated version, 15 August 2025). <https://eur-lex.europa.eu/eli/reg/2019/1239/2025-08-15/eng>

<sup>81</sup> Portbase. *About us, Port Community System for Rotterdam and Amsterdam*. <https://www.portbase.com/en/about-us/>

## 4. Requirements baseline

This section states the preliminary requirements baseline for the port SoS digital infrastructure. Thirty requirements are organized across eight technical domains and one cross-cutting category, following the taxonomy defined in Section 2. Each requirement uses the five-field block template introduced there: identifier, “shall” description, rationale, abstraction level (High or Low), and the architecture component that it most directly constrains in the POTENTX:: namespace. Citations live in the domain introduction paragraphs below and in the narrative sections of this document; they are not attached to individual requirement blocks.

Identifiers follow the scheme POTENTX\_<DOMAIN>\_R<nn>, numbered sequentially within each domain. The same identifiers are used in Section 5 for the preliminary mapping to candidate architecture-component names.

### 4.1 Interoperability middleware and protocols (INT)

This domain addresses the middleware layer that binds heterogeneous port, maritime, energy, terminal, and city-facing systems into a coherent information-exchange fabric. Port digitalization projects such as PIXEL and DataPorts report consistently that the problem is not the absence of data but the coexistence of incompatible message formats, mismatched time semantics, and project-specific interfaces that do not transfer across ports<sup>82 83</sup>. NGSI-LD and OPC UA provide strong building blocks at the platform and at the industrial-integration layer respectively, yet neither defines a complete port-wide profile on its own.

#### POTENTX\_INT\_R01

*Description:* The interoperability middleware shall expose a canonical context API based on NGSI-LD for publishing, querying, and subscribing to port operational context entities.

*Rationale:* NGSI-LD standardizes context exchange, and PIXEL already converged on common context and data models to harmonize heterogeneous port information; this requirement makes that approach a mandatory middleware interface.

*Abstraction:* High

*Architecture component:* POTENTX::platform::InteropMiddleware.ContextAPI

#### POTENTX\_INT\_R02

*Description:* The interoperability middleware shall translate source protocols such as OPC UA and MQTT into the canonical platform information model without requiring pairwise application integrations.

*Rationale:* Port environments combine industrial automation protocols (OPC UA), lightweight telemetry (MQTT) and port-call coordination patterns (PortCDM); adapter-based translation reduces brittle point-to-point integration across multi-actor ports.

<sup>82</sup> PIXEL project. *Port IoT for Environmental Leverage, technical documentation*. Horizon 2020 project, GA 769355. <https://pixel-ports.readthedocs.io/en/latest/>

<sup>83</sup> DataPorts project. *DataPorts, a data platform for the cognitive ports of the future*. Horizon 2020 project, CORDIS GA 871493. <https://cordis.europa.eu/project/id/871493/reporting>

*Abstraction:* High

*Architecture component:* POTENTX::platform::InteropMiddleware.ProtocolAdapterBus

### **POTENTX\_INT\_R03**

*Description:* The interoperability middleware shall preserve original source identifiers, source timestamps, measurement units, and quality metadata whenever it normalizes external data into the canonical model.

*Rationale:* DataPorts emphasised reliable-source-of-truth governance and semantic mappings; preserving provenance and quality metadata is necessary for downstream trust, auditability, and twin fidelity.

*Abstraction:* High

*Architecture component:* POTENTX::platform::InteropMiddleware.NormalisationService

### **POTENTX\_INT\_R04**

*Description:* The interoperability middleware shall register interface contracts and schema versions for every public API and shall reject incompatible changes unless an explicit compatibility policy is configured.

*Rationale:* ISO/IEC/IEEE 21839 and IIRA treat constituent-system interaction management and interface evolution as core SoS concerns; uncontrolled schema drift is a direct architecture risk in federated multi-port deployments.

*Abstraction:* High

*Architecture component:* POTENTX::platform::InteropMiddleware.ContractRegistry

## **4.2 Edge computing and field IoT (EDG)**

This domain addresses edge gateways, field devices, transducers, low-latency local processing, and device-management functions deployed close to the assets of the reference port, meters, substations, cranes, berth equipment, gates, cameras, and environmental sensors. The recurring architectural challenge is reliable operation under poor connectivity and across mixed legacy and modern device estates. MQTT offers a mature mechanism for constrained-network telemetry, while IEC 61850 covers real-time field communication with substation-grade equipment.

### **POTENTX\_EDG\_R01**

*Description:* Edge nodes shall buffer outbound telemetry and inbound control acknowledgements during backhaul outages and shall forward them after reconnection while preserving original event order and timestamps.

*Rationale:* MQTT is designed for unreliable networks and persistent sessions; ports cannot assume uninterrupted wireless coverage across quays, yards, and access areas, so edge nodes must be able to operate autonomously during backhaul outages.

*Abstraction:* Low

*Architecture component:* POTENTX::edge::EdgeNode.StoreAndForward

### POTENTX\_EDG\_R02

*Description:* Edge nodes shall perform local filtering, aggregation, and rule evaluation for designated low-latency or safety-relevant cases before forwarding data upstream.

*Rationale:* IEC 61850 is built for demanding real-time field communications, and many port operations (substation control, shore-power switching, berth equipment protection) cannot tolerate round-trips to a central platform for latency-sensitive or safety-relevant actions.

*Abstraction:* Low

*Architecture component:* POTENTX::edge::EdgeNode.LocalProcessing

### POTENTX\_EDG\_R03

*Description:* Edge gateways shall synchronise their clocks to a common time source and shall timestamp every measurement and control event at the point of acquisition.

*Rationale:* Port-call coordination, cyber-event correlation, and digital-twin reconciliation all depend on comparable event times; IEEE 1588 (Precision Time Protocol) provides the standard mechanism for sub-microsecond clock synchronisation across networked equipment<sup>84</sup>.

*Abstraction:* Low

*Architecture component:* POTENTX::edge::EdgeGateway.TimeSync

## 4.3 Data platform and data fabric (DAT)

This domain addresses the shared data substrate: ingestion, storage tiers, catalogues, semantic mappings, data products, usage control, lineage, and cross-organization data exchange. DataPorts frames a secure, scalable, semantically grounded port data platform aligned with data-space principles. International Data Spaces, the Data Governance Act, and the Data Act add a sovereignty-and-contractual-use layer that matters in a port ecosystem where data owners remain autonomous actors<sup>85</sup>.

### POTENTX\_DAT\_R01

*Description:* The data platform shall persist raw source data, curated domain data, and derived analytical products in separate logical stores and shall maintain lineage links between them.

*Rationale:* DataPorts distinguished core platform components, data access services, and cognitive applications; SoS life-cycle engineering requires traceable information transformations across constituent systems.

*Abstraction:* High

*Architecture component:* POTENTX::data::DataFabric.StoragePlane

### POTENTX\_DAT\_R02

*Description:* The data platform shall reject ingestion records that lack mandatory metadata for source, owner, time validity, measurement unit, and quality status.

<sup>84</sup> IEEE Std 1588-2019, *IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems*. Institute of Electrical and Electronics Engineers, 2019. <https://standards.ieee.org/standard/1588-2019.html>

<sup>85</sup> DataPorts project. *DataPorts, a data platform for the cognitive ports of the future*. Horizon 2020 project, CORDIS GA 871493. <https://cordis.europa.eu/project/id/871493/reporting>

*Rationale:* Mandatory ingestion metadata is the lowest-cost mechanism that gives downstream analytics, digital twins, and audit trails a stable basis; the practice is consistent with DataPorts and the port-data-quality literature.

*Abstraction:* Low

*Architecture component:* POTENTX::data::DataFabric.IngestionValidator

### **POTENTX\_DAT\_R03**

*Description:* The data fabric shall evaluate machine-readable usage policies before releasing a dataset, stream, or API response to an external consumer.

*Rationale:* IDS-RAM places trust, certification, and usage restrictions at the center of sovereign data exchange, and DataPorts used governance services and smart-contract-style access rules for transparent, verifiable dataset access.

*Abstraction:* High

*Architecture component:* POTENTX::data::DataFabric.PolicyEnforcementPoint

### **POTENTX\_DAT\_R04**

*Description:* The data platform shall publish a machine-readable catalogue of datasets, data products, APIs, schemas, access conditions, and steward contacts.

*Rationale:* Reusable port applications depend on discoverability; FIWARE and DataPorts both stress catalogue-like exposure of reusable services, models, and integration endpoints.

*Abstraction:* High

*Architecture component:* POTENTX::data::DataCatalog

### **POTENTX\_DAT\_R05**

*Description:* The data platform shall maintain canonical port-domain entity models and explicit mappings from source schemas to those canonical entities.

*Rationale:* PIXEL used harmonised FIWARE-based models, and DataPorts reported a semantic framework with mappings to standard vocabularies; a downstream reference architecture needs the canonical information boundaries stated explicitly.

*Abstraction:* High

*Architecture component:* POTENTX::data::SemanticModelRepository

## **4.4 Digital twin (DT)**

This domain addresses the live digital representation of port assets, port calls, infrastructure state, and energy/operational interactions, together with simulation and historical replay. ISO 23247 and the Asset Administration Shell in IEC 63278 provide the structural cues on which the two requirements in this section depend<sup>86 87</sup>. D7 does not attempt a full digital-twin framework; it fixes only the twin boundary that most directly shapes the reference

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<sup>86</sup> ISO 23247 series (parts 1–4), *Automation systems and integration, Digital twin framework for manufacturing*. International Organization for Standardization, 2021. <https://www.iso.org/standard/75066.html>

<sup>87</sup> IEC 63278-1:2023, *Asset Administration Shell for industrial applications, Part 1: Asset Administration Shell structure*. International Electrotechnical Commission, 2023. <https://webstore.iec.ch/en/publication/65628>

architecture, namely traceable entity representation and a safe separation between simulation and live operation.

#### **POTENTX\_DT\_R01**

*Description:* The digital twin service shall maintain an explicit trace link, one-to-one or one-to-many, between each twin entity and the physical asset, logical process, or organizational resource it represents.

*Rationale:* ISO 23247 is organized around observable elements and their digital representation; an explicit twin-to-asset trace link is the minimum condition under which twin state can be audited, reconciled, and replayed.

*Abstraction:* High

*Architecture component:* POTENTX::twin::TwinRuntime.EntityRegistry

#### **POTENTX\_DT\_R02**

*Description:* The digital twin service shall isolate simulation and what-if execution environments from live operational write paths unless an authorized operator explicitly approves a control action.

*Rationale:* Descriptive, predictive, and control functions have different safety and integrity properties; IEC 62443-style separation of concerns keeps simulation and what-if optimization from pushing unsafe commands into live systems.

*Abstraction:* High

*Architecture component:* POTENTX::twin::SimulationSandbox.ControlBoundary

### 4.5 Energy integration (EMG)

This domain addresses the coupling between port operations and the emerging port energy system: shore-side electricity, substations, smart metering, distributed energy resources (DERs), storage, and demand-side flexibility. AFIR and FuelEU Maritime make port electrification and shore-side electricity materially relevant to architecture<sup>88</sup>; IEC 61850 covers substation automation<sup>89</sup> and IEC/IEEE 80005 covers the high-voltage shore-connection interface<sup>90</sup>. The detailed energy analyses (future energy utilization, grid-impact modelling, and supply-chain dynamics) remain in WP2 (D3, D5, D6); this domain is limited to the architectural integration points.

#### **POTENTX\_EMG\_R01**

*Description:* The energy integration layer shall ingest shore-power, substation, DER, storage, and smart-meter telemetry through IEC 61850, IEC/IEEE 80005, or architecture-approved

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<sup>88</sup> Regulation (EU) 2023/1804 on the deployment of alternative fuels infrastructure (AFIR); Regulation (EU) 2023/1805 on the use of renewable and low-carbon fuels in maritime transport (FuelEU Maritime); Directive (EU) 2023/959 amending Directive 2003/87/EC as regards maritime transport (EU ETS Maritime extension). <https://eur-lex.europa.eu/eli/reg/2023/1804/oj/eng>

<sup>89</sup> IEC 61850, *Communication networks and systems for power utility automation*. International Electrotechnical Commission. <https://iec61850.dvl.iec.ch/>

<sup>90</sup> IEC/IEEE 80005-1:2019, *Utility connections in port, Part 1: High Voltage Shore Connection (HVSC) Systems, General requirements*. International Electrotechnical Commission / Institute of Electrical and Electronics Engineers, 2019. <https://webstore.iec.ch/publication/30551>

protocol mappings.

*Rationale:* AFIR and FuelEU Maritime make shore-side electricity deployment operationally material, and the cited standards cover substation automation and the high-voltage shore-connection interface.

*Abstraction:* High

*Architecture component:* POTENTX::energy::EnergyIntegrationBus

### POTENTX\_EMG\_R02

*Description:* The energy integration layer shall compute and publish meter-backed energy and emissions accounts per asset, per service, and per vessel-call interval.

*Rationale:* FuelEU Maritime and the emerging digital-emissions accounting stack both increase pressure for auditable consumption and emissions data tied to actual operations rather than to coarse aggregates.

*Abstraction:* High

*Architecture component:* POTENTX::energy::EnergyAccountingService

### POTENTX\_EMG\_R03

*Description:* The port energy-management service shall forecast berth-level and feeder-level electrical demand using vessel-call plans, equipment schedules, and local DER and storage availability.

*Rationale:* PIXEL's energy models and predictive algorithms addressed consumption and renewable-production forecasting, and AFIR-driven shore-power uptake makes berth-aware load forecasting architecturally necessary.

*Abstraction:* High

*Architecture component:* POTENTX::energy::PortEMS.LoadForecaster

## 4.6 Operational monitoring and optimisation (OPS)

This domain addresses detection, KPI calculation, forecasting, scheduling support, conflict management, and human-in-the-loop optimization of port operations. PIXEL and PortCDM show that operational value emerges when port-call milestones, terminal resources, transport flows, and environmental constraints are handled together<sup>91 92</sup>. The architectural challenge is to make optimization services explicit and traceable rather than leaving them as opaque project algorithms.

### POTENTX OPS\_R01

*Description:* The optimization service shall detect berth, gate, yard, crane, rail-slot, and charging-slot conflicts and shall issue alerts together with machine-generated rescheduling alternatives.

*Rationale:* PortCDM shows that port-call predictability and terminal throughput depend on

<sup>91</sup> PIXEL project. *Port IoT for Environmental Leverage, technical documentation*. Horizon 2020 project, GA 769355. <https://pixel-ports.readthedocs.io/en/latest/>

<sup>92</sup> RISE Research Institutes of Sweden. *Port Collaborative Decision Making (PortCDM) project page*. <https://www.ri.se/en/project/port-collaborative-decision-making>

early conflict visibility and rapid replanning, rather than on static schedules.

*Abstraction:* High

*Architecture component:* POTENTX::ops::ConflictDetectionAndOptimiser

### **POTENTX\_OPS\_R02**

*Description:* The optimization service shall expose what-if planning APIs that accept declared objectives, constraints, and horizon parameters and return ranked alternative plans.

*Rationale:* PIXEL's models and predictive algorithms show the value of explicit optimization interfaces rather than embedded, one-off, application-specific implementations.

*Abstraction:* High

*Architecture component:* POTENTX::ops::WhatIfOptimisationAPI

### **POTENTX\_OPS\_R03**

*Description:* The operational monitoring service shall publish planned, estimated, and real-ised milestone updates to subscribed actors when event times change beyond configured thresholds.

*Rationale:* PortCDM is built around synchronized milestone visibility and just-in-time port-call coordination; this requirement turns that idea into a testable notification behavior.

*Abstraction:* Low

*Architecture component:* POTENTX::ops::MilestoneNotificationService

## **4.7 Cybersecurity and IT/OT convergence (SEC)**

This domain addresses secure architectures for ports as mixed IT and OT environments with transient partners, legacy equipment, cloud services, and energy-system interfaces. ENISA and NIS2 classify ports and maritime entities as essential transport infrastructure, while IEC 62443 provides the clearest architecture-oriented framework for zones, conduits, security levels, lifecycle controls, and the IT/OT boundary. The Cyber Resilience Act adds supply-side pressure on secure product and update behavior<sup>93</sup>.

### **POTENTX\_SEC\_R01**

*Description:* The deployment architecture shall segment external, IT, OT, and safety-relevant subsystems into security zones and shall route inter-zone traffic only through explicitly managed conduits.

*Rationale:* IEC 62443-3-3 and related guidance use zones and conduits as a core structuring mechanism for industrial-control security; this is especially important in ports where OT, partners, and city-facing systems coexist.

*Abstraction:* High

*Architecture component:* POTENTX::security::ZoneGateway

### **POTENTX\_SEC\_R02**

*Description:* The security monitoring service shall collect security-relevant logs from edge, OT

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<sup>93</sup> European Union Agency for Cybersecurity (ENISA). *Cybersecurity of critical sectors, Transport*. <https://www.enisa.europa.eu/topics/cybersecurity-of-critical-sectors/transport>

gateways, platform services, and user-access points into a tamper-evident central store with synchronized timestamps.

*Rationale:* ENISA port guidance and IEC 62351 both highlight security-event logging and operational cybersecurity monitoring as foundational capabilities in industrial and maritime environments.

*Abstraction:* High

*Architecture component:* POTENTX::security::SecurityTelemetryLake

### POTENTX\_SEC\_R03

*Description:* Each deployable software or firmware component shall have a recorded version, supplier identity, vulnerability status, and update history in a maintained component inventory.

*Rationale:* IEC 62443-4-1 addresses secure product life cycle, defect management, patch management, and end-of-life; the Cyber Resilience Act pushes products with digital elements toward sustained updateability and traceable security posture.

*Abstraction:* Low

*Architecture component:* POTENTX::security::ComponentInventory

### POTENTX\_SEC\_R04

*Description:* Remote maintenance access into OT-adjacent components shall require multi-factor authentication, time-bounded approval, jump-host mediation, and session recording.

*Rationale:* ENISA port-cyber guidance and IEC 62443 asset-owner and system requirements both point toward tightly governed remote access, because ports depend on vendors and service providers with intermittent but high-risk connectivity needs.

*Abstraction:* Low

*Architecture component:* POTENTX::security::PrivilegedRemoteAccessBroker

## 4.8 Governance and trust (GOV)

This domain addresses onboarding, stewardship, data ownership, usage policies, auditability, sensitivity classification, and the institutional trust mechanisms needed to make voluntary or regulated data sharing sustainable. DataPorts and IDS-RAM both argue that ports must operate shared digital services without forcing stakeholders to give up sovereignty over commercially sensitive or personal data<sup>94 95</sup>. Governance must therefore be implemented as enforceable mechanisms, not as prose.

### POTENTX\_GOV\_R01

*Description:* Data-sharing services shall bind each shared dataset, stream, or API to a machine-readable policy stating owner, permitted recipient, permitted purpose, retention condition, and onward-sharing rule.

<sup>94</sup> DataPorts project. *DataPorts, a data platform for the cognitive ports of the future*. Horizon 2020 project, CORDIS GA 871493. <https://cordis.europa.eu/project/id/871493/reporting>

<sup>95</sup> International Data Spaces Association. *IDS Reference Architecture Model, current edition*. IDSA. <https://internationaldataspaces.org/offers/reference-architecture/>

*Rationale:* IDS-RAM makes usage restrictions and data sovereignty central, and DataPorts implemented transparent, verifiable access-rule enforcement; this requirement turns that governance stance into an enforceable control.

*Abstraction:* High

*Architecture component:* POTENTX::governance::UsagePolicyRegistry

### **POTENTX\_GOV\_R02**

*Description:* The governance service shall record an immutable audit trail of data-access decisions, policy changes, administrator actions, and cross-organization data transfers.

*Rationale:* DataPorts used transparent, verifiable, trackable, and immutable access-control mechanisms, and GDPR accountability reinforces the need for decision and access auditability.

*Abstraction:* High

*Architecture component:* POTENTX::governance::AuditLedger

## **4.9 Cross-cutting requirements (X)**

This domain addresses architectural qualities that cut across all eight technical domains. They constrain how services are observed, deployed, traced, validated, and federated. Correlated observability and end-to-end traceability are particularly relevant for SoS assurance; the federation requirement anticipates the multi-port ambition of POTENT-X beyond the first reference site.

### **POTENTX\_X\_R01**

*Description:* All deployable services shall emit structured logs, metrics, and traces correlated by a common transaction or correlation identifier.

*Rationale:* Life-cycle engineering, cyber monitoring, and port-wide diagnostics all depend on correlated observability across constituent systems; without it, SoS troubleshooting degrades into manual reconstruction.

*Abstraction:* High

*Architecture component:* POTENTX::crosscut::ObservabilityPlane

### **POTENTX\_X\_R02**

*Description:* The platform shall provide end-to-end traceability from field observation to canonical data object, dashboard view, optimisation output, and operator decision record.

*Rationale:* PIXEL and DataPorts both treat traceable transformations as the trust mechanism of choice; opaque pipelines cannot be validated, audited, or transferred across ports.

*Abstraction:* High

*Architecture component:* POTENTX::crosscut::TraceabilityService

### **POTENTX\_X\_R03**

*Description:* The platform shall provide a test and simulation framework capable of replaying recorded event streams and injecting synthetic scenarios for architecture verification.

*Rationale:* Architecture verification in an SoS setting depends on repeatable event-stream

replay and controlled synthetic-scenario injection; without such a framework the D9 architecture cannot be validated at useful coverage before deployment.

*Abstraction:* High

*Architecture component:* POTENTX::crosscut::VerificationFramework

#### **POTENTX\_X\_R04**

*Description:* The federation layer shall allow multiple ports to reuse common services and models while preserving per-port policy domains, namespaces, and tenant isolation.

*Rationale:* IDS-RAM assumes federated, sovereign participation rather than central ownership, and NGSI-LD supports multi-tenant context federations; these patterns match the multi-port ambition of POTENT-X directly.

*Abstraction:* High

*Architecture component:* POTENTX::crosscut::FederationLayer

## 5. Preliminary component mapping

D9 will develop the formal reference architecture for the port SoS; that architecture is not yet available. Table 5 pairs each requirement from Section 4 with a preliminary component name: a candidate element of the reference architecture that the requirement most directly constrains, grouped by the preview layer sketched in Section 7. The point of the table is to make the requirement-to-component link explicit already at this stage, so that D9 can adopt, refine, or reallocate each name while keeping the POTENTX:: identifiers stable for traceability.

These names are *anticipated*, not normative. They are grounded in the representative port scenario of Section 3: field devices and OT equipment (Sensing); local gateways and store-and-forward behaviour (Edge); the port-wide context and data fabric (Platform); analytics and digital-twin services (Analytics); governance and security services (Governance); and qualities that span all layers (Cross-cutting). D9 will replace each candidate name with a concrete component in the modelling language selected at the start of task T3.3, and will produce the formal allocation of components to processors, buses, and deployment bindings.

**Table 5. Preliminary component mapping.**

| Requirement      | Candidate component name                                   | Preview layer         |
|------------------|--|-----------------------|
| POTENTX_INT_R01  | POTENTX::platform::InteropMiddleware.ContextAPI            | Platform              |
| POTENTX_INT_R02  | POTENTX::platform::InteropMiddleware.ProtocolAdapter-Bus   | Platform              |
| POTENTX_INT_R03  | POTENTX::platform::InteropMiddleware.Normalisation-Service | Platform              |
| POTENTX_INT_R04  | POTENTX::platform::InteropMiddleware.ContractRegistry      | Platform              |
| PO-TENTX_EDG_R01 | POTENTX::edge::EdgeNode.StoreAndForward                    | Edge                  |
| PO-TENTX_EDG_R02 | POTENTX::edge::EdgeNode.LocalProcessing                    | Edge                  |
| PO-TENTX_EDG_R03 | POTENTX::edge::EdgeGateway.TimeSync                        | Edge                  |
| POTENTX_DAT_R01  | POTENTX::data::DataFabric.StoragePlane                     | Platform              |
| POTENTX_DAT_R02  | POTENTX::data::DataFabric.IngestionValidator               | Platform              |
| POTENTX_DAT_R03  | POTENTX::data::DataFabric.PolicyEnforcementPoint           | Platform / Governance |
| POTENTX_DAT_R04  | POTENTX::data::DataCatalog                                 | Platform              |
| POTENTX_DAT_R05  | POTENTX::data::SemanticModelRepository                     | Platform              |

| Requirement      | Candidate component name                         | Preview layer   |
|------------------|--|-----------------|
| POTENTX_DT_R01   | POTENTX::twin::TwinRuntime.EntityRegistry        | Analytics       |
| POTENTX_DT_R02   | POTENTX::twin::SimulationSandbox.ControlBoundary | Analytics       |
| PO-TENTX_EMG_R01 | POTENTX::energy::EnergyIntegrationBus            | Platform / Edge |
| PO-TENTX_EMG_R02 | POTENTX::energy::EnergyAccountingService         | Analytics       |
| PO-TENTX_EMG_R03 | POTENTX::energy::PortEMS.LoadForecaster          | Analytics       |
| PO-TENTX_OPS_R01 | POTENTX::ops::ConflictDetectionAndOptimiser      | Analytics       |
| PO-TENTX_OPS_R02 | POTENTX::ops::WhatIfOptimisationAPI              | Analytics       |
| PO-TENTX_OPS_R03 | POTENTX::ops::MilestoneNotificationService       | Platform        |
| PO-TENTX_SEC_R01 | POTENTX::security::ZoneGateway                   | Governance      |
| PO-TENTX_SEC_R02 | POTENTX::security::SecurityTelemetryLake         | Governance      |
| PO-TENTX_SEC_R03 | POTENTX::security::ComponentInventory            | Governance      |
| PO-TENTX_SEC_R04 | POTENTX::security::PrivilegedRemoteAccessBroker  | Governance      |
| PO-TENTX_GOV_R01 | POTENTX::governance::UsagePolicyRegistry         | Governance      |
| PO-TENTX_GOV_R02 | POTENTX::governance::AuditLedger                 | Governance      |
| POTENTX_X_R01    | POTENTX::crosscut::ObservabilityPlane            | Cross-cutting   |
| POTENTX_X_R02    | POTENTX::crosscut::TraceabilityService           | Cross-cutting   |
| POTENTX_X_R03    | POTENTX::crosscut::VerificationFramework         | Cross-cutting   |
| POTENTX_X_R04    | POTENTX::crosscut::FederationLayer               | Cross-cutting   |

Two candidate names appear across more than one layer. POTENTX::data::DataFabric.PolicyEnforcementPoint is placed in the platform data fabric for execution but is driven by usage policies issued in the governance layer. POTENTX::energy::EnergyIntegrationBus



is placed in the platform layer for canonical event distribution while binding through edge gateways to field energy assets via IEC 61850 and IEC/IEEE 80005. Both cases arise commonly in SoS architectures in which a single service bridges layers; D9 will represent them through explicit inter-layer bindings once the reference architecture is formalized.

## 6. Limitations

The requirements baseline reported here is *preliminary*. The limitations that shape it are stated below so that D9 and D10 can account for them where relevant.

**Evidence base.** The requirements are derived via MBSE from published standards, the scientific literature on smart ports and port digital twins, and the authors' domain expertise. The grounding questionnaire returned five valid responses, four from academic organizations; it is used for practitioner grounding only and is not load-bearing on any individual requirement. Broader non-academic practitioner input is not available at the time of this deliverable.

**Scope of the reference scenario.** Section 3 defines a representative mid-size European port, not a specific site. Quantitative ranges in the scenario are synthesized from published values at real ports and are flagged with where they rest on composite inference rather than on a single primary source. The scenario is deliberately agnostic regarding inland-waterway integration (optional) and hydrogen / Power-to-X scale (assumed pilot or tenant-led in the mid-size case).

**Architecture depth.** The architecture material in this deliverable is a preview (Section 7). The formal reference-architecture model, the allocation of components to deployment bindings, and the associated risk-analysis framework are the subject of D9 (task T3.3). The modelling-language choice, between AADL, SysML v2, or Capella / Arcadia, is scoped to the start of T3.3 and is not fixed here.

**Energy analyses.** Energy-integration requirements in Section 4.5 are limited to architectural integration points. Future-energy-utilization assessment, mathematical models for grid impacts of port electrification, and supply-chain modelling for hydrogen and e-fuels remain in WP2 (D3, D5, D6). The energy sections of this deliverable do not reproduce those analyses.

## 7. Relation to deliverable D9

This section previews the reference architecture that D9 will formalize. Nothing in this section is binding for D9; the architecture that D9 produces, together with its risk-analysis framework, will replace the initial conceptual ideas that follow in this section.

The architecture follows an ISO/IEC/IEEE 42010-compliant viewpoint structure<sup>96</sup>. No single external reference architecture covers every dimension of a port SoS, so D9 will work with a composed stack. Each element of the stack is used for the concerns it handles best.

**Table 6. Layered preview.**

| Layer                                      | Scope  | Reference-architecture anchor  |
|--|--|--|
| Sensing and physical assets                | Field devices, meters, OT equipment, shore-power interfaces, cranes, gates   | Industrial Internet Reference Architecture (IIRA) functional viewpoint; SGAM for the energy sub-architecture <sup>97 98</sup>                |
| Edge                                       | Edge gateways, local computing, store-and-forward, time synchronization  | IIRA implementation viewpoint <sup>99</sup>  |
| Platform, interoperability and data fabric | Canonical context API, protocol adapters, semantic model repository, data catalogue, policy enforcement point, ingestion validator | FIWARE / NGSI-LD context broker as the dynamic-data layer; IDS-RAM as the sovereign multi-stakeholder data-exchange layer <sup>100 101</sup> |
| Analytics, digital twin and optimization   | Twin runtime, simulation sandbox, conflict detection, what-if planning, energy accounting, load forecasting                        | Asset Administration Shell (IEC 63278) and ISO 23247 as the digital-twin and asset-representation stack <sup>102 103</sup>                   |

<sup>96</sup> ISO/IEC/IEEE 42010:2022, *Software, systems and enterprise, Architecture description*. International Organization for Standardization, 2022. <https://www.iso.org/standard/74393.html>

<sup>97</sup> Industry IoT Consortium. *Industrial Internet Reference Architecture (IIRA), version 1.10*. IIC, 2022. <https://www.iiconsortium.org/iira/>

<sup>98</sup> CEN-CENELEC-ETSI Smart Grid Coordination Group. *Smart Grid Architecture Model (SGAM) User Manual*. CEN-CENELEC. [https://www.cencenelec.eu/media/CEN-CENELEC/AreasOfWork/CEN-CENELEC\\_Topics/Smart%20Grids%20and%20Meters/Smart%20Grids/4\\_sgcg\\_methodology\\_sgamusermanual.pdf](https://www.cencenelec.eu/media/CEN-CENELEC/AreasOfWork/CEN-CENELEC_Topics/Smart%20Grids%20and%20Meters/Smart%20Grids/4_sgcg_methodology_sgamusermanual.pdf)

<sup>99</sup> Industry IoT Consortium. *Industrial Internet Reference Architecture (IIRA), version 1.10*. IIC, 2022. <https://www.iiconsortium.org/iira/>

<sup>100</sup> FIWARE Foundation. *FIWARE catalogue of generic enablers and data models*. <https://www.fiware.org/catalogue/>. The context-broker interface follows ETSI GS CIM 009 (NGSI-LD).

<sup>101</sup> International Data Spaces Association. *IDS Reference Architecture Model, current edition*. IDSA. <https://internationaldataspaces.org/offers/reference-architecture/>

<sup>102</sup> ISO 23247 series (parts 1–4), *Automation systems and integration, Digital twin framework for manufacturing*. International Organization for Standardization, 2021. <https://www.iso.org/standard/75066.html>

<sup>103</sup> IEC 63278-1:2023, *Asset Administration Shell for industrial applications, Part 1: Asset Administration Shell structure*. International Electrotechnical Commission, 2023. <https://webstore.iec.ch/en/publication/65628>

| Layer  | Scope  | Reference-architecture anchor  |
|--|--|--|
| Maritime process                             | Port-call coordination, milestone notification, MSW and PCS interfaces   | PortCDM as the maritime collaborative pattern; IMO Maritime Single Window as the mandatory external interface <sup>104 105</sup>   |
| Governance and cybersecurity (cross-cutting) | Zones and conduits, security telemetry, component inventory, privileged remote access, usage-policy registry, audit ledger | IEC 62443 across the whole stack as the OT cybersecurity rule-set; ISO/IEC 27001/27005 for the information-security risk process; NIS2 and the Cyber Resilience Act for organisational and supply-chain obligations <sup>106 107 108 109</sup> |

**Modelling and risk analysis in D9.** The reference architecture will be modelled in the modelling language selected at the start of task T3.3. AADL is one candidate, and provides analyzable description of software, hardware, communication, and deployment in a single model; SysML v2 and the Arcadia method with its Capella tooling are alternative candidates, each with a different balance of traceability, stakeholder accessibility, and analyzability (Section 1). Whichever is chosen, the POTENTX: : identifiers from Section 5 will be populated with concrete elements and their inter-layer bindings in D9. The risk-analysis framework that D9 develops under task T3.3 will apply IEC 62443-3-2 security-level reasoning over the zones and conduits defined by POTENTX\_SEC\_R01 and will cover both the technical architecture and the organizational obligations inherited from NIS2 and the Cyber Resilience Act.

<sup>104</sup> International Maritime Organization. Maritime Single Window, *Free flow of trade by ship*. FAL.5/Circ.42/Rev.3, mandatory from 1 January 2024. <https://www.imo.org/en/mediacentre/hottopics/pages/free-flow-of-trade-by-ship.aspx>

<sup>105</sup> RISE Research Institutes of Sweden. *Port Collaborative Decision Making (PortCDM) project page*. <https://www.ri.se/en/project/port-collaborative-decision-making>

<sup>106</sup> IEC 62443 series (parts 2-1, 2-4, 3-2, 3-3, 4-1, 4-2), *Security for industrial automation and control systems*. International Electrotechnical Commission. <https://www.iso.org/standard/78744.html>

<sup>107</sup> ISO/IEC 27001:2022, *Information security management systems*, and ISO/IEC 27005:2022, *Information security risk management*. International Organization for Standardization, 2022. <https://webstore.iec.ch/en/publication/67631>

<sup>108</sup> Directive (EU) 2022/2555 on measures for a high common level of cybersecurity across the Union (NIS2 Directive). 14 December 2022. <https://eur-lex.europa.eu/eli/dir/2022/2555/2022-12-27/eng>

<sup>109</sup> Regulation (EU) 2024/2847 on horizontal cybersecurity requirements for products with digital elements (Cyber Resilience Act). 23 October 2024. <https://eur-lex.europa.eu/eli/reg/2024/2847/oj/eng>

## Annex A: Questionnaire (summary)

The questionnaire reported here was used for practitioner grounding of the requirements derived in Section 4, in line with Step 3 of the methodology in Section 2. It was not used as a statistical evidence base.

**Purpose.** Obtain a qualitative signal from practitioners on the digital-infrastructure priorities, operational pain points, and interoperability concerns that the MBSE-derived requirements in Section 4 need to address in a smart-port SoS setting.

**Distribution and instrument.** The questionnaire was hosted on Microsoft Forms and distributed via e-mail to approximately 94 named contacts across the following organization classes: port authorities, terminal operators, energy utilities and distribution system operators, technology vendors and system integrators, public agencies, and research organizations. Contacts were drawn from the POTENT-X consortium network and adjacent professional networks; no contact was added through anonymous mailing lists.

**Structure.** The instrument consisted of two modules. A *strategic module* addressed the respondent's role, the digital initiatives in progress at their organization, perceived priorities for port digitalization, and observed barriers to implementation. A *technical module* addressed digital-infrastructure characteristics used or planned at the respondent's port, integration challenges, non-functional system requirements (latency, availability, cybersecurity posture), and interest in specific technology families such as digital twins, IoT, and edge computing. Respondents could complete either module or both; free-text fields were available in each module for open comments. Completion time was estimated at 10–15 minutes.

**Topics covered.** Energy-management solutions (shore power, battery storage, photovoltaic, hydrogen and Power-to-X integration), smart charging for heavy-duty vehicles and cargo-handling equipment, digital twin applications, city-port data sharing, cybersecurity concerns for converged IT/OT environments, interoperability between terminal operating systems and port community systems, and experience with standardized interfaces such as OPC UA, MQTT, and IEC 61850.

**Ethical and data-handling considerations.** Responses were collected with informed consent. Individual responses were anonymized before any reporting and are reported in Annex B in aggregated form. No personal data is retained beyond the analysis window.

**Limitations acknowledged at distribution time.** The questionnaire is a light-touch instrument and does not substitute for structured interviews or a representative survey. It was deliberately short to maximize response rate and scope-bounded so that it could be completed without access to proprietary information.

The complete list of questions is retained in the project's internal working folder and is available on request. It is not reproduced here because the aggregated results in Annex B already capture the information relevant to D7.

## Annex B: Consultation responses (summary)

**Response set.** Five valid responses were received against approximately 94 invitations, giving a response rate of approximately five percent. The respondent composition was: four responses from academic and research organizations, and one response from a public-sector organization. No direct responses were received from port authorities, terminal operators, shipping lines, utilities, or technology vendors. Geographic distribution: four respondents in Europe and one in the Middle East and North Africa region.

**Headline themes.** Three themes appeared often enough across responses to be reported as qualitative signals rather than as single opinions.

1. **Energy-related digital integration is a leading priority.** Respondents identified energy-management solutions as the most prominent ongoing or planned digital initiative. Specific examples mentioned include battery energy storage systems, photovoltaic integration, hydrogen and Power-to-X interfaces, and smart charging for heavy-duty vehicles and cargo-handling equipment. This signal is consistent with the energy-integration requirements in Section 4.5.
2. **Interoperability is the most frequently cited barrier.** Respondents reported integration challenges between existing systems, terminal operating systems, port community systems, OT control systems, and energy assets, as the primary obstacle to digitalization, followed by data quality and availability and by budget and business-case constraints. This signal is consistent with the interoperability-middleware, data-fabric, and edge requirements in Sections 4.1, 4.2, and 4.3.
3. **Digital twin and city-port data sharing are rising interests.** Respondents identified digital twin technology and city-port data-sharing arrangements as domains where they expected activity to grow within the next two to three years. This signal is consistent with the digital-twin requirements in Section 4.4 and with the governance-and-trust requirements in Section 4.8.

**Use in the requirements baseline.** The signals above were used as a qualitative check on the MBSE-derived requirements in Section 4. No requirement in Section 4 depends on a single response, and no numerical claim in this document is based on the questionnaire result alone. Where a response raised an issue not present in the standards- and literature-derived baseline, it was examined and either incorporated or noted as an open item for later downstream work.

**Items not addressed in this deliverable.** Three topics surfaced in the responses but are not treated here: (i) shared key-management and identity federation across port authorities and tenants; (ii) concrete KPIs for cruise-terminal shore power uptake; and (iii) cross-stakeholder agreements for port to DSO flexibility bids. Items (i) and (iii) are flagged in the cybersecurity and governance domains as open design questions that D9 will have to take a position on. Item (ii) belongs to D10 and has been flagged for the CTH-led performance-indicator work.



**Limitations of the response set.** The sample is small, strongly biased toward academic respondents, and not drawn from a random frame. The results are therefore reported as initial indications of priorities and barriers in the respondent set, and not as generalizable findings about mid-size European ports.