

Demonstrating a Model-Based Systems Engineering Approach for the Approval of Maritime Autonomous Surface Ships Operation: The Autonomous Mooring System Use Case

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The approval of Maritime Autonomous Surface Ships (MASS) requires a structured and transparent approach to demonstrate that the safety of autonomous operations is at least equivalent to conventional vessels. To achieve this, a Model-Based Systems Engineering (MBSE) framework has been established, combining system modelling, safety analysis, and verification activities within a unified process. This paper presents a use case demonstration of the MBSE approach through an Autonomous Mooring System (AMS) operation, aiming to provide a clear and practical understanding of how MBSE can be utilised in the approval process of autonomous ships. The AMS operation is performed by an autonomous vessel equipped with robotic mooring arms mounted along its sides, which automatically connect the mooring lines to port-side bollards. After receiving port clearance from the Remote Operations Centre (ROC), the Digital Orchestrator (DO), as the onboard controller, instructs the AMS to initiate the mooring sequence using camera-based perception for bollard detection. The AMS operates autonomously or in a highly automated way, with decision-making capabilities to continue or abort based on input from the autonomous navigation and situational awareness systems. Through this use case, the paper illustrates how the MBSE steps, requirements definition, concept of operations (CONOPS) development, system formalisation using modelling language (such as, unified modelling language, UML, system modelling language, SysML), and verification and validation with safety analysis (System Theoretic Process Analysis, STPA) and test cases can be systematically applied to ensure sufficient safety. The demonstration aims to familiarize stakeholders with the MBSE methodology, emphasising its potential to enhance traceability, transparency, and regulatory confidence in the approval of autonomous ship operations.

Keywords: Autonomous Mooring System (AMS), Model-Based Systems Engineering (MBSE), Maritime Autonomous Surface Ships (MASS), UML, Safety analysis, STPA, Safety assurance.

Section 1: Introduction

The approval process for Maritime Autonomous Surface Ships (MASS) faces challenges due to the need to demonstrate safe operations using novel technologies. These technologies reduce or eliminate human presence on the ship and thus need to handle complex tasks traditionally performed by crews. While autonomy promises improved efficiency, safety, and sustainability, it also introduces new challenges in system assurance (Sumon et al., 2024), verification, and regulatory approval. Existing regulatory frameworks, developed for conventional crewed manned operations, are not yet fully adapted to assess or approve uncrewed maritime operations. Regulatory authorities such as the International Maritime Organization (IMO), classification societies e.g., Det Norske Veritas (DNV), flag state administrations e.g., the Norwegian Maritime

Authority (NMA) suggest that unmanned or autonomous ships with new technology must ensure an equivalent level of safety of conventional crewed vessels (DNV, 2024a; IMO, 2013; NMA, 2022a). These organizations provide safety assurance process recommendations through their risk-based guidelines, but there is still a need to understand how to implement these processes in a straightforward and structured way. It is therefore necessary to establish a systematic and pragmatic approach for implementing the proposed guideline processes. Such an approach must enable the elicitation and specification of all safety requirements necessary to demonstrate an equivalent level of safety to conventional operations, while ensuring transparency, traceability, and repeatability of the approval process. To address these challenges, this study presents a Model-Based Systems Engineering

(MBSE) approach that can contribute to the development of a safety assurance framework for the approval basis of autonomous ships. The framework integrates system engineering and safety assessment activities throughout the development and approval lifecycle, allowing a structured linkage between requirements elicitation, operational concepts, system models, and verification activities. By formalising the relationship between system behaviour and safety constraints, the MBSE approach improves traceability, consistency, and reusability across design and approval processes (INCOSE, 2007). “A MBSE methodology can be characterized as the collection of related processes, methods, and tools used to support the discipline of systems engineering in a 'model-based' or “model-driven” context” (Estefan, 2008). MBSE has been successfully applied in safety-critical domains such as aerospace and defense (Campo et al., 2023) and automotive and transportation systems (IBM, 2023; Nolte & Maurer, 2025; Soundarapandian et al., 2017), where high system integration and regulatory compliance are essential. In maritime applications, MBSE remains emergent but promises significant advantages for managing interdisciplinary and multidisciplinary autonomous systems, enabling traceability from regulatory and operational requirements to system behaviors, and supporting iterative refinement of architectures and safety constraints (Estefan, 2008), thereby facilitating a transparent approval process.

This study presents a preliminary step towards developing a comprehensive safety assurance framework to support the approval of autonomous ships. The objective is to establish an MBSE-based approach for autonomous systems and to demonstrate how MBSE can systematically contribute to the development of a safety assurance framework. The study applies the proposed MBSE approach through a use-case example of a robotic-arm-based autonomous mooring system (AMS) for short-sea autonomous vessel operations to show how it creates confidence in the safety assurance process.

The remainder of this paper is structured as follows. Section 2 introduces the MBSE approach and its contribution to the autonomous mooring system used as the case study. Section 3 presents the proposed MBSE application to the autonomous mooring system and the outcomes as the result. Section 5 discusses the resulting insights and their implications for the safety assurance framework and approval process. Finally, Section 6 concludes the paper and outlines directions for future research.

Section 2: MBSE and its contribution

2.1 MBSE: The model-based systems engineering (MBSE) approach in this study focuses on system specification and design by capturing the concept

of operations (CONOPS), system architecture and requirements in a unified model language, or UML. Thus, we present the MBSE approach in two key stages to contribute to the development of the safety assurance framework:

Stage 1: CONOPS development, which defines

1. operational intent, high-level functional decomposition and architectural concepts,
2. the operational envelope, and corresponding fallback strategies.

Stage 2: Formalisation of the System Architecture, which develops

1. structured System Control Tasks (SCTs)
2. UML-based modelling of these system control tasks to visualize operational activities, interactions, and requirements.

Figure 1 shows the two stages, including their steps.

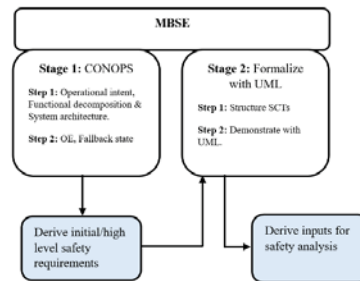


Figure 1: MBSE and its outputs to the safety assurance framework requirements.

Stage 1: CONOPS: The Concept of Operations is a foundational document that defines the design principles, operational intent, and functional objectives of an autonomous vessel. It provides an initial, high-level requirements specification and serves as a primary input to system design, approval processes, and safety and security analyses under evolving MASS regulations (Wennergberg et al., 2020). CONOPS decomposes operational tasks into hierarchical sub-tasks with clearly allocated human and automated responsibilities, and specifies operational modes, operational envelopes, and fallback states for off-nominal conditions (DNV, 2024c), (NMA, 2022b). In the proposed MBSE approach, CONOPS captures system functions, operational boundaries, safety states, and human-automation interactions using structured textual and visual artefacts. These artefacts provide formalised inputs for UML-based system modelling and subsequent safety analysis. The following paragraphs describe two steps of the CONOPS intended to develop the desired MBSE.

Step 1: Operational intent, Functional decomposition, System architecture: The starting point is to describe what the system is intended to do, under which conditions, and for whom. This point mainly presents the requirements of the autonomous system from the user's perspective.

As input for the technology assessment, used to develop the functional description. Hence, a detailed system description should be developed (DNV, 2024c). The functional decomposition of the system provides an explanation of the individual control system, particularly the mechanism, responsibilities of the controllers, actuators' performance, and so on. It is essential for a comprehensive understanding of any system and serves as the primary input for risk analysis. It describes both the dynamic and static behaviour of the control system.

Based on the structured description, a system-level design of the autonomous vessel is illustrated. This is the design-based visualisation of individual control systems (Sumon et al., 2025), (Hagaseth et al., 2023). This includes physical interactions, presenting components such as perception, decision-making, control, communication, etc. A visual connection between the shoreside and shipside systems is well presented in this section.

Step 2: Operational Envelope (OE), Fallback state: *“The Operational Envelope (OE) is proposed as a term for the combined capabilities of the automation systems and the humans that are involved in MASS operations”* (Rødseth & Wennersberg, 2023), and is by ISO (ISO, 2022) described as the *“conditions and related operator control modes under which an autonomous ship system is designed to operate, including all tolerable events.* The operational envelope (OE) shall be defined in accordance with the vessel's capabilities and limitations to ensure an acceptable level of safety under all anticipated operating conditions (DNV, 2024c). Although the operational envelope (OE) may not be fully verified, it is generally considered acceptable to continue safe autonomous operations from a system design and architectural perspective, provided that compliance with acceptance criteria is demonstrated through adequate safety analyses.

Fallback state refers to a set of "designed states" outside the OEnv that can be activated via a fallback function when the OEnv is exceeded in some way (Hagaseth et al., 2023). These fallback states, outlined in the CONOPS, should be detailed and linked to hazards and failures capable of pushing the vessel beyond its operational envelope (DNV, 2024c).

Stage 2: Formalize with modelling language

In the proposed MBSE approach, the system architecture and functional descriptions, including the synthesised safety requirements developed in the preceding steps, are formally specified using the Unified Modelling Language (UML). The objective of this step is to translate the system architecture and functional descriptions into precise, structured, and traceable representations that serve directly as inputs to safety and risk analysis activities. This formalisation focuses on

the ship's autonomous operation as a controlled system, emphasising the sequencing, interactions, and decision logic. To achieve this, the approach introduces System Control Tasks (SCTs) as an intermediate textual abstraction, which are then mapped to UML Activity and Sequence diagrams. Together, these artefacts ensure consistency among operational intent, system behaviour, and safety assessment boundaries.

System Control Tasks (SCTs): Within the operational envelope section, specific operational tasks for the corresponding autonomous operational function are performed. An individual operational task involves a set of system control tasks that complete the task in a sequential manner. System Control Tasks (SCTs) are structured textual specifications of controlled processes executed by an autonomous system, describing their sequential control logic across one or more defined mission phase patterns, such as navigation during berthing/unberthing (Hagaseth et al., 2023). They describe:

- The intent of the autonomous function,
- The preconditions under which the task is initiated,
- The control actions performed by the system,
- The expected outcomes or system states, and
- The interaction with external actors (e.g., environment, other vessels, shore control).

Demonstration with UML diagram: The SCTs are subsequently formalized using UML (Seidl et al., 2015), (Rumpe, 2016) to provide an unambiguous and analyzable representation of autonomous behavior and is used as a basis to perform safety and security analysis systematically (Hagaseth et al., 2023). Two UML diagram types are employed: Activity Diagrams and Sequence Diagrams, each serving a complementary purpose.

UML Activity Diagrams are used to represent the control flow and decision logic within each SCT. They model the progression of operational activities, including branching conditions, parallel actions, and synchronisation points (Seidl et al., 2015). This representation is particularly effective for identifying decision-dependent hazards, degraded modes, and transitions between normal and fallback behaviours. UML Sequence Diagrams capture the temporal interaction between system components and external entities during the execution of an SCT (Seidl et al., 2015). They explicitly model message exchanges, control commands, sensor feedback, and coordination between autonomous subsystems (Kundu et al., 2013). This interaction-focused view supports the identification of interface-related hazards, timing dependencies, and communication failures.

Together, these UML representations ensure that each SCT is:

- Formally defined,
- Consistently interpreted across stakeholders,
- Directly traceable to system architecture and requirements, and
- Readily usable as structured input for safety analyses such as STPA, or scenario-based risk assessment.

However, each stage and its associated steps in the MBSE approach build upon the outputs of the preceding stage, forming an interconnected and progressive development process. For example, the UML behavioural models in Step 2 of Stage 2 are systematically derived from the System Control Task (SCT) descriptions defined in Step 1, ensuring consistency and traceability between textual and formal system representations.

Section 3: Result

3.1 Use case - Autonomous mooring operation

(AMO): This study presents an autonomous mooring system utilizing robotic arm-based operations as a use-case demonstration of the proposed Model-Based Systems Engineering (MBSE) approach, highlighting its traceability, operational efficiency, and safety advantages.

The autonomous mooring operation considered in this study involves robotic mooring arms mounted on the vessel side and bollards located on the quay. The operation commences after completing the berthing at the designated position. Upon reaching the position, a predefined sensor-identified position suitable for mooring, the Digital Orchestrator, or DO activates the Autonomous Mooring System (AMS). The AMS employs sensor-based perception (RGB camera and LiDAR) to detect and align with shore-side bollards and subsequently executes the mooring sequence autonomously or in a highly automated mode. Throughout the operation, the AMS continuously evaluates its operational status using data from the situational awareness system and aborts the mission (as part of the fallback state) if required.

3.2 Application of MBSE on the Use Case:

In this section, we have applied the MBSE steps on the autonomous mooring operation. The aforementioned (see Section 2) two stages of MBSE, including their outputs, are presented here in a step-by-step order.

3.2.1 Stage 1: CONOPS

Step 1: Operational intent

An autonomous mooring system has been developed to enable the mooring operation of the ship without the deck crew present on board. The operation is conducted by the AMS, which executes the tasks in both autonomous and automatic manner.

System architecture: The physical interactions among the control systems between the shoreside and shipside are presented in Figure 2.

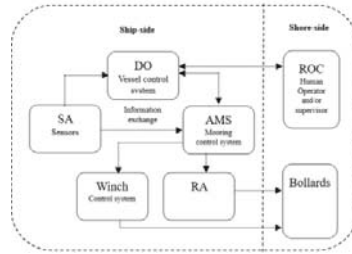


Figure 2: Physical interaction of the control system

Functional Description of the System:

The autonomous mooring operation involves a coordinated sequence of automatic and autonomous functions distributed across multiple control layers. The involved actors in the operation are the Remote Operation Centre (ROC), the DO, AMS, and the robotic arms that physically execute the mooring task. When the vessel approaches the quay, berthing begins with the ROC issuing port-clearance authorization to the DO. Once the Autonomous Navigation System (ANS) confirms that the vessel is within the allowable berthing envelope, the DO activates the AMS, thereby delegating execution of the mooring sequence to the onboard autonomous control system. The autonomous mooring operation, or AMO, consists of several actors and key components:

- **Remote operator** (instead of human operator and/or supervisor)
- **Autonomous Mooring System (AMS)** (sometimes mooring control system is also used, and autonomous control system with the same AMS abbreviation, incorporating sensing, planning, and actuation modules).
- **Vessel control system (VCS):** DO and ANS appear to be used interchangeably as the vessel control system.
- **Robotic arms** (seven-axis manipulators with a reach of approximately 21 meters),
- **Winch control system** for tension and load control,
- **Mooring ropes with a lasso** (MacGREGOR, 2025)

Upon activation, the AMS initiates motion planning based on the vessel’s relative position and distance to the quayside mooring infrastructure (i.e., 4 bollards). The AMS detects the vessel position through a combination of RGB camera, LiDAR, and other navigation sensors (Jørgensen et al., 2023). When the vessel’s position is verified for line deployment, the AMS commands the robotic arms to extend the mooring ropes and place the loops around the bollards. In the considered configuration, four bollards are available at the quay, two on each side of the vessel. The RA

performs its part of the mooring sequence automatically, using a camera mounted at the arm’s end-effector to detect bollard geometry and refine placement accuracy. A motion compensation mechanism within the AMS ensures that the robotic arms maintain correct alignment. While the RA executes predefined automatic tasks, the AMS itself operates in an autonomous supervisory role, issuing decisions to initiate, continue, or abort. Abort decisions may be triggered by perceived risks, such as potential collision hazards detected by navigational sensors. The RA actuator does not incorporate any wireless access points. All communication is restricted to the ship’s internal network and, where required, is routed through a secure Virtual Private Network (VPN). If a critical situation arises, the ROC can request the DO to intervene and terminate the mooring sequence.

Step 2: OE, and Fallback

In this sub-section, OE and Fallback are presented in **Table 1** in a structured way. The operational envelope here presents the operational boundary related to the specific autonomous mooring operation that is executed by the AMS. The boundary is determined by the human-automation interaction (HAI), weather and environmental condition, failure modes, probable hazardous events, etc. We focus on the mooring perspective only. In addition, the table presents the entire fallback plan that includes “fallback state/s, fallback activation and fallback recovery”.

Table 1: Operational envelope and fallback plan for the autonomous mooring system.

Operational Envelope	Fallback plan
Operational tasks	1. Fastening mooring lines 2. Maintain line tension 3. Communication 4. Follow the safety measures (fallback) when it is required.
Autonomy level	Constrained autonomy (Hagaseth et al., 2023)
Accountability	Automation
Attention mode	Low-high (Nordahl & Wenersberg, 2024)
Dynamic operational condition	Visibility varies depending on the weather, and high connectivity
Environmental condition	Shielded, little current, low wave.
Failure mode/s	Technical failure, sensor failure, power failure, and mechanical failure.
Probable hazardous event/s	Collision to quay side, mooring line breakage.

3.2.2 Stage 2: Formalize with UML

Step1: System control tasks (SCTs): The SCTs are organised here from the description of the previous stage. The operational envelope from **Table 1**, and the functional description of the controllers and their interaction from **Figure 2** have guided the development of the SCTs. The four operational tasks mentioned in **Table 2** are performed to complete the AMO. While performing the individual operational task, AMS executes specified SCTs. The interactions between the actors are shown in **Figure 2**, and the functional description from **stage 1** provides the systematic description of the operational task. This section presents the SCT's in a structured and sequential manner, as outlined in **Table 2**.

Table 2: Operational tasks along with their corresponding SCTs.

Operational task	System control task
Fasten mooring lines	SCT 1.1: The robotic arm locates the mooring line on the ship.
	SCT 1.2: The robotic arm grabs the mooring line with the gripper.
	SCT 1.3: The robotic arm calculates and detects the specific bollard position.
	SCT 1.4: The robotic arm places the lasso on the detected bollard.
	SCT 1.5: The robotic arm releases the lasso from the gripper and returns to the parking on the ship.
Maintain line tension	SCT 2.1: Winch control system adjust and maintain line tension
Communication	SCT3.1 (Initiate sequence): The digital orchestrator (or alternatively the vessel control system) requests the autonomous mooring system to initiate the auto-mooring sequence when the ship is in the mooring position at the quay.
	SCT3.2 (Sequence in progress): The AMS informs the ROC during robotic arm operation, during fastening mooring ropes on the bollards. (Preferably, information exchange of what parameters?).
	SCT3.3 (Sequence complete): AMS informs DO and ROC after completing the mooring task. (Preferably, information exchange about the load control situation by the winch, other external and internal conditions of the vessel)
	SCT3.4 (Sequence aborted): AMS informs DO (and ROC) on mooring arm status when a sequence is aborted so that appropriate safety measures can be applied.
Safety measures during mooring sequences	SCT4.1: Move to fallback by aborting mooring and maintain position towards quay by use of thruster and propulsion forces (manoeuvring or dynamic position system) (no fixed mooring lines)
	SCT4.2: Move to fallback by aborting mooring and maintain position towards quay by use of thruster and propulsion forces (manoeuvring or dynamic position system) (fixed or partially fixed mooring lines)

SCT4.3: Move to fallback by aborting mooring and move away from quay by use of thruster and propulsion forces (manoeuvring or dynamic position system) (no fixed mooring lines)

Step 2: UML diagrams

UML Activity and Sequence diagrams are used in this section to demonstrate the SCTs' overall activities and sequence of activities. **UML Activity diagrams** represent the sequential and concurrent execution of SCT steps, including decision points and control flows, to capture the operational logic of the autonomous system. **UML Sequence diagrams** model the temporal interactions between system components (e.g., controllers, sensors, actuators, and remote operators), illustrating command-feedback loops and information exchange during task execution. Figures (3) and (4) present the Activity and Sequence diagrams, respectively, developed based on the SCTs of the autonomous mooring system.

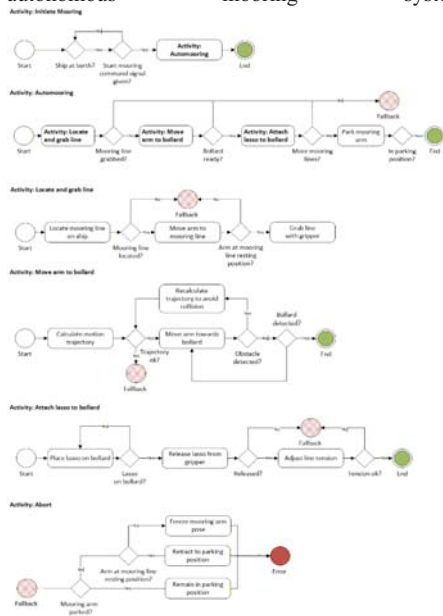


Figure 3: Activity diagram of the AMS.

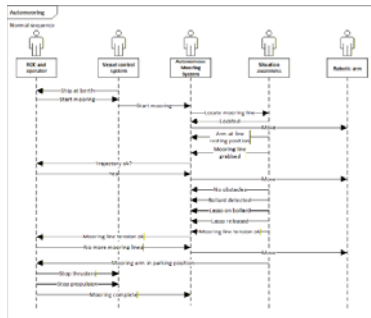


Figure 4: Sequence diagram of AMS

3.2 Safety requirements:

From the AMS case study, two illustrative approval-relevant safety requirements can be derived:

Requirement 1 (Perception-Dependent Control Action):

The Autonomous Mooring System shall not initiate the “fasten mooring lines” control action unless the appropriate bollard is detected and confirmed by perception sensors. This requirement is derived from the operational task “fasten mooring lines”, where SCT1.3 performs bollard detection, followed by SCT1.4 and SCT1.5 to complete the fastening operation. Stage 1 of MBSE defines the mooring sequence and identifies potential hazards associated with incorrect or premature mooring actions. In Stage 2, the Activity Diagram formalises the procedural steps of this control task, while the Sequence Diagram captures the temporal and logical interactions among system components. The AMS processes perception data and issues execution commands to the robotic arm accordingly. This requirement directly addresses regulatory concerns regarding the reliability of autonomous perception and the integrity of decision-making processes.

Requirement 2 (Operational Envelope and Fallback):

The autonomous mooring operation shall implement a verified fallback state that aborts the mooring sequence and maintains or manoeuvres the vessel away from the quay when operational envelope limits are exceeded, or system faults are detected. This requirement originates from the CONOPS-defined OE and fallback strategies and reflects the expectation of classification societies and Flag States for fail-safe or fail-operational behaviour equivalent to manned operations. When AMS determines a condition which is out of the OE (such as a failure mode, an interruption in the task sequence, missing communication for a predefined period, etc.), it initiates a predefined fallback plan. The operational task “Safety measures during mooring sequences” in Table 2, states the fallback plan, and the activity diagram visualises the particular condition of the fallback during the mooring sequence. However, additional requirements can be derived from the CONOPS stage; however, the two most precise and traceable requirements relevant to regulatory approval are presented here to illustrate the outputs and contributions of the MBSE approach within the safety assurance framework.

3.3 Safety analysis inputs

Within the mooring operation, 13 SCTs (see Table 2) are executed to accomplish four operational tasks, each performed by designated controllers. The manner in which these controllers execute the SCTs, whether they operate safely, and how deviations may lead to hazardous situations must be systematically analysed through safety analysis,

preferably using STPA. Consequently, the SCTs and their associated controllers constitute structured and effective inputs for the safety analysis and are used to construct the system control structure model for identifying unsafe control actions and causal scenarios.

Section 4: Discussion

This study demonstrates how a Model-Based Systems Engineering (MBSE) approach can support the safety assurance and approval of autonomous maritime systems by providing structured, traceable, and reusable engineering artefacts. Using the autonomous mooring system (AMS) as a representative safety-critical use case, the proposed approach illustrates how operational concepts and system models can be integrated to derive safety requirements and inputs for safety analysis and verification activities into a coherent approval-oriented engineering process.

The AMS use case highlights the multi-layered nature of autonomous maritime operations, involving interactions between the Remote Operation Centre (ROC), Digital Orchestrator, AMS controller, robotic arms, perception systems, and ship control systems. By formalising these interactions as System Control Tasks (SCTs) and visualising them through UML activity and sequence diagrams, the MBSE provides an explicit control structure model. Such structured modelling is essential for regulatory approval, as it supports transparency and traceability between operational intent, system design, and safety constraints. The use case further shows that MBSE artefacts, such as system architecture models, SCTs, behavioural UML models, and derived safety requirements, can serve as structured evidence for approval processes. These artefacts enable traceability from stakeholder and regulatory requirements to system implementation and verification results, supporting safety case development and regulatory audits. In contrast to traditional document-centric approaches, MBSE provides a consistent and model-centric representation of system knowledge, facilitating iterative refinement as design assumptions evolve. An important observation from the use case is that MBSE supports early and continuous verification and validation activities. Simulation-based testing can be directly linked to modelled control actions and safety constraints, while sea trials can validate real-world compliance with the defined operational envelope. This aligns with emerging approval paradigms for Maritime Autonomous Surface Ships, where incremental approval and experience-building phases are anticipated. Overall, the AMS case study illustrates that MBSE can function as a unifying backbone for autonomous system approval, integrating system engineering, safety analysis, and assurance documentation.

Section 5: Conclusion

This paper develops an MBSE- approach to develop a framework to support the safety assurance and approval of autonomous maritime systems, demonstrated through a use case involving an autonomous mooring system. The results show that MBSE enables the systematic integration of operational concepts, system architecture and modelling, creating inputs for safety analysis and providing traceability for regulatory approval. The derived safety requirements illustrate how model-based artefacts can be translated into approval-relevant engineering and regulatory requirements.

Future research: This paper represents an initial step toward the development of a comprehensive safety assurance framework for autonomous ship operations. Future work will extend the framework to additional autonomous ship functions and align it with emerging MASS regulatory frameworks and classification society guidelines.

Acknowledgement

Funded by the European Union, Grant Agreement N° 101096923. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.

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