INSIGHTS INTO

MARITIME COMPLEX SYSTEMS

PART 2: MANAGING COMPLEXITY

ABS

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EXECUTIVE SUMMARY

With the introduction of complex maritime systems in Part 1 of the paper, it is clear that the underlying motivation to continuously improve productivity and efficiency through technological advances will only continue. Future systems become even more interconnected, with more operational data collected and with analytics becoming increasingly critical.

In addition, with this new data driven system-of-systems (SoS) philosophy, the heart of these system capabilities resides in the underlying software and algorithms. As software is used more extensively and with more emphasis on software driven technologies, including the life-cycle management of change of such software, they introduce a further layer of complexity.

With the heavy reliance on software algorithms and heavy inter-dependency on constituent systems, although it is still necessary to consider individual system behavior in design and testing, the overall behavior of the system-of-systems will also need to be considered. A model-based systems engineering approach including the incorporation of simulation-based testing and validation into the design process is a key tool in the better understanding, managing and verification and validation of SoS behaviors.

The American Bureau of Shipping (ABS) as a classification society recognizes the challenges posed by increasingly complex maritime systems and the need to address and manage complex systems within its classification processes in fulfilling its mission.

INTRODUCTION

Part 2 of this paper will look at how we can manage increased complexities with systems engineering and systems thinking. In addition, the paper will introduce the systems engineering methodology Model-Based Systems Engineering (MBSE) and explain the benefits of adopting this methodology in managing complex systems compared to the conventional approach.

At the organizational level, the paper will also explore the roles of various stakeholders in assuring the functionality and safety of future maritime systems with increasing complexity, as well as areas to consider moving forward.

DEFINITIONS

For the table of key definitions, refer to Insights into Maritime Complex Systems Part 1: Concepts and Definitions Section 2.1.

MANAGING COMPLEXITY

To understand and manage the complexity in any system, work must start at the design phase. Throughout the system's life cycle, as new components and upgrades are introduced, there can be an increase in complexity, in what is known as complexity creep. Hence, only a discipline that can manage a system throughout its life cycle can effectively manage its complexity. That discipline is known as systems engineering.

WHAT IS SYSTEMS ENGINEERING

The U.S. National Aeronautics and Space Administration (NASA) defines systems engineering as "a methodical, multi-disciplinary approach for the design, realization, technical management, operations and retirement of a system." [1]
System engineers balance technical depth with project management competencies. While keeping a holistic system view, system engineers also ensure the stakeholders' needs are fulfilled. System engineers maintain a set of life-cycle processes as shown in Figure 1 from conceptual phase all the way through to system retirement [2].

CONCEPT DEVELOPMENT			ENGINEERING DEVELOPMENT			POST DEVELOPMENT	
Needs analysis	Concept exploration	Concept definition	Advance development	Engineering design	Integration and evaluation	Production and deployment	Operation and support

Table 1: System life-cycle processes.

Under the concept development stage, the need of the system is identified followed by the search for feasible concept before choosing the preferred system concept. In the engineering development stage, the chosen technology is first validated before translating the concept into hardware and software designs, followed by building and testing production model. In the post development stage, the system is produced and deployed for operations, followed by maintenance support for the system lifetime. The development of a large system such as the design and construction of a vessel requires a lot of resources and involves high risks. A system engineering process allows the development to be performed in a logical and comprehensive way, ensuring that the risks are effectively managed.

SYSTEM THINKING

System thinking requires the system engineer to view the system of interest holistically. They are taught to view the system in varying perspectives to better understand the inter-relationship within system elements and how they give rise to the systems' characteristics. Interactions with external elements and influences throughout the system's life cycle are also considered.

As system thinking is a holistic way to look at a problem, Kasser and Mackley suggest using the following systems thinking perspectives in succession [3] when developing a system:

1. Operational – this perspective describes how the system will operate in the operating environment, and this perspective is documented in the concept of operation document.
2. Functional – this perspective describes the functions performed by the system and is used when creating functional requirements.
3. Big picture – this perspective views the system in the context of its environment. This view explores the relationship with external systems outside the system boundary.
4. Structural – this perspective is a traditional view on the system architecture and internal boundaries between subsystems.
5. Generic – this perspective compares the system of interest with other similar systems either in the same or different domain, current or historical. This perspective can help to gather similar requirements, identify solutions to already solved problems and leverage lessons learned that can be applied to the current system in development.
6. Continuum – this perspective acknowledges the fact that things are not binary (e.g., pass-fail, one right way), and there are in-between states. For example, a failure of one engine in a dual engine setup does not mean that the operation must stop, the vessel can continue its operation or return to harbor under degraded mode where the non-faulty engine is used but with reduced capabilities such as slower speed.
7. Temporal – this perspective studies how the system behaves over time, looking at past data if available and predicting future patterns.
8. Quantitative – this perspective looks at the first three perspectives to develop the performance requirements. It looks for quantification rather than absolute measurement, meaning that a relative comparison would also suffice.
9. Scientific – this perspective encompasses the formulation of test cases to validate the system, akin to a "trial and error" method of solving the problem.

Table 2 below provides some examples of each perspective with respect to Autonomous Navigation System used for Marine Autonomous Surface Ship (MASS).

AUTONOMOUS NAVIGATION SYSTEM FOR MASS	
THINKING PERSPECTIVE	**EXAMPLES**
Operational	Formulation of the CONOPS for the MASS use case, including details such as area of operational environment, operation envelope, operational procedures, manpower requirement, roles and responsibilities, logistics requirement.
Functional	Creating the functional description document that describes the functionality of the autonomous navigation function. E.g., Waypoint navigation, collision detection and collision avoidance, stationkeeping.
Big Picture	Looking at the wider context such as the IMO regulation for MASS, flag Administration or port regulation for MASS, port infrastructure readiness for MASS (e.g., autonomous docking/undocking), interaction with other vessels (e.g., COLREGs for CDCA), societal acceptance of MASS (e.g., perception of job loss due to MASS).
Structural	Traditional structural plans, equipment or sensor specifications, installation plans and system architecture drawings.
Generic	Comparison of similar systems of interest in different domain, e.g., autonomous driving cars, autonomous drone navigation.
Continuum	Defining the states or modes of operation such as degraded mode or transitional mode. E.g., when certain essential equipment failed, and their redundancy backups are used resulting in reduced capabilities, or for transition out of narrow channels or congested ports where the performance of the vessel (e.g., speed) is intentionally limited.

WHY SYSTEMS ENGINEERING FOR COMPLEX SYSTEMS

Systems engineering manages the entire life cycle of a system from conceptual design to retirement of the system, systematically monitoring each phase of the life cycle including changes made to the system whether due to planned system upgrades, obsoletion of parts, adoption of innovative technology or adherence to new regulatory requirements. With a systems engineering approach, system complexity can be better understood early in the development stages and complexity creep post development can be managed throughout the life cycle of the system.

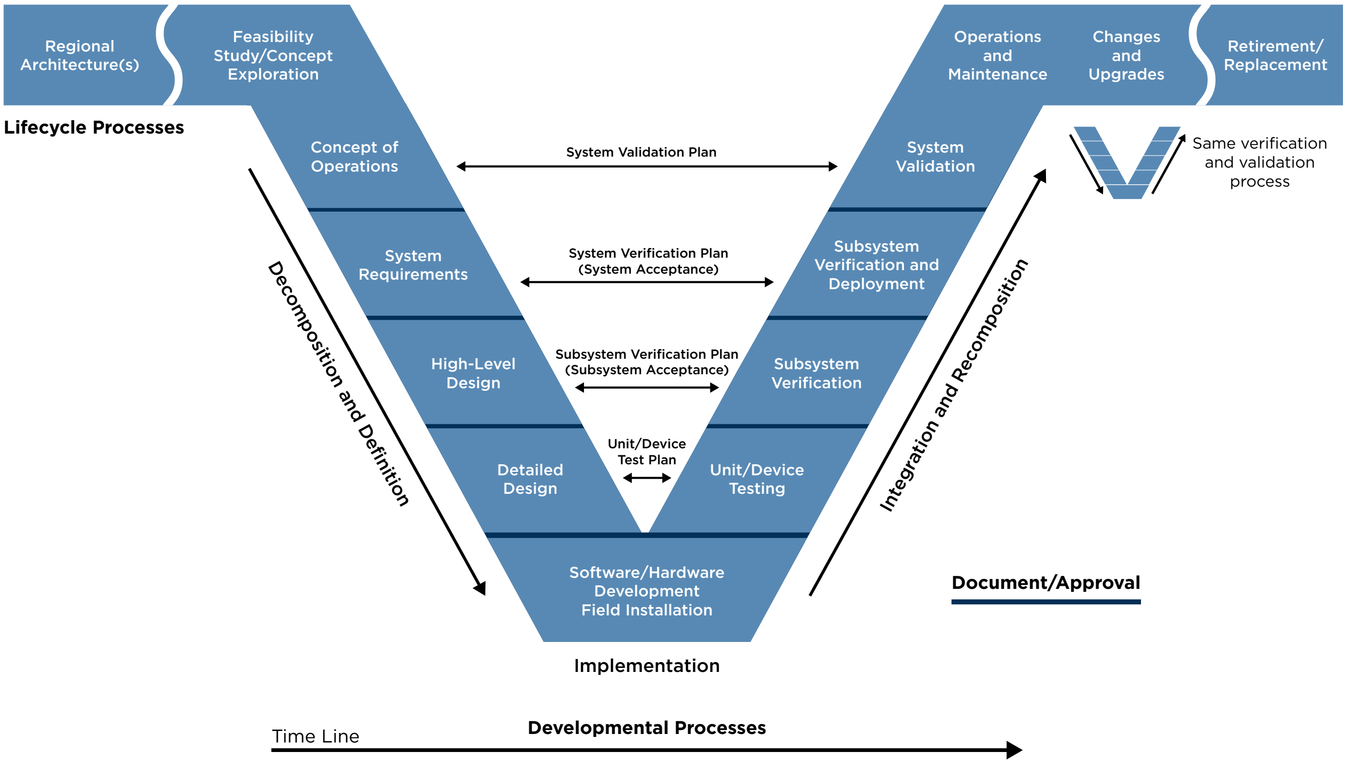

Figure 1: V-Model on the system life cycle development. [2]

Figure 2 shows the widely used V-Model illustrating the life-cycle processes. It shows how verification and validation are performed starting from the lowest level component to subsystem and then to the entire system, constantly tracing back to the requirements. Simulations can be incorporated into the verification and validation processes to ensure that complex system to be developed can be thoroughly tested in simulation to uncover any emergent behavior. Similarly, when changes and upgrades are required, the system will reiterate the verification and validation process to uncover any new emergent behaviors.

In ABS Guide for *Autonomous and Remote Control Functions*, the system engineering V-Model is also adopted for guiding the implementation process for autonomous and remote control functions [4]. The V-Model is simple to follow, and the advantage of testing in parallel with development ensures the discovery of defects early in the development stage.

MODEL-BASED SYSTEMS ENGINEERING

In the traditional system engineering approach, paper documents are the main source of information, be it structural drawings, system requirements, technical specifications, or any other system related information. Any changes to one document will require other related documents to be manually updated to ensure consistency within the many discrete documents throughout the entire life cycle of a system [5]. The result is the high possibility of having outdated and inconsistent documentation especially when the life cycle of a system, in maritime context, can easily last more than 10 years.

As the modern systems get more complicated and complex, the interconnections and interactions between hardware and software increases across different constituent components or systems made by different manufacturers. To improve the effectiveness and efficiency of capturing, communicating and exchanging data, a new paradigm emerged in the form of model-based systems engineering, where models are used to contain, manage and baseline system information. International Council on Systems Engineering (INCOSE) defines model-based systems engineering (MBSE) as follows [6]:

“Model-based systems engineering (MBSE) is the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life-cycle phases.”

A suitable definition of a model, as defined by the Department of Defense Modeling and Simulation Enterprise is “a physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process” [7].

MBSE is the amalgamation of modeling, system thinking and system engineering approach to develop and manage a system throughout its life cycle. The advantage MBSE has over the traditional document-based system engineering (DBSE) approach is that the integrated models provide traceability, infrastructure for collaboration and communication between various stakeholders, and easy detection of inconsistency and errors between discrete source documentation.

Another benefit of using MBSE is that the models developed for the system during early conceptual design phase can grow and improve through progressive refinement throughout the development life cycle of the system until a high-fidelity baseline is achieved. These models can be used to run system simulations to study the system behaviors under varying conditions.

For increasingly complex systems in an era of potential cybersecurity attacks, MBSE can enable threat-modeling analysis in the early system development stage to create a system that is secure by design [8]. MBSE can also support digital twin [9] and simulation-based verification and validation to manage the increasing complexity [10].

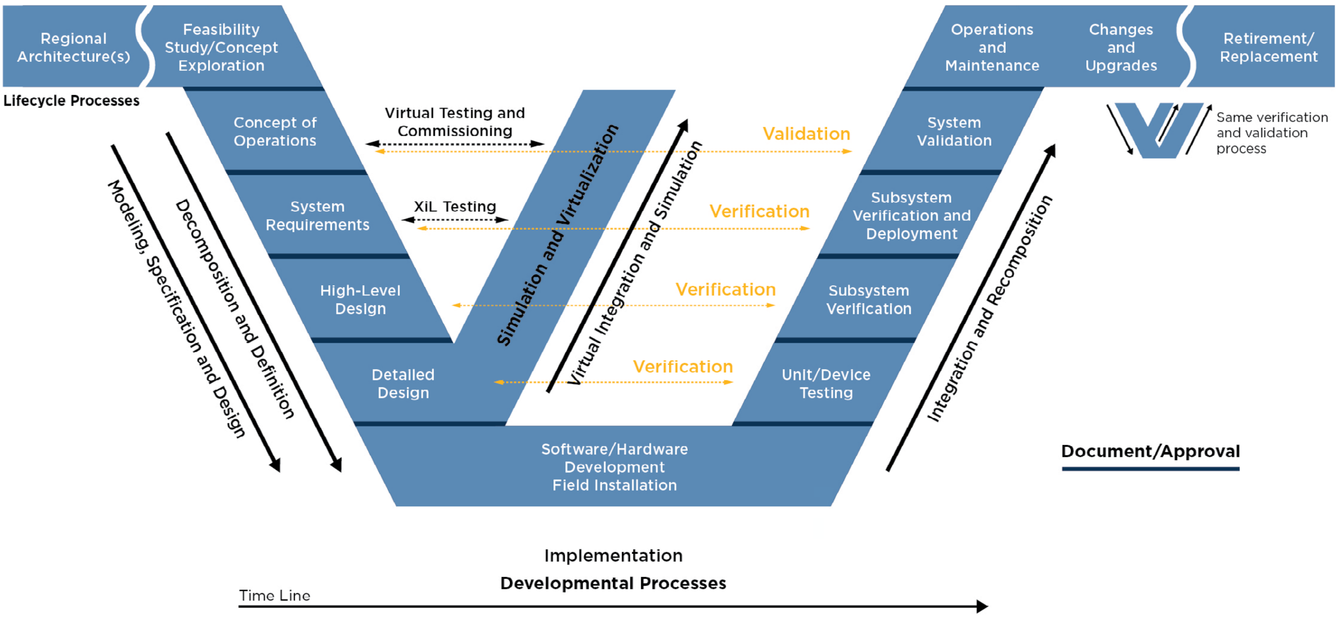

Figure 2: Modified V-diagram for MBSE development processes. [11]

Figure 3 illustrates the additional processes introduced by MBSE as compared to the traditional document-based systems engineering approach presented in Figure 10. Additional processes include modeling of the system, virtualization, and simulation. A parallel iterative branch is introduced for virtual verification and validation of the system through XiL testing (e.g., hardware in the loop, software in the loop or model in the loop), virtual testing and virtual commissioning. Despite the additional time and effort required in modeling, simulation and virtual testing, the use of these simulation and virtual testing can uncover and rectify defects early in the development life cycle, eliminating costly rectification work in the physical world in later stages of the system life cycle. The system models created will be maintained and updated throughout the system life cycle and it can be easily reused for verification and validation of the system during changes or mid-life upgrades later in the system life cycle as shown in Figure 3.

Table 3 summarizes the benefits of using MBSE over the traditional DBSE approach as well as the barriers hindering the adoption of MBSE [12]. Note that the main barriers are the initial investments such as for training the team, procuring MBSE tools and computing infrastructures necessary for implementation of MBSE, but the expertise and experience acquired can be reusable for subsequent MBSE implementation.

BENEFITS OF MBSE OVER DBSE	BARRIERS TO ADOPTING MBSE
• Completeness in requirements set • Improved consistency with a common repository of information • Improved communication across project teams and stakeholders • More thorough planning and traceability for verification and validation, testing and evaluation • Reusability of models for related products • System models can be used to run system simulations • Supports digital twin and simulation-based verification and validation	• Lack of skilled MSBE system engineers • Time and resource investment in training and development of staff in MBSE • Investment in the full set of MBSE tools • Resources required for managing and updating system models throughout the system life cycle • Requires computing infrastructure for MBSE throughout system life cycle • Resistance to change as users are comfortable reviewing documents rather than MBSE models

Table 3: Benefits and barriers to adopting MBSE over DBSE.

SYSTEM SIMULATIONS

With the MBSE approach to system development and life-cycle management, system models can be used to run system simulations to analyze system behavior and performance under varying conditions. For maritime systems, the ability to control and vary the external conditions of the system of interest and running the simulations in a lab environment helps to reduce operation cost, operation risk, and time required for trial preparation or for specific scenario to occur in real time. Table 4 summarizes a list of benefits and cost of utilizing simulation tests instead of performing system tests onboard physical marine vessel or platform.

BENEFITS OF MBSE OVER DBSE	BARRIERS TO ADOPTING MBSE
• Able to recreate scenarios conditions that is dangerous or not easily available (e.g., extreme sea state conditions caused by harsh weather) • Eliminates the risk of operation crew onboard vessel or platform during physical sea trial test • Eliminates operation cost of physical sea trial test • Simulation test duration not limited to daytime or limited by weather or sea conditions (e.g., can run 24 hours to cover more test scenarios)	• Need to hire or train staff for skilled in modeling and simulation • Requires capable computing infrastructure to run simulation test • Additional resources to setup and sustain the simulation test facilities • Simulation test augments actual system test but may never fully replace it

Table 4: Benefits and costs of simulation.

ROLES OF REGULATORY BODIES AND CLASSIFICATION SOCIETIES

ROLES AND RESPONSIBILITIES

Key components governing maritime safety are the Statutory Regulations and Classification Rules. The International Maritime Organization (IMO) is the global authority in creating and maintaining the regulatory framework. A flag State enforces maritime regulations for ships under their flag. The International Association of Classification Societies (IACS) is a membership organization of classification societies that establish minimum technical standards and requirements that address maritime safety and environmental protection and ensures their consistent application. And the individual Classification Society provides classification, statutory certification and services as a Recognized Organization (RO) acting on behalf of a flag Administration.

ONGOING ACTIVITIES

As innovative technology emerges, statutory regulations governing them are formulated at IMO. Statutory regulations usually take a longer time to catch up to technology development in the industry. One example is the MASS Regulatory Scoping Exercise at the IMO that commenced in 2018 to assess the degree to which the existing regulatory framework may be affected in order to address MASS operations. The scoping exercise concluded in May 2021, paving the way to develop the MASS requirements with the target to publishing them in 2028 [13].

Keeping pace with the implementation of increasingly complex systems, IACS also established a complex systems working group to address how classification requirements and processes can continue to assure the safety of systems. They are currently reviewing their Unified Requirement E22 for On Board Use and Application of Computer-based Systems in view of the increasing complexity in systems being adopted.

ABS is keeping pace with the changing technological landscape with their Rules 2025 development program to augment and future proof existing Rules and Guides.

AREA OF CONSIDERATION

As novel complex system implementations progressively gear towards goal-based approach such as for MASS, it became increasingly difficult to set requirements to follow. One area of consideration is the development of goal-based standards to support the design and review of novel and complex system implementations. In this regard, IMO's Maritime Safety Committee had first approved the Generic Guidelines for Developing IMO Goal-based Standards on its 89th session in May 2011 and the latest revision approved on the 101st session in June 2019 [14]. Figure 4 below shows the goal-based standards framework presented in the generic guidelines.

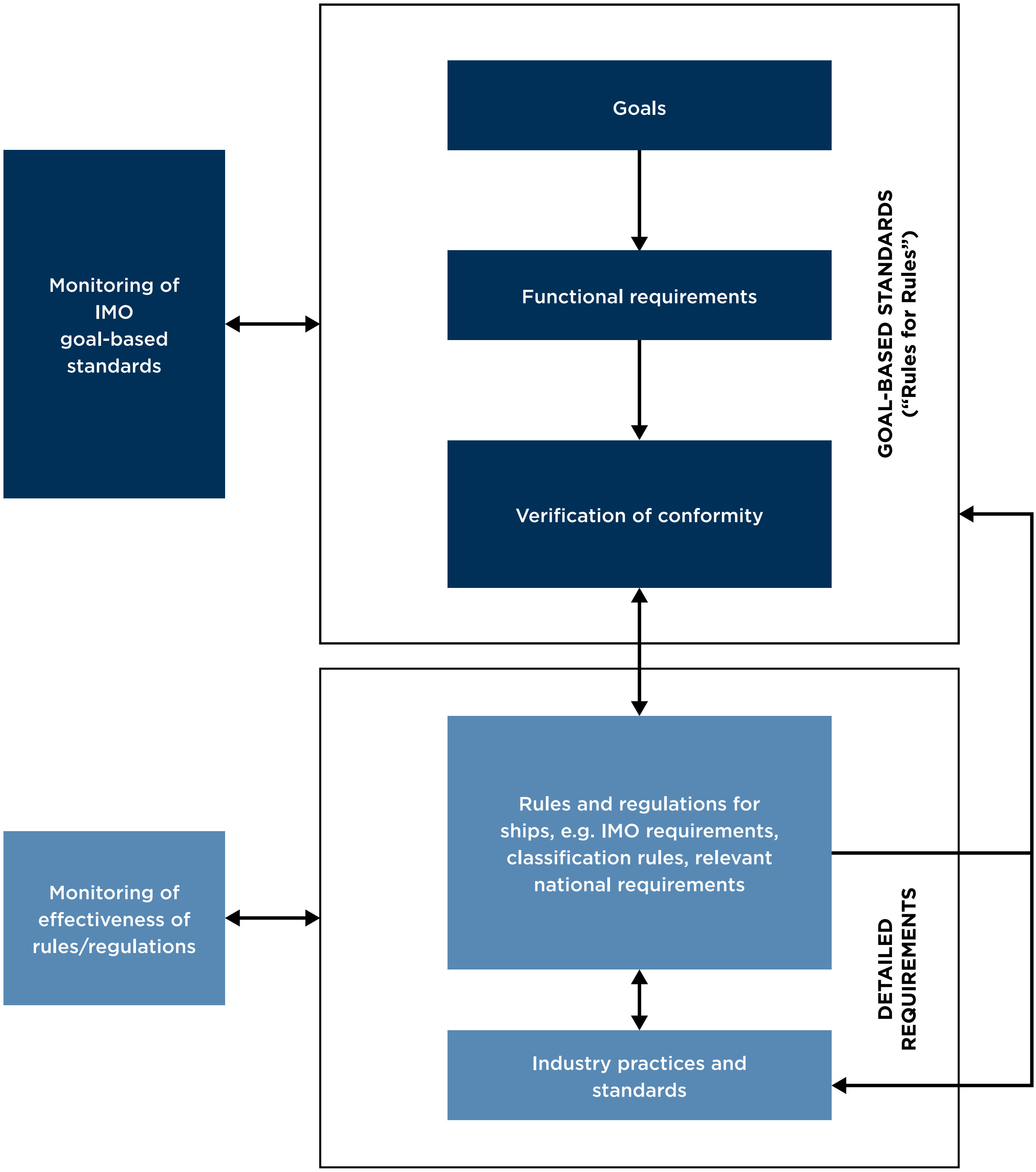

Figure 3: Goal-based standards framework.

To address complex systems, conventional prescriptive requirements that examine the suitability of individual system element are still necessary but may not be adequate to cover the safety assurance of emergent behavior of the complex system as a whole. Hence, another area that can be considered is the increased emphasis on examining the entire system behavior rather than in parts. This can be in terms of assessing risk scenario resulting from unsafe system behavior. However, to first identify any unsafe system behavior, system simulation tests need to be performed. And for classification societies to guide the industry in this new frontier, standards and rules need to be implemented for the use of simulation-based verification and validation.

S/N	BENEFITS OF SIMULATION
1	Able to recreate scenarios conditions that is dangerous or not easily available
2	Eliminates the risk of operation crew during physical sea trial test
3	Eliminates operation cost of physical sea trial test
4	Simulation test duration not limited to daytime or limited by weather or sea conditions
5	Simulation test runs can be automated
6	Simulation test can run in accelerated time
7	Able to test the system over an extensive range of conditions to uncover possible strong emergent system behaviors

Table 5: Summary of simulation benefits.

As mentioned in Section 3.5, simulation can uncover system behaviors that are not easily replicable under physical testing and trials. Simulation also allows a testing of the system within a wide range of conditions at accelerated speed with reduced resources compared to physical sea trial test. The benefits are summarized in Table 5. As a first step, developing a framework for simulation testing with standardized test scenarios as baseline can provide guidance to system builders and ensure that the system is sufficiently tested to a certain confidence level. When such testing framework is in place, system builders will also be encouraged to adopt the MBSE approach for system development and management because of the many benefits MBSE provides especially its support for system simulation.

CONCLUSION

For development of new systems, the MBSE approach can be implemented early in the conceptual design stage to manage the system complexity. For existing systems, adopting the MBSE approach after the vessel has been commissioned and is operational can still provide value in the maintenance or upgrading of legacy systems.

Statutory regulations governing maritime safety may lag behind the rapid technological advancement and increasing complexity of systems, but work is in progress to ensure that the regulatory framework can address the safety requirements of each novel technologies.

Complex systems are here, they are increasing in their application and ABS is at the forefront ready to address this topic through the classification process.

ABS SUPPORT

The ABS *Guide for Cybersecurity Implementation for the Marine and Offshore Industries, ABS CyberSafety® Volume 2* provides cyber-related safety and security requirements and recommendations for the assessment of marine and offshore cybersecurity systems.

The ABS *Guide for Hybrid Electric Power Systems for Marine and Offshore Applications* provides requirements for the design, construction, testing and survey of marine and offshore assets utilizing hybrid electric power systems.

The ABS *Guide for Dynamic Positioning Systems* covers ABS requirements for the design and testing of DP systems and provides optional notations and technical specifics that reflect current industry practice and DP technologies.

The ABS *Guide for Autonomous and Remote Control Functions* provides a mix of goal-based and prescriptive requirements set against a wider risk-based framework to guide the implementation of autonomous and remote control functions on marine vessels and offshore units.

ABS is equipped to assist owners, operators, shipbuilders, designers and vendors in the verification and validation of several types of complex systems utilizing the principles in the above-mentioned Guides along with the *ABS Guidance Notes on Qualifying New Technologies and the Guidance Notes on Review and Approval of Novel Concepts*.

LIST OF ABBREVIATIONS

CDCA	Collision Detection and Collision Avoidance
CONOPS	Concept of Operations
DBSE	Document Based Systems Engineering
IACS	International Association of Classification Societies
IMO	International Maritime Organization
INCOSE	International Council on Systems Engineering
MASS	Maritime Autonomous Surface Ships
MBSE	Model-based Systems Engineering
NASA	National Aeronautics and Space Administration
RO	Recognized Organization
SoS	System-of-Systems
TSS	Traffic Separation Scheme
XTE	Cross Track Error

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