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A systems engineering–based approach for framing reliability, availability, and maintainability: A case study for subsea design

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Abstract

Framing reliability, availability and maintainability (RAM) aspects are critical for an engineering design, as RAM is concerned with the sustained capability of a system throughout its useful life. RAM analysts are responsible to consider both functional and dysfunctional behavior of a given system beyond the perspective of system designer. However, the system concept baseline developed by RAM toolset is often a partial view, which is either too abstract when preparing RAM analysis or too overloaded when integrating RAM analysis with design process. Such practice may not give systemic insights of the design concept, considering specific subsea design challenges such as limited accessibility and requirement for automate control. For this reason, it is of great importance to ensure an effective and sufficient communication between the domain of design and domain of RAM. Integrating with a well-known engineering discipline, such as systems engineering (SE), may help analysts to create the collaborative design environment necessary to control the design risks for a system with high complexity. This article proposes a new framework that links SE with RAM engineering by connecting relevant concepts and models used. A novel subsea design concept is offered as a case study to demonstrate the key changes in subsea design activities for addressing RAM with the proposed framework.

KEYWORDS
availability, reliability, subsea system, systems engineering

1 | INTRODUCTION

Reliability, availability, and maintainability (RAM) is concerned with the sustained capability of a system throughout its useful life. RAM plays an essential role in the engineering design process of subsea systems to create competitive advantages, such as reducing capital investment (CAPEX) and operational costs (OPEX), controlling the risk of redesign, and mitigating potential future production disturbances.[1] RAM of technical systems are receiving center stage attention in many sectors, such as automotive,[2] aviation,[3] nuclear,[4] oil and gas (O&G),[5] and railway.[6] RAM analysis based on feedback from existing legacy systems imposes constraints on systems requirements, architecture, and design.[7(p97)] However, managing RAM is often viewed as a separate activity in many subsea engineering practices, and the relationship to other established engineering frameworks, such as systems engineering (SE), are often not developed. For example, in discussions that have taken place inside the research center of SUBPRO[8] with manufacturers of subsea systems, we see that they have established both RAM and SE processes, although the tasks may not be coordinated and there is no well-established practice for how to share and use results across the two processes. One specific concern is that misinterpretations may arise due to the inconsistencies in backgrounds, jargons, and models used by the different engineering frameworks. This is a real concern in the O&G domain where a myriad of contractors and subcontractors must cooperate to achieve a final solution. Another, and perhaps even more important concern is that the SE and RAM engineering frameworks are not utilized at full potential to identify, address, and solve design challenges that involve new operating environments or new technology. Some research initiatives have been studied to resolve similar problems, such as concurrent engineering[9] and Design for Reliability (DfR).[10,11] However, concurrent engineering is more about coordination of technical engineering discipline, where the focus may not be placed on its interrelation to RAM engineering. DfR toolset mainly focuses on how to improve the design through complete testing and experiments carried out in later stages of design, where the analytical methods and modeling of RAM engineering receives limited attention. Our hypothesis, which forms that basis of the research in this article, is that it is necessary to integrate RAM analyses with SE analyses, to holistically address the generally high complexity associated with technical systems.

The authors investigate and suggest a new framework to integrate RAM engineering with SE. The International Council on Systems Engineering[12] defines SE as "an interdisciplinary approach and means to enable the realization of successful systems." RAM engineering shares some similarities with SE. For instance, they both employ models developed to give an abstract view about system behaviors and physical configurations, albeit for different analysis needs. This article provides a view on how to make specific couplings between SE and RAM engineering in terms of concepts and models used. RAM engineering is often considered as a specialty subset of SE,[7] and even then it seems that the specific interfaces between SE and RAM engineering are given limited attention. The authors select some literature from the SE community and discuss the interrelationship with typical RAM analysis methods and steps. A new framework is proposed on basis of this evaluation, to mirror SE for extending the current practice of framing RAM aspects in design.

A review of the literature uncovered references that discuss the potential integration and proposes some tools to support exchanges between RAM and SE. Jigar et al[13] presented ways to extend the existing availability allocation process to the relevant stakeholders involved by applying a SE approach. The work indicates that the availability allocation problem can be redesigned within SE principle, so that the analysis is conducted in an iterative and systematic manner. Garro and Tundis[14] showed the possible extension of reliability analysis of a system to that of the System of Systems (SoS) concept, to solve the main issues arising in system reliability analysis considering particular properties of SoS. Leveson[15] proposes the new accident model based on systems thinking, that is, Systems Theoretic Accident Model (STAMP), where the safety problem is reformulated as a control problem thus make greater progress toward safety analysis of complex system. Shainee et al[57] apply SE to the design of a technical marine SoS, while Ramírez et al[56] discuss ways that SE serves in coordination and communication by alleviating potential friction between multidisciplinary actors.

This article uses a subsea O&G production system to explain the foundation of the framework and demonstrate its applicability. Due to lower oil prices and changing field conditions, the Norwegian-based O&G industry is increasing the installation of subsea equipment to accommodate pressure assistance, O&G separation, and water treatment.[16] The *marinization* of topside technology (eg, fixed or floating facility) offers several benefits, such as increasing recovery from the field and saving costs associated with manning and maintaining the platforms. Hereafter, such innovations for improving current production solutions are referred as *new subsea design*. As of today, manufacturers and system integrators of subsea systems use internally developed procedures for framing RAM in the design, following standards such as ISO 20815[5] that link production assurance with reliability management in a wider context, and more detailed recommended practices such as DNV-RP-A203[17] and API-RP-17N.[18] However, the current practices are not optimized for recognizing new and specific design challenges or new operating environments. For instance, failure mode, effects and criticality analysis (FMECA) is often used as "one size fits all" method for failure analysis, regardless of whether systems are installed subsea or topside. In the proposed framework, we will discuss how outdated practices can benefit by using SE methods as a foundation.

Subsea Production and Processing (SUBPRO) is an initiative funded by the Norwegian Research Council to address current and future challenges in subsea systems that require multidisciplinary collaboration. The project combines researchers and industry partners to address the gaps in knowledge and accelerate the level of innovation in O&G field development and operation.[8]

The rest of article is organized as follows. Section 2 explains some of main characteristics of a typical design processes within SE and RAM, including highlighted similarities and differences. The new framework, referred to as RAM-SE, is introduced and explained in Section 3 and followed by a presentation in Section 4 about how these two discipline get advantages from such integration. A new subsea design concept is presented in Section 5 to demonstrate the application of the proposal. The case study has been selected on the basis of systems relevant for the research based innovation center for SUBPRO. A summary with concluding remarks and suggestions for future research is given in Section 6.

2 | RAM ENGINEERING AND SE

The following subsections give a brief introduction to the practice of RAM engineering and SE, including general considerations and practical challenges with respect to new subsea design. The discussions and reflections are based on literature review, investigation of the current industry practices, and feedback received from participants in the research project SUBPRO.[8]

2.1 | RAM engineering

RAM engineering aims at using engineering knowledge and techniques to control the risk of failures and reduce engineering uncertainties.[19] The main activities of RAM engineering covers (a) artificial experiments to test out the properties of a given system or parts, and (b) analysis and modeling techniques to reveal the cause-effect relationships between failure and specific conditions.[20] Activities, such as life time testing, carried out later, are of little relevance for this article and thus will not be further discussed.

Figure 1 gives some state of art methods for RAM analysis at different stages of a design process, based on discussions by Bertsche[21] and Johansson.[22] RAM analysis identifies issues to consider in the evaluation of design concepts, beyond what are already identified by the designer's own models and tools, such as provision of information (eg, monitoring of technical state), allowance for testing (eg, remote and diagnostics), protection of equipment, and behavior upon fault conditions. RAM analysis can be both qualitative and quantitative. Qualitative analysis is used to identify failure modes, mechanisms and causes (such as FMECA), and determine the possible maintenance and test strategies. Probabilistic analysis uses the result of qualitative analysis as the basis to quantitatively execute the comparative evaluation to support follow-up decision making. With the design evolution, these

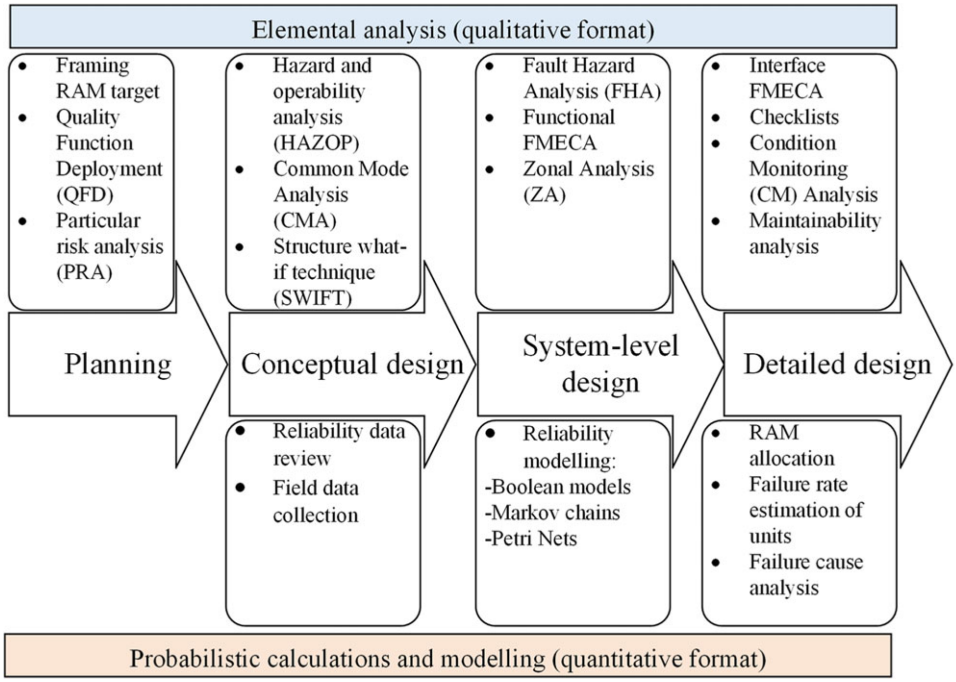

FIGURE 1 Mapping RAM methods in design process

analyses may be iterated, and updated via communication and consultation with operators, manufacturers, and designers.

However, the current process may not be optimal for complex system design. Highly complex systems are characterized by highly coupled parts and nonlinear interactions.[23] Unfortunately, alone many RAM methods in Figure 1 are not well suited for identifying and studying the effects of these interactions. Using them in this way introduces design risks that stem from insufficient considerations of engineering aspects, and will be latent on the first day of operation. The traditional RAM models follow *reductionism* (or analytical reduction), which fosters a *bottom up* approach by assuming that parts are operated independently and are not subject to feedback loop and interactions.[15,23] Such "system concept" developed by RAM analysts is not efficient for a complex system, as the hierarchy structure does not explicitly express any dependencies. Taking subsea as an example, high-level complexity is introduced by modular and compact design, software implementation (programmed functionalities), digitalization for communication technologies, interconnected hardware devices, and use of new technologies under more demanding (eg, autonomous) operating environment. These issues require efforts to systematically manage complexity, otherwise the framing of RAM aspects could be incorrect.

In addition, the heterogeneity of the multidisciplinary context in the design phase also restrains the use of current processes. System designers (who are responsible to organize system models considering various engineering disciplines at stakes) may have conflicting interests with RAM analysts, reflected by inconsistency of their models and focus of their elaborations. New subsea design is a concurrent and collaborative process, where different engineering teams are involved including RAM analysts. The RAM issues for new subsea design must be considered as early as possible to support decision making about redundancy, modularization, strategies for interventions, and the like. However, the effect of RAM considerations is not easily observed by other engineering teams, as confirmed by O&G industry partners who indicate that RAM analysis is not fully and actively used to support new subsea design. This said, many of the abovementioned methods do not have a well-defined interface with other analyses carried out in parallel phases of the design. A similar problem is also identified by Barnard[24] who points out that the overemphasis on probabilistic modeling frequently leads to misinterpretation of RAM analysis, which can lead to bad design or waste of engineering efforts.

For instance, a successful FMECA depends on a clear understanding of system concepts.[25] However, in practice one may start FMECA without establishing the holistic vision, due to the limited project time or independence of RAM analysis in the design process. The approach itself is unable to deal with critical combinations of failures modes, which means the failure or deviation is only analyzed individually within local perspective.[17] In the case of novel or unproven design, such as a new subsea design, many failures are systemic rather than the result of individual parts degradation, in particular for systems where software and communication technologies are used to implement a majority of the functionality. Systemic failures include "one of a kind" errors caused by improper operation procedure, software errors and flawed controls, and whose effects are complete or partial loss of functionality. Such failures may not be sufficiently identified through FMECA, which relies on a well-defined understanding of how the system can fail and the effects of failure. Therefore, the effect of failure at a system level is studied only partially. On the other hand, FMECA may take on a too large scope covering many trivial cases, which limits its support for decision making in design process.[26] It is therefore not ideal for engineers with different backgrounds to capture the useful concepts in their own models and analysis.

Table 1 summarizes some of the challenges of old practices in RAM engineering and indicates what we have suggested as requirements to a new approach. A relevant candidate to support the realization of

TABLE 1 Foundations for new practice of RAM engineering

Some typical errors in the old practice of RAM analysis	New requirements toward RAM analysis for complex design
Some engineering aspects may be ignored or misunderstood. Example: System familiarization is often subject to the competence and experience of RAM engineers instead of designers	Need to master complexity of design concept in a systematic and organized way before any specialty analysis.
The interactions between components/functions are not sufficiently considered in evaluating RAM performance. Example: The failure effect is only identified and evaluated on the selected hierarchical decomposition. The maintenance activities are evaluated in similar fashion.	The loss of RAM performance is beyond a chain of events. Need to organize the interactions between components/functions of system so the effect of failure is well understood.
The results of RAM analysis could be misinterpreted or misunderstood. Example: Probabilistic methods dominate in most practice. Human errors, software reliability, and systematic failures are not sufficiently covered in such analysis.	Need to communicate the result of RAM analysis in other ways than probabilistic based indicators so that systematic failures can be correctly communicated.
(Model-based) RAM activities are often "disconnected" from design process or have little interface with other engineering disciplines. Example: Heterogeneity in knowledge base	Need to integrate RAM engineering with other engineering disciplines involved in design process by connecting the produced models and used concepts.

these requirements has been identified within the SE framework. SE includes methods to support design team coordination, ensuring that the system concept is communicated correctly and that the correct system concept is communicated. SE also includes analyses that can improve the basis on which the RAM analysis is carried out.

2.2 | SE in subsea design

The core of SE is to apply system thinking to solve complex problems, where problems are viewed holistically instead of individually.[27] SE provides an iterative and systematic approach for problem solving, although the definition of SE varies across the literature.[28,29] The SE concept can apply to many industries to systematically analyze the given complexity, given two assumptions.[15] The first assumption is that the engineering effort for improvement on an individual component may not lead to an overall optimization. Returning to the subsea case, some subsea equipment cannot be replaced without pulling a whole module. This means that the effect of failure is not isolated to one component and one system function alone, but may include many others as well. Therefore, the individual improvement on component reliability may not improve the overall RAM performance. The second assumption is that the performance of individual component cannot be understood without considering internal and external interactions. For instance, subsea operation involves a high degree of automation and process control as manned actions have been dramatically reduced or eliminated in the subsea environment. This implies some errors are related to inadequate operation, flawed control process, and missing or wrong interactions. Analyzing failure caused by physical degradation is no longer considered as sufficient practice for framing RAM aspects on new subsea design.

This said, SE takes a lead role in organizing complexity for many disciplines including RAM engineering. Model-based SE (MBSE) suggests the use of models to support the view of a system concept. The system concept can be viewed from different perspectives, with the support of a rich set of model notations to capture the operational, functional, physical/architecture aspects of the system being evaluated. The traits of these models are briefly discussed in previous literature.[30–32] System Modeling Language (SysML)[33] is a commonly accepted technology for MBSE, which uses the same profile mechanism as Unified Modeling Language (UML) with some extensions made to give support to SE activities like requirement allocation. In this article, SysML is considered as the example SE tool for developing system architecture views.

Supported by a consistent system concept, one can eliminate the inconsistencies and misinterpretations caused by maintaining two sets of artifacts from the analysis of RAM Engineering and SE. Therefore, the pursuit of integrating RAM concepts along with the design process is realized by transferring between SE artifacts to analytical methods that solve the RAM-related problem. Figure 2 presents a conceptual map of these two types of models and the design itself. A SE artifact is a set of models that capture different levels of abstractions (ie, operational, functional, and architectural) of design, where RAM models inherit the same view with adjustments made due to accommodate the selected mathematical framework. Using RAM techniques or tools to construct the system concept may not be efficient as most of them are based on an error-prone point of view. SE models should be a prerequisite for developing a RAM model, and the consequent implications of RAM model influence the development of design concept by incorporating RAM aspects that extend most of design models based on SE tools.

3 | APPLYING SE TO INTEGRATE RAM IN SUBSEA DESIGN

This section will elaborate on SE activities with an outlook on RAM integration.

3.1 | Requirement analysis

The SE engineering process starts with identifying the requirements of stakeholders.[7] A complex system often involves multiple disciplines and is verified by multiple analyses rooted in different domains. The stakeholders can be classified based on their contributions as "primary," "secondary," and "tertiary."[34] Both RAM analyst and system

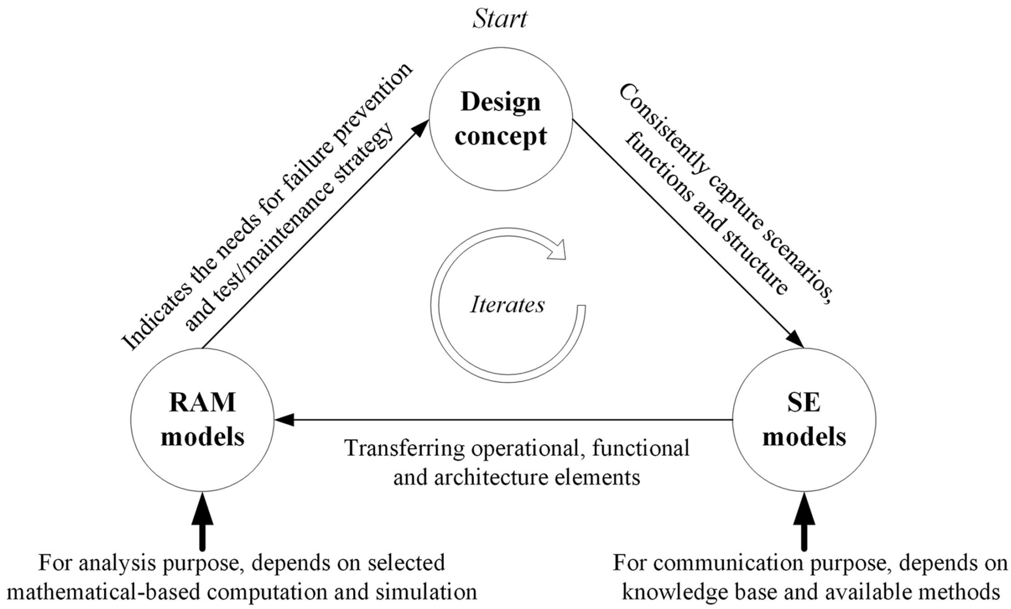

FIGURE 2 A conceptual map of RAM and SE models

designers who maintain a unified vision of the system concept are the primary stakeholders in new subsea design.

The glue that integrates the different contributing teams is the system level requirements that allow useful design concepts to be generated.[15] The study of operational concepts provides a preliminary overview to describe system missions, operating environment, and the internal/external interfaces. The typical models used for capturing a conceptual architecture are *operational context model*, *sequence diagram*, and *use case diagram*. The results of operational analysis are used to formulate contractual requirements. For example, with SysML one can model the text-based requirements supported by these diagrams together with a requirement table to clarify their relationships in the design.[35]

Much of the effort of a system designer is devoted to the functional requirements that define the behavior of system for fulfilling the needs, whereas RAM engineers aim to specify required RAM performance under different operating conditions. RAM requirements would be meaningless unless use profiles, environmental conditions, and operating conditions are specified.[36] The distinction between functional requirements and RAM requirements are important for eliminating inconsistencies between contributing engineering teams. Fulfilling the functional requirement does not implies the satisfaction of RAM requirement. The introduction or update of RAM requirements needs to update functional requirements and vice versa, but there are many constraints, for example, schedule and budget, on the simultaneous updates. In the context of subsea design, such conflicts can end up being more problematic, as most equipment and their interconnection cannot be modified after installation subsea. Therefore, it is more important to identify a *best* RAM performance considering the constraints of the operation and environment, rather than the theoretically *optimal* RAM performance. For example, the duplication of critical components (ie, redundancy) may add more flexibility in long-run subsea operation, but this decision implies costly installation and intervention due to the hiring of a larger vessel (ie, larger CAPEX).

The design should proceed with respect to these constraints and requirements to analyze functions and physical structure. Subsection 3.2 presents system architecture analysis as one of the most important SE activities and identify the role of RAM within.

3.2 | System architecture and analysis

As stated above, RAM engineers are accustomed to focus on the hierarchical function structure, since failure can generally be described as the termination or loss of functions and each function could be analyzed independently. Such practice is suitable for a system with simple interactions, decoupled functions, and straightforward part-function relationships, but not complex systems. Complex systems are better served by the SE suite of tools to systematically develop a vision of behaviors, interfaces, elements, and control structure for a new subsea system.

3.2.1 | Functional (behavior) analysis

Functional decomposition as a *static* representation of the hierarchy structure of functions is often adopted by RAM analysts to become familiar with the system concept. However, the tree-like decomposition with a local perspective cannot give the systemic view showing how the functions are coupled. The dependencies are not explicitly highlighted in functional decomposition.

In the SE community, different types of functional models are categorized as *flow-based* and *event-based*, and their representatives in SysML are *activity diagram* and *state diagram*, respectively. As a specialized form of flowchart, the activity diagram uses "tokens" to illustrate the concurrency of flow of control and data. This semantic aligns the structure of activity diagrams with that of Petri nets accepted in RAM community, although the activity diagram is more concise than standard Petri nets, especially when it comes to modeling the reactivity of workflow.[37] Considering the needs of quantitative notations, different mapping methods are proposed to translate UML activity diagrams to

Petri nets[38] or SysML versions.[39] The state diagram (or state machine diagram) explicitly describes the dynamics of an object or system. It consists of potential states and triggering events that drive the transition between states. The state diagram resembles Markov chains, perferred in RAM community on the surface, but with the distinction that Markov chains as the formal model based on strict mathmatical framework represent less content state diagrams. For instance, when transferring a state diagram to Markov chains for quantitative modeling, sychronization and parallelization of state diagram are abstracted away. The flow-based functional model and the event-based model are intended to be consistent; that is, if all transitions on a state diagram can be triggered by the completion of activities, then the context captured in activity diagram and state diagram are consistent. Activity diagrams based on flow of control are better used for modelling a process of operation, whereas the state diagram emphasizes events.

They are other models that are not covered in SysML that also support functional analysis. For example, the Function Flow Block Diagram (FFBD) represents the control structure and emphasizes the sequence of a successful operation. It is often implemented in conjunction with other models, such as N-squared diagram, in order to encompass all details of behavior.[32,40] In similar fashion, these graphical notations ease the communication of conditional system behavior between designers and RAM analysts even when no corresponding methods are found in RAM community.

Solely relying on functional architecture to analyze RAM performance of complex systems could be superfical and incomplete, as it only assists in identifying potential failure and repair events but not the associated cause and consequence. Therefore, the physical architecture of a design concept should be developed.

3.2.2 | Architecture (physical) analysis

The physical (architecture) analysis defines the components that realize the identified functions. Depending on the role RAM analysts have in the design phase, a technical system is generally considered from a functional instead of architecture point of view. However, it shall not be the case for new subsea design. Even if the well-rounded functional analysis is completed, we may not be able to evaluate the potential failure modes due to the incomplete view of given system concept.

The most commonly used approach to study physical aspects of system is the physical decomposition, which is often used as the "checklist" for the dysfunctional analysis, such as physical FMECA. However, such breakdown structure does not help in the context of complex system as many parts are interrelated and ought not be analyzed individually. Often times, studying physical aspects in RAM community is a brainstorming process that requires participations from multiple disciplines, for example, Hazard and Operability analysis (HAZOP). Few methods are proposed to exclusively incorporate physical properties in framing RAM aspects. Pioneering works have been encountered in the aviation industry, where the method zonal analysis is proposed to highlight the impact of proximity in Common Cause Failure (CCF) modelling.[3] Zonal analysis have not been fully exploited in O&G sector yet, but we can foresee this approach is meaningful as subsea modules are designed compactly thus the combination of effect of local failures or unwanted events may generate the potential hazards or increase the stress on the other components due to proximity. For example, the leakage of a pipeline can cause gradual contamination in neighboring areas. Such effects must be considered in some RAM methods for evaluating the failure rates upon environmental stress or other influencing factors, using analysis tools such as cause-effect diagram or Bayesian belief networks.

Using SysML, one can generate block definitions that contain physical attributes such as weight and size and they can also inherit attributes from other (higher-level) blocks. In such practice, building physical models of a subsea system can ensure coverage and traceability of defined constraints and assumptions (eg, height, width, mass, and the like). However, relying on the requirement table provided in SysML only gives an indication about constraints. The lack of 3D model can be compensated by using computer-aided design tools when needed. The complete architecture analysis can assist in understanding how the local effects on basic components can disturb the system and updating stochastic descriptions of unwanted events, together with expert judgments and experienced practices, for example, using finite element method to study the failure rate of a pipeline considering the effect of sand, fluid composition, ambient temperature, and pressure.

Additional attention should be paid to system structure, that is, the modularity in subsea design environment. Modularity deserves attention even in the early phase of subsea design, and can be illustrated as shown in Figure 3. Some subsea functions are realized by components located within different modules, but the replacement takes place at a module level.

Design structure matric (DSM) is rather a straightforward modeling technique to handle the modularity replacement problem.[41] The component-based DSM is often adopted in SE even though it is not available in SysML and here recommended for new subsea design. DSM is efficient in organizing the interactions between components and visualizing the shared patterns, and it can help designers to identify the relatively independent modules, and support some tasks such as RAM allocation.

3.3 | Trade-off analysis

Multiple conflict objectives are typical in an engineering design process. For example, the choice of materials to guard against internal corrosion in a pipeline may improve the reliability but may reduce the efficiency of production (ie, OPEX). Decisions are needed to find a balanced solution considering all the assumptions and constraints.

Trade-off analysis is ideally suited to the preliminary RAM analysis, and iterated for several rounds before finding the best possible solution. The relevant techniques for trade analysis have already been discussed in Refs. 42 and 43. Inputs from RAM analysis to trade-off analysis are ideally based on the methods mentioned in Figure 1. However, one should remember that quantification of all the factors identified in the dysfunctional analysis is nearly impossible. Establishing a set of scenarios (eg, accidental scenarios and maintenance

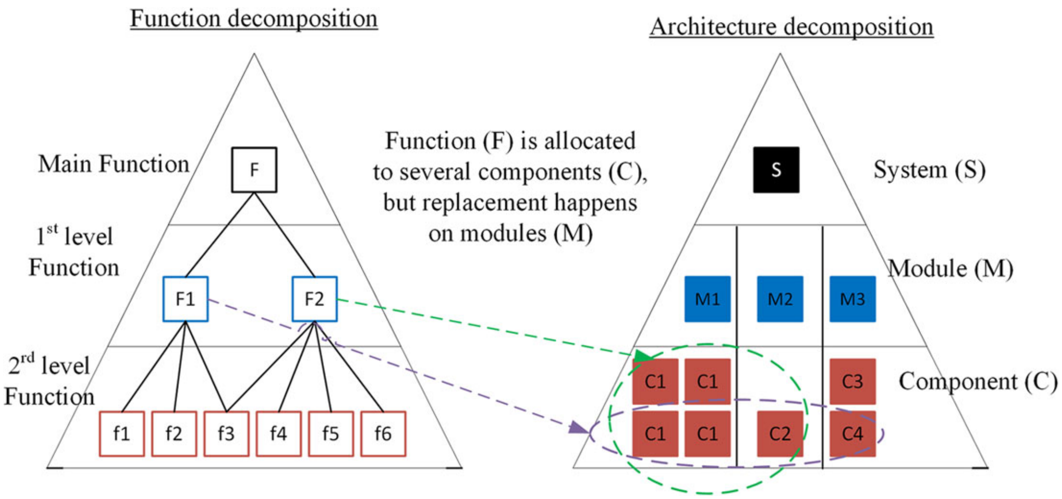

FIGURE 3 Modularity of subsea design

scenarios) is always considered as the supplement to communicate the implications on design. The subjective judgments are largely implemented in such analysis.

4 | RAM-SE FRAMEWORK

This section proposes a new step-wise framework for supporting RAM engineering in new subsea design. The proposed framework, shown in Figure 4, has been named RAM-SE. The RAM-SE framework revisits the current process of framing RAM aspects as given in Figure 1, and proposes several steps integrating both the SE and RAM community.

1. Step 1: *Operational analysis*. The operational analysis introduced here takes place alongside requirement analysis introduced in Subsection 3.1. It covers the identification of interactions, environment, and boundaries of the system for an overall view but offers only an abstract conceptual view of the design. The main objective is to systematically formulate RAM and functional requirements of a system, based on the needs of identified stakeholders.
2. Step 2: *Design analysis*. Hereafter, we use the term *design analysis* to cover both functional and architectural analysis introduced in Subsection 3.2. Design analysis assists in the systematic establishment of the design concept and supports the effort to understand and organize the system structure. RAM-SE uses often-cited methods from the SE community to establish the system architecture. The advantage for having design analysis is to efficiently eliminate the inconsistency caused by the variations in competence, knowledge base, and experience of RAM analysts. The highlighted methods in Figure 4 only consider subsea design environment. The refinement and complement of tools for design analysis should consider following criteria: system complexity and novelty, commonality, availability of software-based tools, plausibility, as well as the correspondence to RAM tools.
3. Step 3: *RAM analysis*. As opposed to the static system structure formulated in design analysis, RAM analysis focuses on the "dynamic" changes within the system structure. Table 2 summarizes the main objectives of the methods included in RAM-SE, and specifically discusses the possible extensions based on systems thinking. After defining the static system structure that explains how the components are distributed and connected, RAM methods are reorganized to simulate how the potential occurrences of events (eg, failure, test, repair…) affect the states of the structure (eg, parts, modules, configuration…). As always, the proposed methods in the framework should be updated or replaced based on the real analysis of needs.
4. Step 4: *Joint concept analysis*. This step is beyond the scope of Figure 1 but an important step that helps ensure sufficient interfaces between the design analysis and RAM analysis and appropriate follow-up actions. This analysis requires the involvement of RAM analysts and designers to accumulate results from discipline-specific analysis and decide on necessary follow-up based on the design implications of analyzed results. Some scenarios generated by RAM analysis may imply modifications of the existing design concept. Constraint-based trade-off checks whether the recommendations made based upon the results of RAM analysis are economically, technologically, and operationally feasible. For example, lifecycle cost analysis, sensitivity analysis, and technology evaluation must be conducted in this step.
5. Step 5: *Communication*. The communication block is centrally located to indicate its importance during all steps of RAM-SE framework. Communication is indispensable to link the separate contributions of design teams. The multiple players involved in the design process must agree on the "disagreement," and *continuously* evaluate the proposals from others. Effective communication should take place to ensure that all stakeholders understand the basis on which decisions are made and the rationale behind. Then the system concept configuration baseline should be based on both the contributions from RAM analysis concerning potential occurrence and damages, and trade-offs related to the system structure formulated in design analysis. Every revision should be registered as a *design risks* until it is validated.

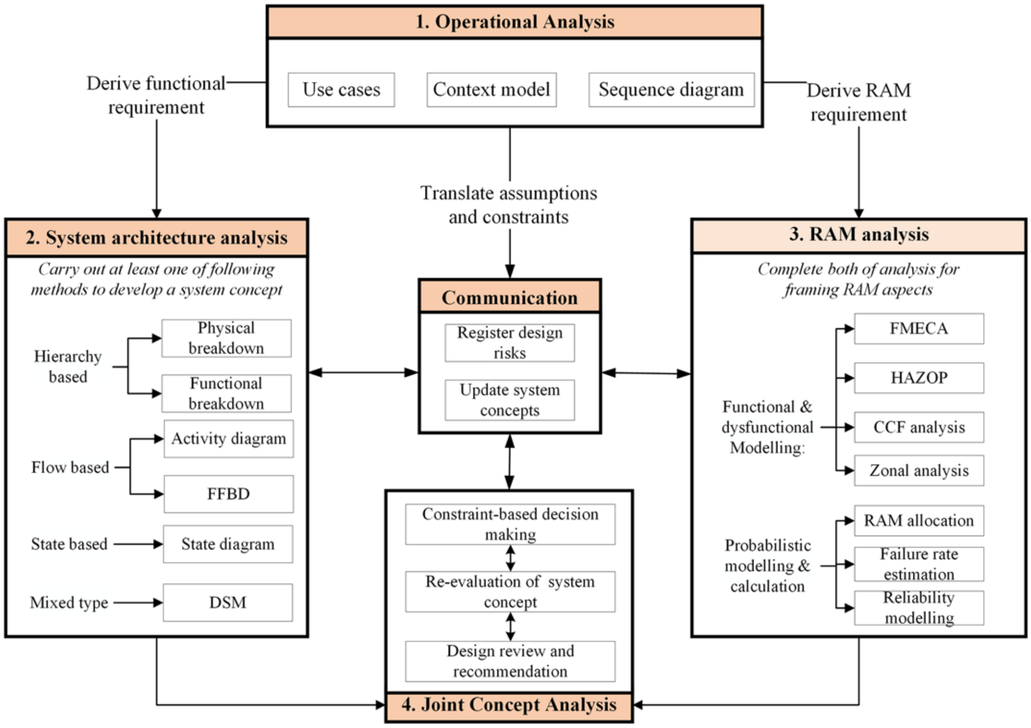

FIGURE 4 RAM-SE framework

5 | CASE STUDY

This section introduces an existing design concept-fiscal metering system. Adaptations must be made considering subsea specific issues.

5.1 | System description

The fiscal metering is one vital part in O&G sector to precisely measure petroleum product exported from delivery to the eventual recipient, a schematic is given in Figure 5. The accuracy and validity of flow measurement are very important for contractual obligation between custody transfer parties (eg, consumer and supplier). Statoil[44] has proposed a design concept for subsea fiscal oil export system using ultrasonic flow meter (USM). The main advantage is that USM has no moving parts so the maintenance requirement is rather low. Figure 5 presents the schematic of this design concept that consists of sampling module and metering module. The sampling module includes sampling devices (QS) and pumps. When the oil exported from subsea storage passes the sampling module, a representative amount of oil is extracted by sample probe. The pumps are installed to provide sufficient power for lifting the sample to the dedicated facility located topside via umbilical. The metering module consists of USMs, pressure transmitters (PT), and temperature transmitters (TT). When the oil is routed into pipeline of metering module, the volumetric flow rate, pressure, and temperature of flow can be measured. USM, QS, PT, and TT can be duplicated for backup use and improvement of monitoring capacity. In this design concept, one metering run contains a duty USM, a master USM, and a spare USM installed in series. The installation of multiple USMs enhances the ability of monitoring the quality of meters and reduces the measurement uncertainty if the resulted measurement is the average of readings from different USMs. The spare USM serves as redundancy to both master USM and duty USM. The metering module is considered as fully functional when two flow meters are available, where the spare meter can serve as duty or master when needed. The control system is located on topside to control the operation of sampling module and metering module. Subsea electronic unit (SEU) is installed to distribute the necessary coded control command to each instrument and collect the data for further transmission to other subsea units or control system. Assuming that duplicated SEUs are installed in the metering section to ensure the long-term stability, all the equipments are connected to two SEUs, so that there are redundant communication passes for metering station.

The validity and accuracy of signals from USM, PT, and TT may lessen after installation due to various factors such as outdated calibration, bad piping conditions, and physical damage of parts. This design concept is assumed to function in spite of failed PT and TT, since the loss of pressure and temperature measurement can be compensated by other transmitters adjusted by calculations. When there is a need to replace the USM, the metering station should be lifted through the rig and recalibrated at the accredited calibration laboratory. Replacement of USM causes an interruption of production as the downtime of metering station is significant.

This design concept includes many parts including PT, TT, valve connection, and tubing that have been qualified for subsea applications, except the USM. The following presents the evaluation of this design concept following the key activities in RAM-SE framework, where the main focus is directed to RAM performance of this design concept and necessary adaptations considering subsea conditions.

TABLE 2 Advancements for RAM methods in SE context

Methods	Objectives	Improvement by SE methods
FMECA	• Uses a basis for detailed RAM analysis and maintenance optimization and planning. • Document the effect of failure on system.	• Systematically identify all operational modes and functions attached to each potential failure modes. • Carry out an extended/revised type of FMECA that is able to involve dynamic aspects of key scenarios, see also the discussion in Ref. 52.
HAZOP	• Review all system sections for abnormal operational situations for all modes of operations. • Identify hazards and hazardous situations that must be encountered for or removed from design concept.	• Be less resource and time consuming. • Instead of brainstorming, focuses on the solid system architecture to evaluate the possible hazardous situations.
Maintainability analysis	• Establish maintenance strategies before put into the operation.[53]	• Incorporate operational and maintenance mode in the design analysis. • Develop the subsea system-specific or module-specific maintenance strategies.
CCF assessment	• Encounter common mode errors that lead to the loss of independence.	• Systematically indicate the possible dependencies among functions and system architecture, such as proximity, overlaps in functionality, and dependencies on resources (eg, data, information, and power supply).
Zonal analysis	• Encounter the malfunction that could result in serious effects on the adjacent components.	• Benefit from building a consistence system architecture that incorporates physical properties.
RAM allocation	• Decide the necessary improvement on component level to achieve the minimum required RAM performance in an optimal way.	• Benefit from building a consistence system architecture that considering modularity or other architecture aspects that may influence the efficiency of component improvement, for example, DSM.
Failure rate estimation	• Provide failure rates and other input parameters for reliability modeling and calculation.	• Integrate a comprehensive set of influential factors on identified failures brought up by design analysis. • Involve subsea designers as the experts via joint concept analysis for judging upon some particular issues, such as the excess of working loads, variations in internal or external pressures.
Reliability modeling and calculation	• Prepare a set of suitable models to be used for reliability and availability analysis. • Identify relevant failure scenarios and evaluate model capacity in light of these.	• Identify the characteristics of architectures (eg, modularization, obsolescence, and degradation) and scenarios/events (eg, delay on repair, imperfect testing or harmful testing, failures of activation of backup) needed to be considered in suitable modeling approaches.

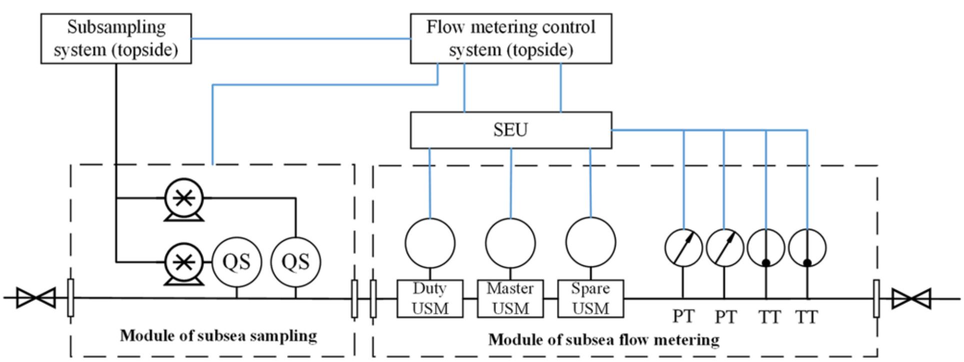

FIGURE 5 Subsea fiscal oil export metering system[44]

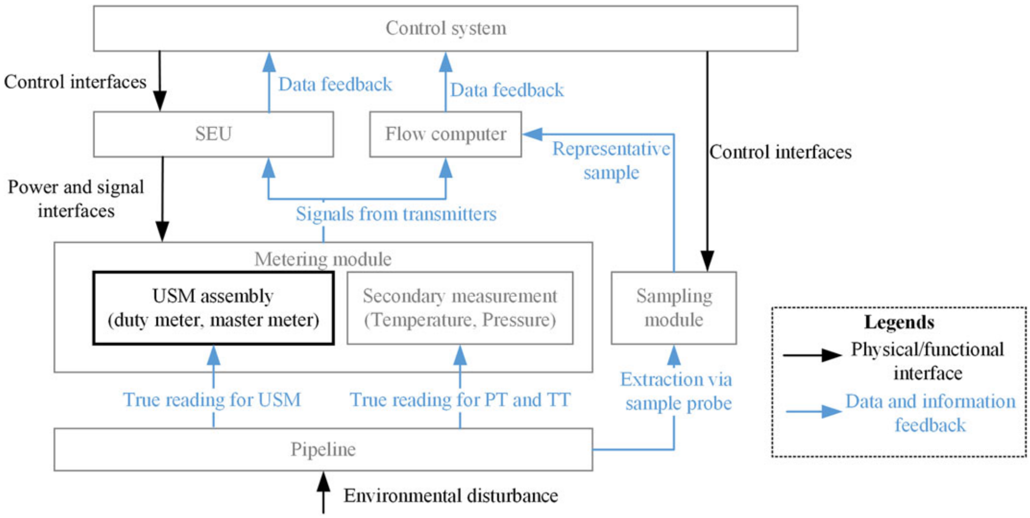

FIGURE 6 Context model for design concept

5.2 | Operational analysis

As shown in Figure 4, operational analysis frames the scope and paves the ground for both design analysis and RAM analysis by abstractly characterizing the life cycle, interactions, and externals of the system in question. Figure 6 presents a simplified context model for describing the surrounding elements (ie, blocks with gray) of USMs (ie, the block with black) and associated operational description and interface, in order to share this core concept agreed by various stakeholders.

The major need from stakeholders is to ensure the accuracy of USM readings against potential deterioration and expected variations from externals. The functional requirements can be elicited by analyzing the interfaces in Figure 6. For instance, factors related to the reading and calculation of USMs are setting of flow computers, readings of PT and TT and on-site master prover. In addition, environmental conditions on metering site (eg, ambient temperature and pressure, humidity), piping arrangement and thickness, and power and signal interfaces with electronic units, all can impact the performance of USMs. These functional requirements result in upgrading or detailing the existing design concept. For instance, the uninterrupted power unit may be needed by the flow computer to avoid possible power outages that cause the loss of data. The Norwegian measurement regulation requires the uncertainty to be less than 0.3% of standard volume. Given the analysis of current laboratory result, the uncertainty of this design concept is estimated to be less than 0.2% of standard volume at 95% confidence level.[44]

Based on Figure 6, it is assumed that each functional channel that fulfills the operational needs requires the signal interfaces between USM and SEU. There are two alternatives for configuration: configuration 1 is that all three USMs are connected to two SEUs, and configuration 2 is that one USM is connected to SEU and other two are connected to another SEU. This said, when there is a failure on a SEU connected to two USMs, the whole metering station loses two signal inputs from the USM assembly. Configuration 1 clearly offers higher operational flexibility as the SEU is fully redundant for each USM, at the same time introducing more complexity to the system due to the increasing number of jumpers. The failure of jumpers can cause jammed, interrupted, or missing signals, which can immediately cause an increase of measurement uncertainty and the need for maintenance. The maintenance of USM assembly includes several tasks such as full isolation of the metering station from the pipeline, removal of hydrocarbon in the units of metering station and lift of whole metering station through the rig. The length of downtime related to maintenance activities of USM assembly is assumed as 2 months (ie, 1440 hours). The faulty SEU and jumpers (ie, flexible connection between units) can be restored in 1 week (ie, 168 hours) after two signals from USM are lost.

Considering the expensive retrieval and intervention, the maintenance requirement agreed by stakeholders is that retrieval for calibration and adjustment is not required during the lifetime of the system (ie, 20 years). Consequently, a degraded performance of the flow metering module may be acceptable, which means operator may not immediately shutdown the flow metering module if two out of three USM outputs are lost. Assuming that uncertainty contributions from each USM are uncorrelated, the resulting measurement uncertainty approximately equals the reciprocal of the square root of the number of meters. For instance, if the measurement uncertainty is estimated as 0.15% for a single USM, the resulting uncertainty for two and three USMs are 0.11% and 0.09%, respectively.

To compare various maintenance strategies for USM assembly, the three possible maintenance strategies are as follows given the considerations from system designer:

- Strategy I: The activities related to maintenance starts immediately when two USM functions are affected, the metering station is shut down during maintenance.
- Strategy II: The activities related to maintenance postpone 1 year (ie, 8760 hours) when two USM functions are affected, the metering station is shut down during maintenance.
- Strategy III: The activities related to maintenance starts immediately when two USM functions are affected. At the end of lifetime

(ie, the last 5 years before intervention), it is acceptable to operate metering station with only one USM.

The three maintenance strategies imply different RAM performances for the given design concept. The insights to maintenance management had not been discussed in the prior versions of the design proposal from Statoil,[44] as it required participation of RAM analysts to build up a RAM model to simulate system responses under different maintenance strategies. This work requires the design analysis to study the system behavior for different configurations and under different maintenance strategies, which is elaborated in Subsection 5.3.

Considering two possible configurations and three different maintenance strategies, there are six cases in total for evaluation. The selection of design concept should consider the maintenance and spare parts costs related to the revealed failure modes and the risk for loss of profit and income related to measurement uncertainty, where all the losses are converted into a monetary unit, that is, Norwegian kroner (NOK). The result is briefly discussed in Subsection 5.5.

5.3 | Design analysis

Figure 7 presents different phases (retrieval, normal operation) in the life cycle of USM assembly and associated state transitions. In Figure 7, transitions including *component failure of USM*, *prepare for retrieval*, *shutdown and retrieval*, and *restoration* receive the main focus. The system is initially in the working state, where the measurement uncertainty is 0.09%. When one USM is lost, the system reaches minor degradation state and the measurement uncertainty is increased to 0.11%. When two USMs are lost, the system reaches the major degradation state and the measurement uncertainty is increased to 0.15%. When the system reaches this state, the maintenance event may be planned immediately (strategy I), or postponed with acceptance to operate under severe degradation (strategy II), or ignored, when in the later phase of operation (strategy III). This said, the condition for transition "*prepare for retrieval*" varies based on maintenance strategies. When all USMs are lost, the system must shutdown and prepare for maintenance immediately. After maintenance, the faulty USM are replaced (ie, as good as new) and metering station is restored to working operation state. The state diagrams for SEUs and jumpers can be established in the similar fashion. The functional dependencies between SEU, jumper, and USM can be established by synchronizing the transitions, see details in Subsection 5.4.

The state diagram clarifies the possible events, system states and associated transitions, which helps RAM analysts to correctly define the relevant modeling elements, that is, the required actors of normal operation and maintenance and conditions for retrieval processes. The functional dependences can be highlighted by employing such state space modeling, which is beyond the traditional analysis for hierarchy based analytical reduction such as functional trees or physical breakdowns. It may be noted that state-diagram is one of many methods to complete design analysis. The same information can be obtained using flow-based diagrams such as FFBD and activity diagrams.

The architectural aspects are obtained through design analysis in order to provide insight on the causes and consequence of hazards and the suitability of associated countermeasures. The physical attributes (eg, dimensions, materials, component quality, manufacture process, and locations) may impact system behavior. For instance, the location of metering should be distant from control valves, as the noise of valve operation can interfere with USM measurement. The identification of architecture for given system concept assists in following RAM analysis, especially for dysfunctional analysis as shown in Subsection 5.4.

5.4 | RAM analysis

RAM analysis starts with dysfunctional analysis as indicated in Figure 4. Here, FMECA is selected as hazard identification methods, and the part of the FMECA are presented in Table 3. The failure rate for each failure mode is shown in the last column of Table 3, which is estimated based on the original data provided in the recognized database for subsea application OREDA[45] together with expert judgments about influencing factors for each failure mode. The reader interested in a detailed specification for criteria for selecting influencing factors and procedures for failure rate estimation can refer to Brissaud et al.[46,47] In this case study, only critical failures that lead to the loss of performance are taken into account, where the incipient failures or degradation are removed from scope.

With the information in Table 3 and the system concept developed in design analysis, it is possible to construct a RAM model. The general assumptions and constraints are made on the basis of both design analysis and operational analysis as follows, and they are valid for all cases to be evaluated:

- For each USM, SEU and jumper only consider two states: faulty and working.
- The sensor lines are continuously checked, thus the delay for detecting failures on jumper and SEU can be ignored.
- All components are considered as good as new after maintenance. The activities of maintenance are considered as perfect, thus no adverse effects are induced.
- Ideally, the subsea operator does not expect any retrieval during the operation until the metering system cannot perform the function as intended. Assuming that restoration duration $\omega = 8$ hours and mobilization time $\eta = 1440$ hours (ie, 2 months), and the intervention will be carried out after 20 years of installation (ie, 175 200 hours).

There are many suitable approaches for the following quantitative analysis, for example, Petri nets. Figure 8 presents partial Petri nets for case 1 (ie, configuration 1 following strategy I), where state-transitions in Figure 7 are mapping into Figure 8 by the *predicates* and *assertions* in the Petri nets. Predicate (represented by "?") is a formula to validate the transitions, and assertion (often represented by "!") is a formula to update the variables after the associated transition is fired.[48] The instruction for constructing Petri nets model can be found in articles of Signoret et al[48] and Signoret.[49] The synchronization of transitions indicates how each USM input is considered as valid or invalid given the states of USMs, jumpers, and SEUs. The number of valid USM input is used to determine when to start maintenance and the uncertainty increment. For instance, case 1 follows maintenance strategy I

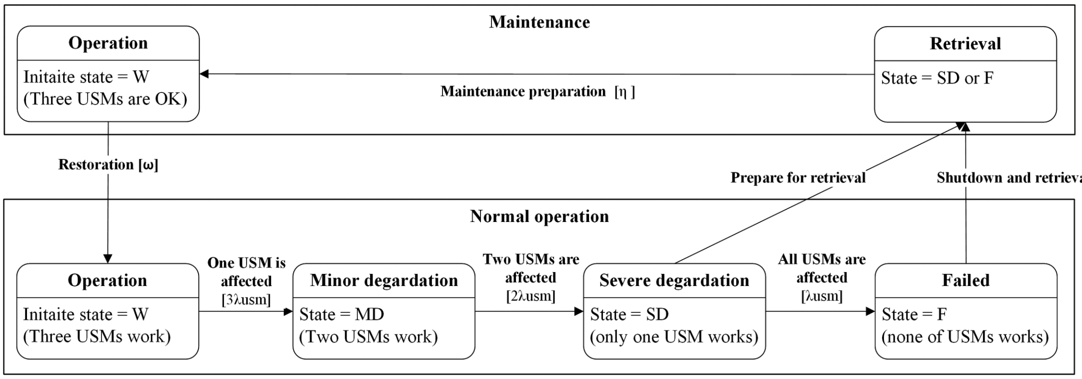

FIGURE 7 State diagram for USM assembly

TABLE 3 Selected results for qualitative RAM analysis

Unit	Failure mode	Failure mechanism	Failure rate (per 10^6 hours)
USM	Abnormal instrument reading	Changes in flow profiles, ultrasonic noise, high velocity (eg, turbulence)	0.82
	Erratic output	Transducer failure, instrument or material failure	0.6
Jumper	Lose of connection	Water intrusion or loss of resistance	0.35
SEU	Control failure	Flawed control algorithm (fault signal/alarm), leakage, software failure	3
	Other types	–	1.05

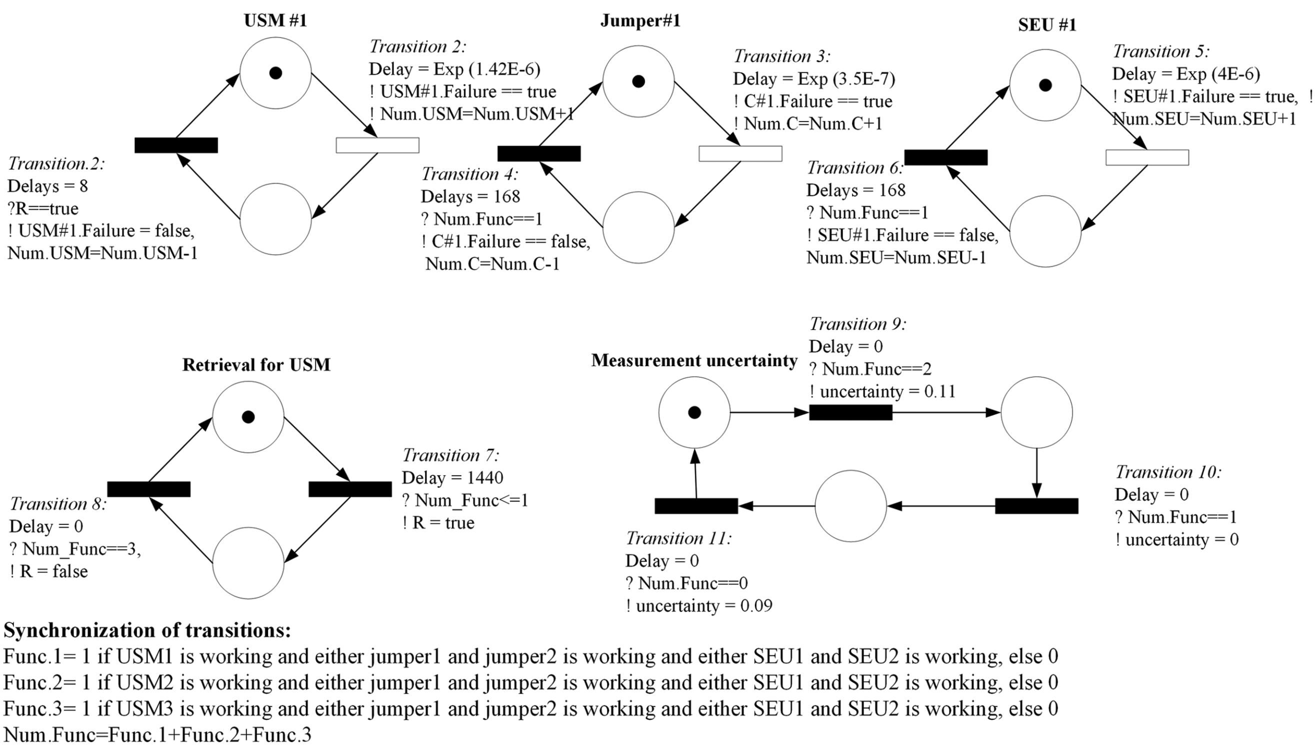

FIGURE 8 Petri nets model for case 1

and then the maintenance of USM assembly is planned when two valid USM inputs are lost. Petri nets model of cases 2-6 are constructed in the same way.

The computation for RAM modeling is completed by the software GRaphical Interface for reliability Forecasting.[50] The simulation run is set to be 100 000 to get the result with confidence. The downtime and retrieval frequency of cases 1-6 is reported in Table 4 and measurement uncertainty of cases 1-6 is illustrated in Figure 9. From Figure 9 and Table 4, one may notice the following points:

- The downtime reported in Table 4 not only considers the retrieval frequency of USM assembly but also the downtime to replace

TABLE 4 Downtime and retrieval frequency for cases 1-6

Case number	Expected downtime (hours)	Expected retrieval frequency
1. (Configuration 1, strategy I)	249	0.1733
2. (Configuration 1, strategy II)	225	0.1563
3. (Configuration 1, strategy III)	157	0.1092
4. (Configuration 2, strategy I)	418	0.2127
5. (Configuration 2, strategy II)	402	0.1988
6. (Configuration 2, strategy III)	391	0.1923

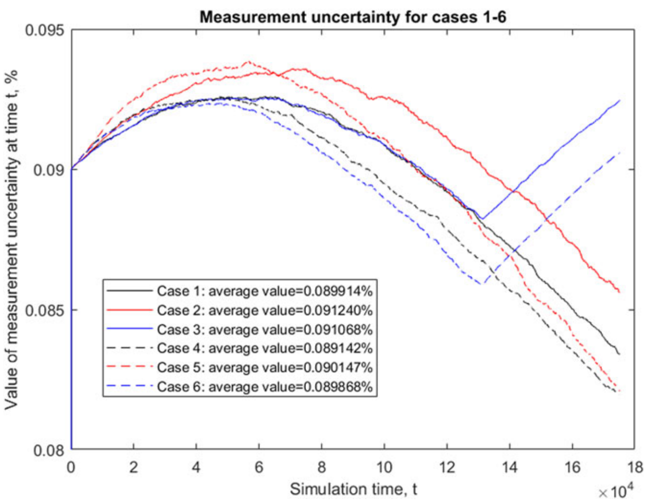

FIGURE 9 Measurement uncertainty for cases 1-6

jumper and SEU. As a result, configuration 2 (cases 4-6) has much more downtime than configuration 1 (cases 1-3).

- Applying strategy II (cases 2 and 5) needs less maintenance than applying strategy I (cases 1 4) by paying the price of allowing an increase in measurement uncertainty.
- Applying strategy III (cases 3 and 6) results in the increment of measurement uncertainty in the last 5 years of lifetime (ie, the turning points in Figure 9) as the system is allowed to operate with single USM. The downtime due to maintenance is significantly reduced compared to strategies I and II for configuration 1 (cases 1 and 2), however, not for configuration 2 (cases 4 and 5).
- Configuration 2 (cases 4-6) has more maintenance needs than configuration 1 (cases 1-3), and the maintenance need does not vary too much given the different maintenance strategies. As result, the measurement uncertainty is decreased.
- The peak value of measurement uncertainty for configuration 2 (cases 4-6) comes earlier than configuration 1 (cases 1-3). The reason is that configuration 2 loses flexibility as the SEU is not fully redundant for each USM.

5.5 | Joint concept analysis and communication

The objective of joint concept analysis is to present some common themes that cannot be solved or considered by any individual engineering discipline. Table 5 presents some major considerations derived from the selected analysis in RAM-SE framework. These considerations may either require designers to reevaluate the system concept, or RAM analysts to reconstruct the RAM model to achieve more realistic design implications. For example, the maintainability analysis shows that it is necessary to consider the separation between measurement instruments and sampling systems. Therefore, DSM is required for design analysis for mastering the interaction between these two modules and subsequent RAM analysis. Another example could be CCF assessment. The series connection of duty USM, master USM, and spare USM can introduce the common mode errors due to the same design, installation, and function. In this case study, common failure mode for USMs is mainly the deposits, for example, wax. The designer indicated that the implemented measure is to heat the flow, thus prevent wax formation.[44] Such communication should be documented and registered. If the related measure cannot be implemented given other design constraints (eg, space and cost for heating strategy), then the effect of CCF should be incorporated in the calculation and modeling and the RAM model in Figure 8 will be updated to introduce the associated events.

The constraint-based decision making, such as lifecycle cost analysis, should be used to select the cost-effective alternatives for this design concept. The result of previous RAM analysis gives indications for two cost functions in lifecycle analysis: the total cost for maintenance including resource mobilization and spare parts, and the profit loss due to system downtime and measurement uncertainty. The selection criteria for costs functions and procedure of cost analysis can follow the existing standards such as NORSOK I-106[51] or the internal procedure of the oil company. For instance, in this case study, the net present value of oil in subsea storage is assumed as 200 billion NOK and direct costs to replace the USM assembly is estimated as 25 million NOK. The result of cost analysis shows that case 1 saves the most. Compared to the most costly case 2, case 1 can save 4.03 million NOK in stakeholder's favor during the operation of 20 years, without considering the purchase order cost, project costs, and technology development costs.

Communication plays an essential role in any engineering process as illustrated in the RAM-SE framework. What is meant by communication here is not documenting the numerical results that may fall into "playing a number game" but *telling the story* based on a consistent background. In this case study, by performing operational analysis and design analysis, RAM analysts can easily identify what is beyond the normal operations viewpoint and clarify the assumptions and simplifications for RAM modeling. The result of RAM modeling is thereby

TABLE 5 Considerations for USM design

Analysis	Key results and comments	Updated design constraints or required follow-up analysis
Zonal analysis[3]	• The noise of control valves can influence USM performance. • PT installed in the close location may cause the turbulences that influence USM performance.	• Develops strategy and associated equipment to reduce the effect of noise if cost and space allows, for example, noise trap or bends in piping. • Keep the necessary distance between PT and USM, for example, at least three diameters of downstream.[54]
CCF assessment	• The series connection of USM offers better quality monitoring capacities but common mode errors of USM are introduced, which can influence the performance of USM and calibration process.	• Develops strategy for eliminating the potential factors on CCF, for example, improve manufacturing process and upgrade on-site calibration process by taking CCF into account, see also the guideline in IEC61508.[55] If not, CCF must be incorporated in relevant RAM modeling.
Maintainability analysis[53]	• The sampling system has higher maintenance needs than metering module.	• The sampling system can be in a separate module to offer better RAM performance if cost and space allows.

situated in a well-defined context to support the decision making in a design process. In this case study, by starting with operational analysis, the issue to be investigated is specified: the impact of maintenance strategies and configurations. Design analysis identifies the functional and architectural aspects behind the issue: the system behavior (ie, states and transitions) of selected configurations under different maintenance strategies. The information can be used to construct a RAM model and the numerical results through simulation can be used for selection of design alternatives. It is important to remember that the using RAM-SE framework is never to prove that models are close to the reality but to ensure RAM analysis are illuminating and useful to consider the design implications when the context is defined properly.

6 | CONCLUSION

It has become apparent that incorporating RAMS aspects as early as possible gives several advantages in form of engineering efforts and budgets. Many companies involved in subsea development have their procedures for framing RAM in design but they still claim that they are not adequate. The similar problem already exists in many industry sectors such as nuclear, satellite, and aviation, where the problem is further amplified by the complexity of design solutions. This article selects subsea design as the starting point. Analysts in this context, often dive into RAM analysis before correctly stating the system concept. Development of a system concept by RAM techniques relies on competence, experience, and the knowledge base of analysts, which often results in inconsistency and misunderstandings. Without a more holistic framing, RAM in subsea design has limited possibility to give systematic insight of the design concept, making it necessary to integrate other disciplines to complete industry practice.

This article discloses the link between the RAM discipline and SE. Through the analysis, the authors propose a RAM-SE framework to connect the concepts and models used by these two disciplines, in light of specific issues encountered in subsea design. The framework identifies the benefits that RAM engineers appreciate the SE methods that can support RAM and vice versa. Analysis based on the SE suite of tools could be a prerequisite for specialty analysis like RAM analysis to reduce the risk of working from an inconsistent and incorrect system concept. Then, system designers can correctly capture the indications derived from RAM analysis conducted in a systematic and iterative manner. The case study demonstrates how the new subsea design was evaluated from different point of interests using the RAM-SE framework. Although the selected case is quite restrictive and simple, it can be used to illustrate the challenges encountered when framing RAM aspects of subsea design, such as functional/physical interactions that can result in complex maintenance and test strategies.

This framework serves as a baseline for further refinement in order to direct future effort to improve the process of framing RAM in subsea design. The process described by the RAM-SE framework is highly simplified and idealized. First, RAM-SE framework only restrictively discusses interlinks between these two disciplines in light of models with high acceptance and commonality in each community, for example, SysML. This said, the design analysis and RAM analysis are conducted in sequence thus some overlaps may be latent as system theory or system thinking is indirectly placed in conducting RAM analysis. Additional research could develop RAM methods directly using system theory. One such pioneer work has been completed by Leveson[15] who use system theory to create a new accident model used for safety analysis. However, similar work has not been found in RAM domain yet. Moreover, the application is here only demonstrated within subsea design. One remaining work of this article can be to expand the analysis to consider other sectors to enrich the content of the proposed framework and hopefully bring ideas for transfer of knowledge from this article to other domains of interest. Our suggestion for improving this framework is to further test the proposal against an industry-size case.

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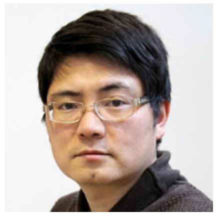

Yiliu Liu has been an associate professor in the Department of Production and Quality Engineering, Norwegian University of Science and Technology (NTNU) since the beginning of 2013. Before that, he had worked as a post doctor fellow in the same department from 2011 to 2012. His main research interests include system reliability and resilience engineering, safety critical systems and risk management. Dr Liu is very active now in the relevant fields, with publishing 3 book chapters and more than 60 peer-reviewed papers (28 on international journals). Most of the publications appear in the recent 5 years. He is also serving the academics as the reviewer for more than 20 international journals and the technical committee member for more than 10 international conferences. Dr. Liu is the coordinator and main lecturer for two master courses in NTNU, and he also serves as the director of the international master program of RAMS (reliability, availability, maintainability and safety). He has deeply involved in several research projects funded by Norwegian research council, NTNU and other institutions. In addition, Dr. Liu has a robust research network with universities in different 10 countries.

Mary Ann Lundteigen has been a professor in Department of Mechanical and Industrial Engineering since 2011, with a period with DNV-GL as Principle Engineer from 2012-2013. She has a PhD in reliability of safety-instrumented systems (2009), and a MSc. in engineering cybernetics (1993). Before starting on her PhD, she worked for several years in industry, including as instrumentation engineer (onshore) and automation and electrical supervisor (offshore) in Phillips Petroleum, automation leader at the factory of Nidar, and senior researcher at SINTEF, department for applied cybernetics. Her main research focus and interest concern functional safety and reliability of safety-related electrical/electronic/programmable electronic (E/E/PE) systems. She is also a member of IEC 61511 committee who maintains the standard on functional safety for process industry sector. As a co-director and responsible for reliability subject in the 8-year research centre on subsea production and processing (SUBPRO, see http://www.ntnu.edu/subpro), she has extended her research to cover reliability, safety, and condition-based maintenance of systems with particular demanding environmental and operational conditions, such as subsea systems. Lundteigen has a long-lasting and extensive contact network in Norwegian industry work, due to involvement in SINTEF projects over several years, many of the m through the PDS forum (http://www.sintef.edu/pds). She has more than 50 publications peer-reviewed papers, including around 20 papers in international journals. She has also been contributing to a high number of studies for industry companies.

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