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Model-Based Maintenance Planning and Analytics for Oil & Gas Offshore Systems

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Abstract. Good planning and data management have become increasingly essential for companies in the oil and gas industry, as well as in other complex and task-dependent industries. Digitalization has, for that reason, become more prevalent. It has allowed businesses to re-evaluate how they operate and set up their goals and strategies, allowing them to build resilience that has helped them harness data to gain better insights and analytics. The oil and gas industry could use a more holistic model-based approach to planning integrated maintenance. This may be accomplished using model-based systems engineering (MBSE) principles adapted to the oil & gas industry. MBSE usage for maintenance and test concepts can be further enhanced by using analytics to deal with failure rates of different types of components. Calculations based on design and operational experience data can improve overall maintenance planning and management. On/off valves, as defined in the international standard, ISO 14224, have various applications in industrial processes and are commonly used in safety systems. Therefore, on/off valves have been selected for the scope of this manuscript. The analysis presented in this paper indicates that utilizing MBSE in maintenance planning and management, together with data-driven analysis, could make maintenance more efficient and streamline the process.

Keywords. Model-Based Systems Engineering, Maintenance Planning, On/Off Valves, Failure Rates Analytics.

Introduction

Maintenance planning and scheduling have become essential strategies for improving efficiency in recent decades. According to Palmer (2019), implementing proper planning and scheduling can improve productive maintenance time from 25% - 35% in an organization without planning to 50%, doubling the ability to get work done. Brad Peterson, founder and president of Strategic Asset Management Inc (SAMI), argues that a significant problem in maintenance improvement in most plants is that the planning discipline is difficult to establish and maintain because it must be developed and nurtured carefully (Palmer, 2019). A sample provided by Nyman & Levitt (2010) shows that 35% of direct work is performed in reactive mode, in contrast to 65% of direct work in proactive mode. They argue that organizations have seen a significant amount of technician capacity loss due to the lack of proper planning regarding maintenance jobs when these are primarily reactive rather than proactive. This argument gives an apparent reason and confirmation why establishing a planning, scheduling, and coordination function is vital for maintenance.

An essential part of maintenance planning and handling is handling safety-related parts of the enterprise, such as on-off valves. When used in a safety system, the valve is often part of a safety instrumented system (SIS) comprising sensor(s), logic solver(s), actuator, and the valve.

Several standards govern the operation of SIS, including the IEC (International Electrotechnical Commission) standards (IEC 61508, 2010), (IEC 61511,2016), OLF-070 (NOG GL-070, 2018), etc. These standards require that the SIS can fulfill its required Safety Instrumented Function (SIF) throughout its lifetime, and the operator must be able to demonstrate compliance during the design/installation phase and operation. Compliance with the standards, as mentioned above, comes in the form of estimating the probability of failure on demand, which gives the average probability that the SIS will not function when required. Other performance indicators or targets, such as the expected number of failures or failure fractions, can also be used. In the early stages of design, it's usually enough to use the reliability data from the original equipment manufacturer (OEM) to show that the design meets the required standards. However, following installation, it is necessary that appropriate follow-up activities are carried out and that compliance is maintained throughout the operation phase.

All the above must be considered part of the planning and maintenance management.

Well-performed maintenance involves maintenance planning, and even though planning is said to be one of the most time-consuming activities, if an organization requires anything done effectively and efficiently, it needs to implement a good planning and scheduling strategy. When done correctly, maintenance planning provides several benefits, such as a safer workplace, a more proactive workplace culture, an increased asset life, lower equipment downtime, and increased maintenance productivity with decreased costs. Eventually, having a robust maintenance plan strengthens the equipment's reliability, increases profitability, and improves production (Kovacevic, 2023).

System engineering principles applied to maintenance

To create a holistic and integrated maintenance plan, this paper suggests using systems engineering (SE) principles and technological methods as a starting point since this can facilitate automation and data-driven maintenance. The International Council on Systems Engineering (INCOSE) defines systems engineering as a transdisciplinary and unifying approach that enables the use, understanding, and retirement of engineered systems by applying systems concepts, principles, and methods from science, management, and technology. (INCOSE, n.d). “Engineered systems” may be composed of any or all of people, products, services, information, processes, and natural elements. Using the system engineering principles will enable the creation of an integrated model with the help of model-based systems engineering (MBSE), which INCOSE defines as “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”. MBSE’s objective is to create and exploit domain models as a primary way of information exchange instead of a document-based information exchange (Arnold, R. D., & Wade, J. P., 2015).

A system model using MBSE will provide an efficient way to analyze, update, and communicate system aspects and, at the same time, significantly reduce and even eliminate the dependency on traditional documents. Its objective is to improve communication, increase the ability to manage system complexity, enhance knowledge capture, improve product quality, and improve the ability to teach and learn system engineering (SE) fundamentals (Carroll & Malins, 2016). This approach will produce an integrated system model with multiple views connected to multiple discipline models across the life cycle, from the system level to the component level. The model will then be an authoritative source of information. In the context of maintenance planning, utilizing system engineering principles and the formalized application of modeling using MBSE will enable the creation of a holistic model to support integrated maintenance planning. MBSE may also help connect equipment conditions and updated test intervals with the maintenance plan to improve stability and predictability. It will support planners, schedulers, and all relevant stakeholders better to understand the maintenance plan and its associated risks.

Maintenance Planning Techniques

(Gackowiec, 2019) identified five central maintenance policies: Corrective Maintenance (CM), preventive maintenance (PM), condition-based maintenance (CBM), predictive maintenance (PdM), and proactive maintenance. (Kobbacy et al., 2008) They also mentioned the same groups, including opportunity-based maintenance (OBM). Prescriptive maintenance goes beyond PdM and can support decision-making, planning, scheduling, and control systems (Ansari et al., 2019).

Maintenance and Test Concepts (MTC): An MTC is a company-specific Generic Maintenance Concept (GMC) often captured as a document. It is developed at the design phase of an asset and updated over the asset's life cycle to suit the asset's and stakeholders' operations and maintenance needs. Most oilfield operators on the NCS (Norwegian Continental Shelf) use MTCs in their maintenance management work processes. It contains detailed maintenance requirements for an object type, references to other company documents, and the standards that are relevant for developing its framework.

Document data cannot be traced or connected to sensor data or analysis and simulations. To enable data-driven maintenance, a holistic modeling approach with all relevant relationships to failure modes, barrier elements, and testing requirements is required.

Many maintenance activities are primarily corrective and calendar-based; reactive maintenance is mainly based on manual processes, which means there is usually a significant backlog and processing time related to barrier integrity (IOGP, 2016) and management of activities. Implementing a comprehensive and holistic plan that visualizes all maintenance activities is suggested, as planning is ordinarily fragmented and unstable, with low predictability. Risk analysis for maintenance planning still needs to be established, meaning that the lack of a proper plan can cause risks and challenges. Not having a comprehensive and holistic maintenance plan means that stakeholders cannot visualize all maintenance activities related to each asset entirely; risks can, therefore, be overlooked, some of which could be risks related to workload, manpower capacity, and simultaneous operations (SIMOPS) taking place, not just within maintenance but also other departments. Additionally, there is the risk related to material availability, bed capacity offshore, and the critical path of the plan (a technique that identifies tasks necessary for completion. In other words, mapping out essential or critical tasks required to complete a project). Along with the above, the budget must be aligned with the plan to determine how much is being spent, creating financial stability that allows the organization to focus on its goals and key performance indicators (KPI)

In the oil and gas industry, production, operation, and maintenance tasks are carried out daily during offshore operations; this is why planning within the oil and gas industry is done at various levels, including tactical, strategic, and operational (Sarshar, 2018).

NORSOK Z-008 (2017) provides a short description of the steps that are typically involved in maintenance management. Maintenance management is illustrated as a work process where products are produced with low health, safety, and environmental (HSE) risks and high production performance. The standard suggests a basic model as an industry best practice.

This involves:

- Manage resources by identifying organizational structure, materials, IT systems, and documentation needs.
- Oversee the maintenance work process, including setting goals, developing programs, planning, and execution. Continuously verify and adjust these elements based on work reports and performance analysis, as well as identify opportunities for improvement.
- Analyze the results to perform risk analysis and production assurance.

Goals and requirements: These goals should focus on the following:

- Risk, production, cost, regulatory requirements, and technical conditions of the facility.

Maintenance strategies must be defined for each asset.

Maintenance program: Failure causes, modes, and mechanisms that significantly affect safety and production must be identified along with the risks to establish a maintenance program. The activities typically involved are:

- Carrying out consequence classification for functions.
- Equipment associated with high-consequence failure modes, failure causes, and their corresponding maintenance programs must be documented, developed, and fully traceable.
- Reliability requirements for the functions must be defined, along with a testing program to maintain functionality.
- The criteria for updating the maintenance program should be based on experience, failures, and time. Failures of safety-critical systems must be analyzed, and the program must also be updated regularly.

Planning: A maintenance plan should consist of a structured set of tasks that include the activities frequencies, procedures, resources, and the time required for maintenance. It also includes budgeting, day-to-day planning, prioritizing, and long-term planning. The activities typically involved are:

- Competent personnel should execute the work according to the plans, procedures, and relevant work descriptions.
- A plan that verifies the work's quality must be in place.
- The condition of the equipment must be stated after the work is done.

Reporting: This involves quality assurance and collection of data, which should be presented to the maintenance management and department as indicators. Technical integrity data for barrier functions must be reported and known at each level to help decision-making. The activities typically involved are:

- A set of KPIs that follow up and monitor performance.
- KPIs' performance outside of set goals must be reported and acted upon.
- A set of performance data should be compared and reported.

Analysis and improvements: This includes the examination of unwanted incidents and historical maintenance data through methods such as root cause failure analysis and trend analysis. The typical activities involved are:

- A defined analysis process that addresses trigger values, responsibilities, and analysis techniques must be established.
- The analysis process must include the extent to which the maintenance program handles risks, key components, performance requirements for each system, and maintenance effectiveness.
- Actions should be implemented, and the effect of the identified improvements should be monitored.

Materials (resources): These include the tools, consumables, and spare parts necessary for maintenance.

Documentation (resources): Includes maintenance data organized into a database where plans, technical information, and historical performance are available to decision-makers and users. This documentation must be updated, controlled, and available to relevant users.

Management and verification: The management team must follow all maintenance work processes. The activities typically involved are:

- Leaders must define the maintenance area's responsibilities, qualifications, and role requirements.
- Leaders must have a solid understanding of risk-based maintenance management and ensure adherence to the main workflow.
- Leaders must follow defined KPIs and act upon deviations.
- Leaders must institute and plan audits of contractors, suppliers, and the organization.

Risk level (technical condition): This reflects the outcome of the asset's operation and maintenance history.

Production assurance (technical condition): This results from the activities implemented to maintain and achieve a performance optimum in terms of the overall economy and, simultaneously, consistent with the conditions of the framework.

Cost (technical condition): Related to corrective and preventive work, consumables, and spare parts, in addition to loss or deferral of production under the maintenance function.

An organization should perform maintenance tasks and activities to fulfill the set requirements. Overall, the process shows the resources, management of the maintenance work process, and results, detailing a set of sub-processes and products.

The above requires creating an operational plan, a work order plan, and work permits. The operational plan includes the most crucial operations, modifications, and maintenance information. It should consist of significant tasks within HSE, tasks requiring external resources, additional bed capacity, production-related tasks requiring shut-down, monitoring, and tasks requiring coordinated actions such as heavy lift operations. The goal of such a plan is to ensure that the risk profile of the installation is acceptable—both in terms of major accident potential and production. It also ensures that decisions and actions from the main plan are carried out; that there is effective coordination around priorities, resource management, and risk levels both within and across installations, that a structured framework is in place for lower-level activities (top-down planning); and that the activity level on the installation is carried out within the defined framework conditions.

This can be further detailed as follows:

- **Operational plan:**
  - Define framework conditions: Communicate decisions and activities from the main plan and establish installation-specific framework conditions.
  - Quality assurance plan data: Risks that can affect the accomplishment of activities shall be identified and reported using relevant risk management tools.
  - Establish plan: The planner establishes the operational plan based on the quality-assured plan data.
  - Analyze plan and risk: Analyze the plan and propose alternatives if deviations exist from framework conditions.
  - Coordinate plan and risk: Prepare for planning meetings, identify alternatives, and assess economic impacts.
  - Perform operational plan meeting: Prioritize the activities on the plan to decide on measures and approve the plan.
  - Adjust plan: Adjust the plan based on the activity level.

- Distribute plan

- **Work order plan:**
  - Identify the need for a work order (WO): Assess the criticality of the work needed by considering the increased risk to the plant's operation.
  - Establish WO: The work order describes what should be done and what equipment and resources are required.
  - Review the work order and update its status—for example, when material requirements are fulfilled or when scheduled dates approach readiness for the next planning phase. This review should also account for major accident risks, as these may affect the needed resources.
  - Review status for WO plan: Coordinate WOs that are not on plan and provide input to these WOs.
  - Manage WOs for the new plan: Evaluate the last active WO plan and the status of its WOs, coordinate these, and provide the status of the active WO plan.
  - Date WOs on resource needs: Assess whether the plan can be completed within the available time and with available resources.
  - Approve WO plan.

- **Work permits:**
  - Establish a day plan: Based on the WO plan, make a work permit (WP) plan for the next few days that includes which activities to carry out and when.
  - Establish and apply WP: Ensure that the work can be performed safely and (as part of that) to ensure that the work can be performed safely simultaneously with other activities (coordination).
  - Perform safe job analysis (SJA): A safe job analysis is a systematic, step-by-step review of all risk factors associated with a specific work activity or operation. Its purpose is to identify potential hazards in advance and implement measures to eliminate or control them during both the preparation and execution phases.
  - Approve WP and day plan.

Stakeholder mapping

Table 1Table 1: Key Stakeholders with Mapping illustrates the key stakeholders identified to elaborate the planning model. The table has been color-coded to present how the stakeholders relate to the interest versus influence matrix shown in Figure 1: Interest Versus Influence Matrix (Jensen, 2023). The stakeholders have been ranked based on their influence and interest in having a more digitalized planning approach to maintenance. The influence factor defines the degree to which the stakeholder can influence the achievement of the planning approach; the interest factor, on the other hand, establishes the degree to which the stakeholder has a perceived interest in achieving the goal. Figure 1 shows the matrix of stakeholder interest versus influence; it shows which category each stakeholder identified falls under: "keep informed," "manage closely," "minimal contact," or "keep satisfied." (Gardiner, 2005) argues that each stakeholder should be addressed differently; for instance, stakeholders that fall under the category "keep informed" are the most challenging to manage; even though they present a low interest in the project, they can have significant influence. Stakeholders under "manage closely" are crucial players, and their reactions should be considered. The "keep satisfied" stakeholders must be monitored and updated if their position in the matrix changes (Gardiner, 2005). The stakeholder roles listed below are considered relevant in an oil and gas organization for the scope of this paper. An asset can be composed of one or several oil and gas fields located in a defined area in the context of this research.

Figure 2 presents an onion model where stakeholders are divided into separate categories based on their proximity to the system. Stakeholders close to the system will often have more direct needs from the system, while regulations and standards usually represent the other stakeholders in the broader environment. The colors in Figure 2 are described in Table 1. Here, the darker colors illustrate the proximity each stakeholder has to the system, which means that the darker the color, the nearer the stakeholders are to the system. The score, ranging from 1 – 10 in Table 1, is associated with the level of influence and interest of the stakeholders related to the system. The colors used here are indicative and not intended for standardized usage.

Stakeholder	Influence	Interest	Owners	Users	Technical & business support	Wider environment
Asset Integration Manager	8	10				
Asset Scheduler	7	10				
Maintenance Engineer/ analytics	7 - 8	10				
Asset Maintenance Manager	9	10				
Data Management & Governance Specialist	5 - 6	10				
Technology Engineer	4	10				
Maintenance & Integrity Engineer /SAS	6 -7	10				
Asset Operation Manager	10	10				
Asset Engineering Manager	4	10				
Asset Development Manager	3 - 4	9 - 10				

Table 1: Key Stakeholders with Mapping (Jensen, 2023).

The analysis is inspired by Responsible, Accountable, Consulted, and Informed (RACI) matrix but uses different terms. Any known stakeholder analysis method may be used.

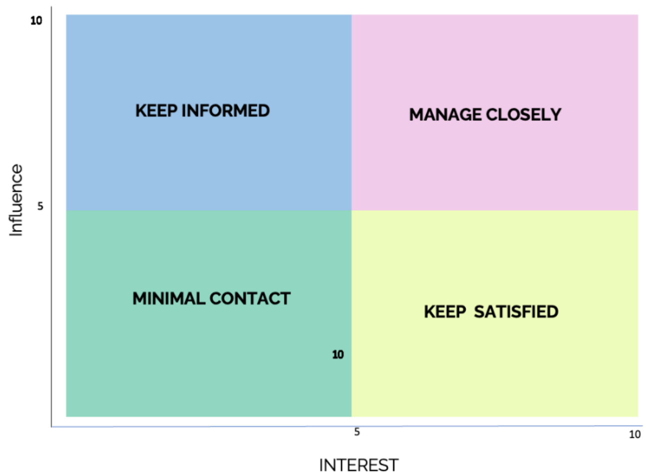

Figure 1: Interest Versus Influence Matrix (Jensen, 2023).

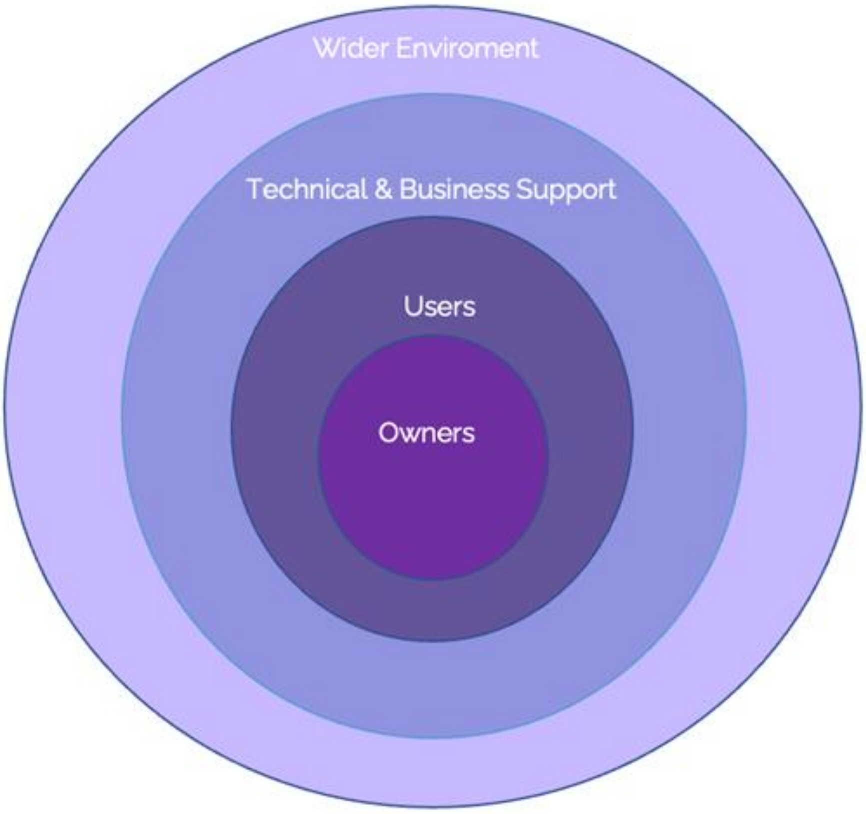

Figure 2: Onion Model (Jensen, 2023).

Documenting The Planning model

A use case diagram has been prepared to model the system's behavior and help capture its requirements. The diagram describes the system's high-level functions and scope and identifies the interactions between the system and its actors. The actors and the use cases illustrate what the system does and how the actors use it, but not how the system operates internally. Figure 3 shows how different use cases interact with one another. Here, the straight lines and arrows between the elements define how the remote element is viewed in association with the text.

In some cases, the connection is assumed to be unidirectional (one arrow) and, in other cases, bi-directional (no arrows on either end). The actors have been established from the findings and results of the stakeholder interviews. The associations have been stereotyped, showing that the influence and interest values retrieved from the thesis findings and company processes have been included as values for the connections to the use cases. A possible annual maintenance planning model has been prepared by establishing the different characteristics of the maintenance activities, as illustrated in Figure 4.

The proposed modeled annual maintenance plan defined here uses SysML (Systems Modeling Language) (OMG, 2019) and UAF (Unified Architecture Framework) (OMG, 2022a, 2022b, 2022c) stereotype definitions and should be viewed as a first draft. The basis of this model is the UAF element called the information element, essentially a set of structured information that connects many existing elements in the overall model, which are intended to be used as a living element.

Not all elements and information will exist when the plan is being established; instead, additional information will be added as the execution progresses, providing in that way a detailed report of what has been performed throughout the year. This is why various plan versions can be delivered during the planning and scheduling phases.

The concept model is extensive, so a simplified form has been created to give a good overview and understanding of its composition (Figure 5). The package in the model contains all catalog profiles, all possible Capital Facilities Information Handover Specification (CFIHOS) equipment classes, and all performance standards.

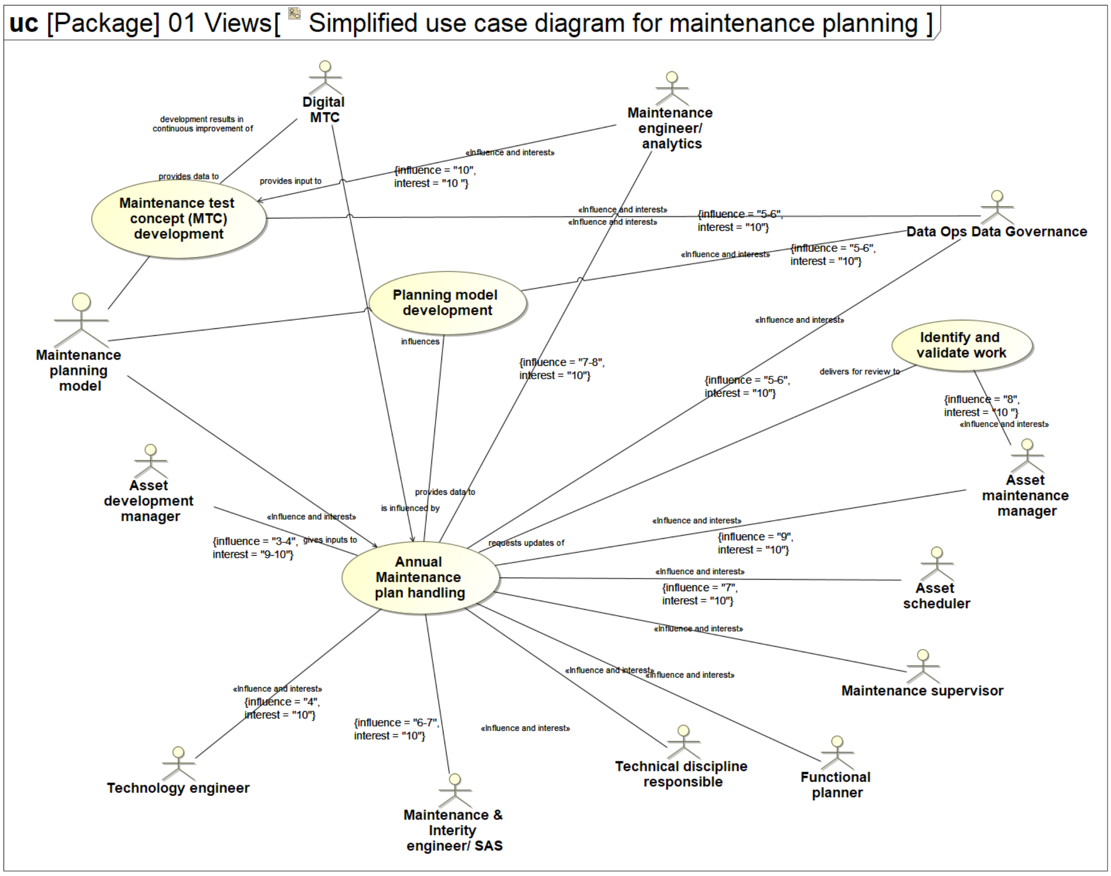

Figure 3: Simplified Use Case Diagram with Focus on Maintenance Related Roles- based on (Jensen, 2023).

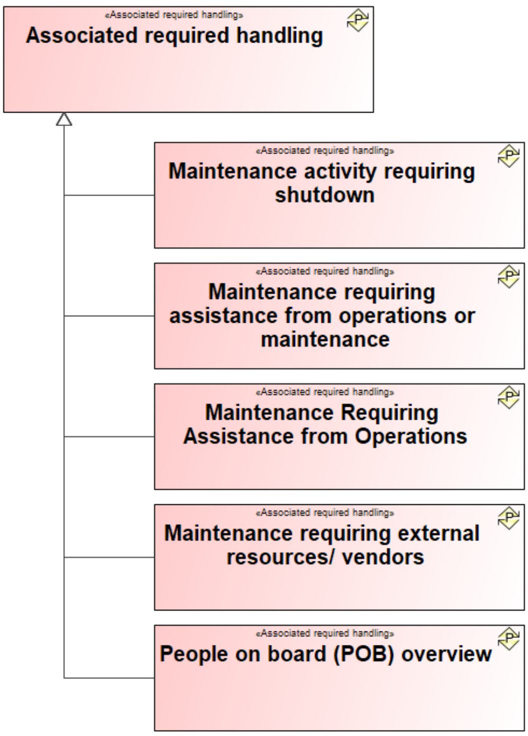

Figure 4: Associated Required Handling (Jensen, 2023).

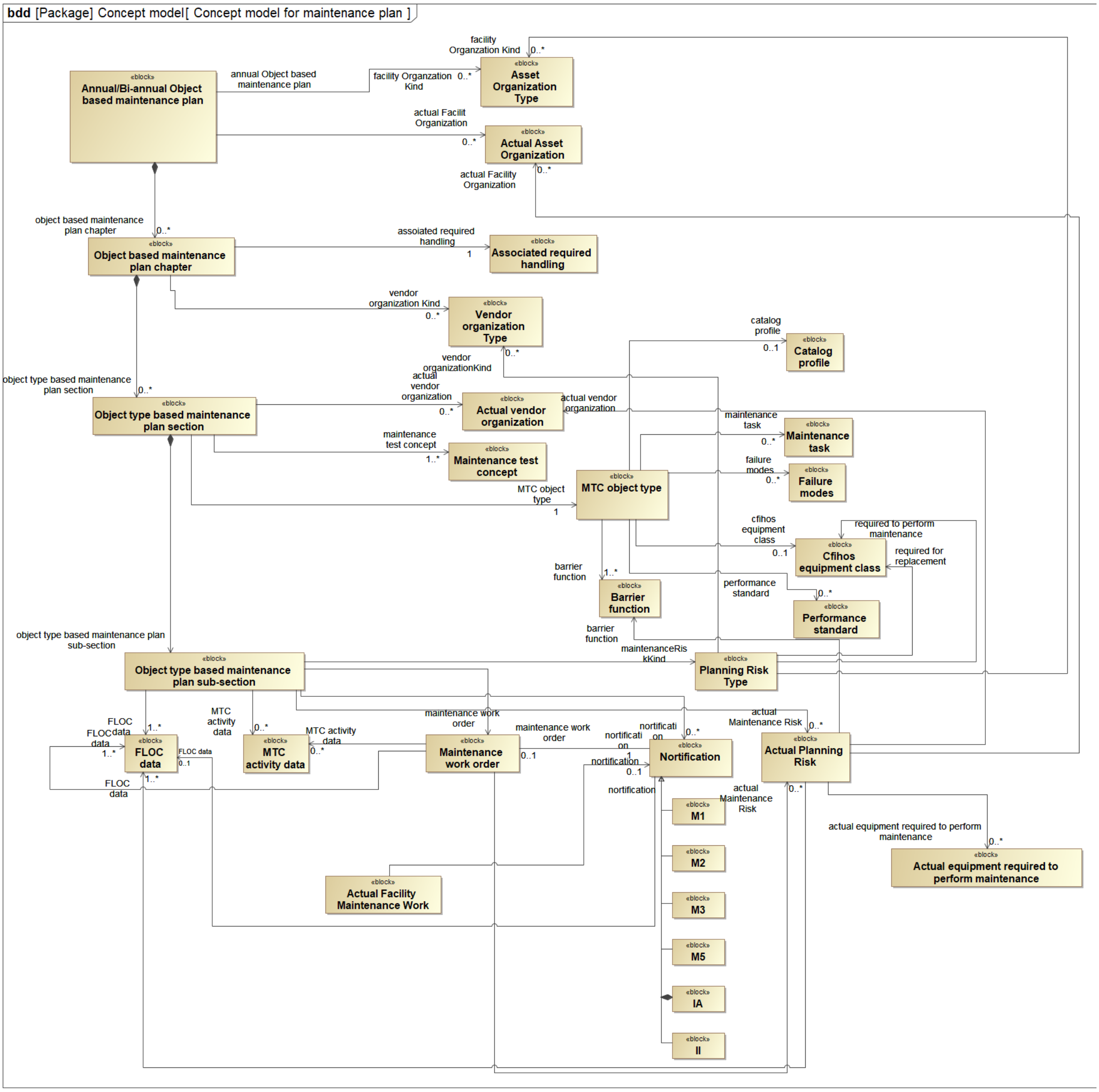

Figure 5: Concept Model for a Maintenance Plan (Jensen, 2023).

There are two types of relationships shown in Figure 5.

- Containment (relationships with a filled diamond at one end). This means that the maintenance plan contains chapters, a chapter contains sections, and a section contains subsections.
- Associations (links between elements, either with an arrow at one end or no arrows). In the case of an arrow, this implies that the element that does not contain the arrow contains a link to the other element. As an example, there is a link from the element MTC object type to catalog profile with the multiplicity 0..1. This means that within the MTC object type, there is information named catalog profile that links directly to the actual catalog profile that is stored in a separate directory in the model. The multiplicity implies that only one or zero catalog profiles can be referenced within the MTC object type. Similarly, within the plan, there is a reference from the object type-based maintenance plan section to the MTC object type. Since the entire section is devoted to a single object type, there can be many sections, and the reference indicates that only one such reference can exist within the section. Creating this reference from the section to the MTC object type is the

only action the planner requires since all the references that the object type consists of are already present in the object type within the model. In case there is a straight line between elements, they are referenced in both directions; for example, a maintenance work order contains a reference to the notification that applies to it, and the notifications reference the maintenance work order that resulted from the notification. It is vital to note that if a maintenance work order exists, a notification that applies to it must exist. However, a notification that results in a work rejection will not reference a maintenance work order.

Figure 5 describes a set of elements, and these are explained in more detail below:

- **Annual object-based maintenance plan**: The plan is assumed to be asset-specific, meaning each asset has a separate annual or bi-annual plan.

- **Object-based maintenance plan chapter**: Maintenance tasks can be grouped into different types of handling: maintenance activity requiring a shutdown, maintenance requiring assistance from operations, maintenance requiring critical equipment out of service, maintenance requiring external resources/vendors or Personnel on Board (POB) overview. As shown in, the plan is assumed to have a chapter for each.

- **Asset organization type**: This connection is intended to allow the plan to schedule maintenance tasks at a facility. For this to be possible, a structural definition of the organization must exist. There may be more than one organizational structure. Note that the structure is defined as part of the total model.

- **Actual Asset Organization**: For a given asset, the organization's instantiation must exist to handle the actual scheduling of tasks and the persons doing the actual work. This is also defined in the model.

- **Associated required handling**: The activity grouping used for each chapter is an actual model element that ensures that any updates or changes are reflected in the plan. Such changes require management decisions.

- **Vendor organization Type**: Since one of the chapters discusses outside vendors and the need to handle their schedules, this chapter would also relate to the outside vendor's organizational structure. This allows an actual vendor organization to be used for detailed scheduling. Both the kind of vendor organization and the actual organization would be part of the model.

- **Object type-based maintenance plan section:** Deals with a specific MTC object type and the associated maintenance test concept, which is the configuration of elements used to perform the test. Both the MTC object type and the MTC itself already contain a significant amount of model data.

- **Planning risk type**: The types of risks considered in the plan related to needed or replaceable equipment or the types of organizations that need to perform maintenance tasks.

- **Actual planning risk**: The instantiated risks for a given work order are based on the risks identified and connected to the actual equipment. These can also be connected to the actual organizations, either an asset or the actual vendors.

- **Notification**: General notification class that can be specialized as needed once it has been dealt with. Note that if rejected, the work order will never be created.

- **Maintenance work order**: Once the work notification has been approved, the maintenance work order is created with all the data.

- **MTC activity data**: Data recorded concerning the maintenance being performed.
- **Actual Facility maintenance work**: This represents the work activity that can be dealt with in the Gantt chart and is connected to the actual internal and external resources. These are connected to the actual facility or maintenance activities so that scheduling conflicts of the work being performed at the facility can be visualized, handled, and defined for the facility's organizations.

- **FLOC**: Functional Location where equipment is installed.

Using stereotypes to define needed maintenance and planning data

Special stereotypes have been created to facilitate the construction and handling of the planning model and the storage of meta-data for each element (Figure 6: Portion of a created set of stereotypes). These stereotypes allow for the creation of elements of a specified type, enabling the meta-data to be injected into the element. The meta-data in question can be simple texts, values, or links to other elements of a given type. The creation of stereotypes governs the data that can be stored in the model for different types of elements, and accordingly, a great deal of data can be combined. This allows the plan to take a great deal of information into account. The key here is that working with the plan relies solely on creating chapters, sections, and subsections since all the other data is assumed to exist within the complete model environment or worked out separately from the plan. The elements dealing with planning risks and the elements dealing with the organizational structure will need to be developed within the model to be used during the plan's creation. Based on the combined data, scheduling the maintenance tasks should be possible by combining the work effort with the available personnel.

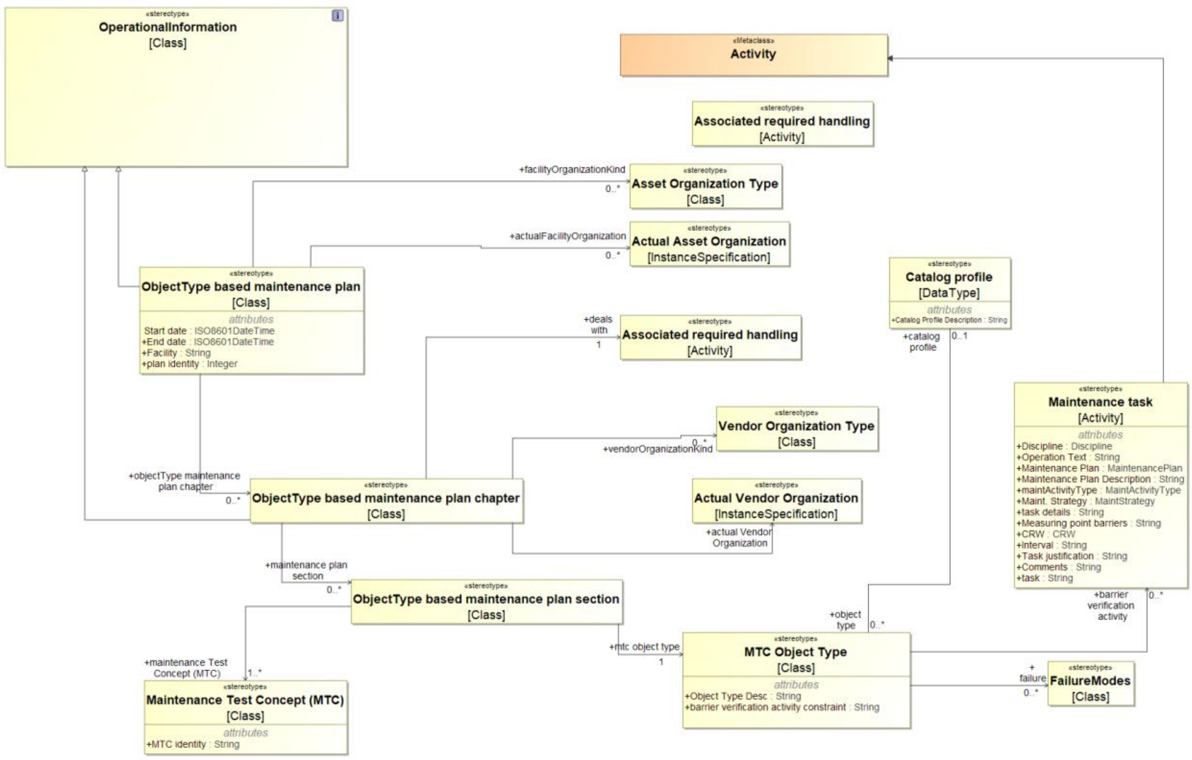

Figure 6: Portion of a created set of stereotypes

Before constructing the different object types, a definition of object type will be presented.

Inspired by (ISO 14224, 2016), the MTC defines a set of inspection, test methods, procedures, and maintenance actions; these are described generically for a specific group of equipment that may have similar functions, failure mechanisms, and operational scenarios.

For example, the table below illustrates a relevant set of on/ off valves grouped according to ISO 14224 in object types.

OBJECT TYPE	OBJECT TYPE DESCRIPTION
VAL-BAL	Ballast valve
VAL-BIL	Bilge valve
VA-ESDVBD	Blow down (ESDV)
VA-ESDVB	Sectioning valve CR
VA-ESDVG	Offloading ESDV
VA-ESDVOL	Riser ESDV (barrier)
VA-ESDVR	HIPPS/IOPPS valve
VA-HIPPS	PSD valve
VA-PSDVG	PSD valve – general
VA-PSDVIL	PSD valve with IL R
VA-PV	Pilot valve
VA-SOL	Solenoid-safety/crit

Table 2: On-off valve list

The construction of the model for the annual maintenance plan based on object type 1 goes as follows:

- Built up in levels, the first level indicates start and finish dates within a year, connected to an element named maintenance plan chapter and an asset name. The model is also connected to two other elements intended to handle the asset's personnel organization within the different facilities.
- The Asset organization element type defines the type of organization the facility uses. The actual asset organization defines the actual instances of the organization being used at the facility. The organizational work structure must be defined to handle conflicts between maintenance activities and regular facility work.
- The chapter part of the plan structures the plan such that only maintenance activities with a single characteristic are contained within the chapter. Since one of the characteristics defines maintenance activities where equipment vendors need to be present for this chapter, an ability to define the kind of vendor organizations and the actuals have been defined.

The construction of the model for the annual maintenance plan based on object type 2 goes as follows:

- The chapter's sections are structured around a single object type and contain connections to the maintenance concepts and types of maintenance tasks to be used. The actual barrier function levels have been used as properties within the element.

- The sub-sections define the functional location (FLOC) and MTC activity data, describing the activities performed.
- The sub-sections also connect and identify all work orders and notifications. It is assumed that a work order can only be created once a notification identifying the FLOCs concerned has been dealt with. Nothing stops notifications and work orders from being referred to by more than one section. Both work orders and notifications identify the FLOCs concerned.

The construction of the model for the annual maintenance plan based on object type 3 goes as follows:

- The planning model utilizes different types of risks, which are possible types of risks that can arise and be related to maintenance planning. These are generic and can be considered options for all relevant use cases. Not all may apply to all use cases. These types of risks are used in a broad sense to refer to what can be labeled as a risk source, risk event, and consequences. Risk sources (e.g., SIMOPS) are all the actions or circumstances that can lead to an unwanted event. A risk event (e.g., limited bed capacity) is uncertain and can lead to either good or bad consequences. Consequences are the outcome of an event that can affect the objectives.
- The different types of risks are associated with a maintenance work order and its associated notifications. The planning risk types and the actual planning risks (case-relevant risks) are also connected to the sub-section of the plan. Typical examples of the planning risk types are shown in Figure 7**Fel! Hittar inte referenskälla.** It should be noted that these types of risks are not actual planning risks (case-relevant risks), which refer to an instance of the possible risk types relevant to a specific use case. This means that the risks associated with actual planning risk define the maintenance of equipment, representing risks associated with the actual maintenance activities, the actual personnel performing it, the actual work it may conflict with, etc.
- Planning risk types are instance specifications based on the appropriate type applicable directly to the specific maintenance performed on equipment instances. Additionally, these planning risk types relate to planning risk and are not related to the criticality or vulnerability of the equipment. This stereotype connects the risks to organizational descriptions and possible equipment issues.

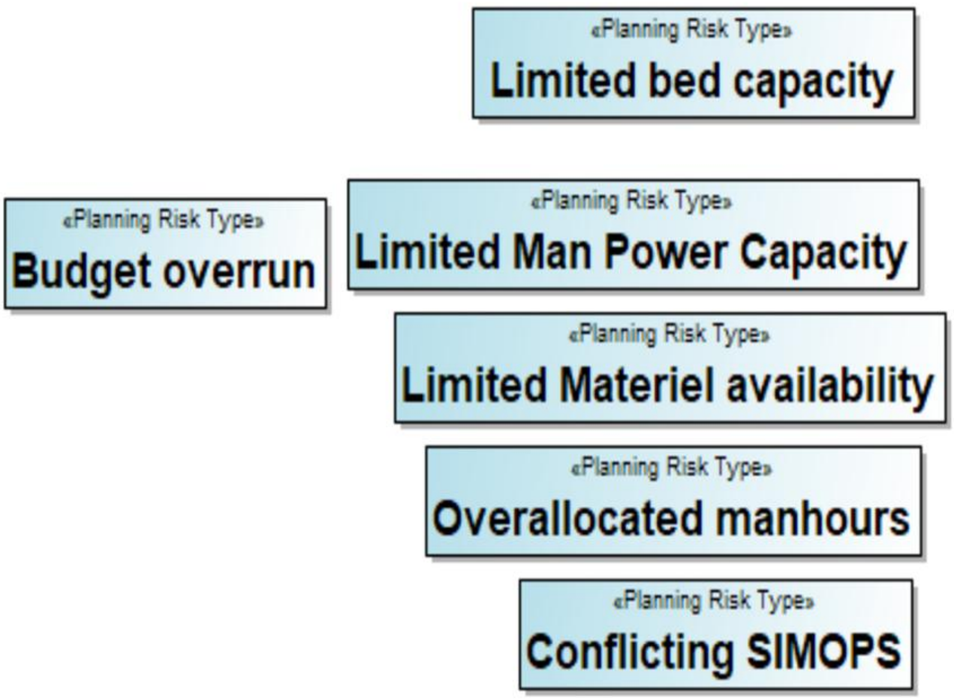

Figure 7: Planning risk type examples (Jensen, 2023).

Below, a description of how the planning risks are handled will be presented, including risk type definition and corresponding meta-data.

Risk type definition:

The risk element within the model requires two types of treatment: different planning risk types and actual planning risks (case-relevant risks). Both are planning risks related to maintenance activities that may or may not be performed as scheduled due to conflicting operations, lack of personnel or material, etc. These risks should not be confused with actual risks related to the execution of an activity since these are related to, for example, HSE or similar risks, as these are defined separately and generally under a Safe Job Analysis (SJA) conducted offshore before executing or planning any activity. The SJA, according to Norsk olje&gass (2003), is a step-by-step process that reviews the risks in advance of an operation or work activity that will take place. It is conducted to identify and mitigate any identified risks and to control them. To consider a type of risk, the stereotype shown in Figure 8 can be used to capture the meta-data associated with a type of risk.

Figure 8: Planning Risk shows risk before mitigation X and risk after mitigation Y. X and Y can be related to financial risk, Environmental risk, Personnel risk, etc.

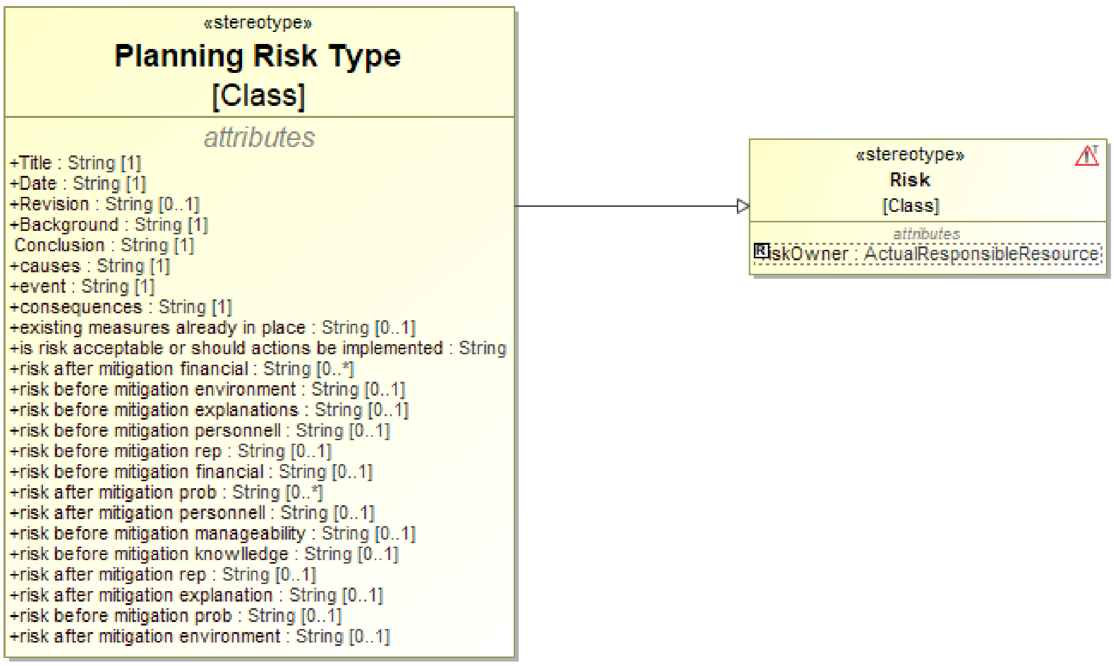

Figure 8: Planning Risk Stereotype definitions (Jensen, 2023).

Risk meta-data definition:

An example of an actual risk (case-relevant risk) based on a risk type is shown in Figure 9. The example illustrates the large amount of meta-data that can be entered into the planning model. Based on the risk templates, it is assumed that a part of the model will consist of a set of elements to which the stereotype maintenance risk type has been applied. Within the model, for each type of risk, X's values should be used as one sees fit (the multiplicity 0..1 implies that the element may not be present). Case-relevant risk elements would also exist based on risk assessments. When it comes to risk categorization, it is possible to create different types of risk categories under which the different risk types would be placed. This also allows for differences in meta-data between risk types in various categories. Using inheritance from a common risk type, commonality, and special handling of different categories could be possible. This could further be reflected in the meta-data for case-relevant risks.

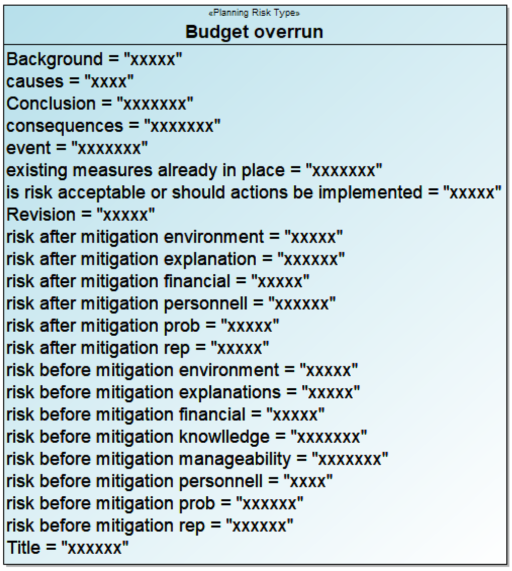

Figure 9: An Example of Case-Relevant Risks Based on a Risk Type (Jensen, 2023).

A significant attribute of the planning model is its ability to generate Gantt charts, as shown in Figure 10. This is usually a preferred way of communication among stakeholders and vendors, as it allows planners to schedule tasks easily, showcasing the time frames in a way that represents all activities. Furthermore, the planning model may also connect to any enterprise planning tools, supporting the integration of the company's plans within any business unit. Note that the integration capabilities of the planning model with other systems will depend on the alignment of the data collection among systems and quality governance of the data feeding the model.

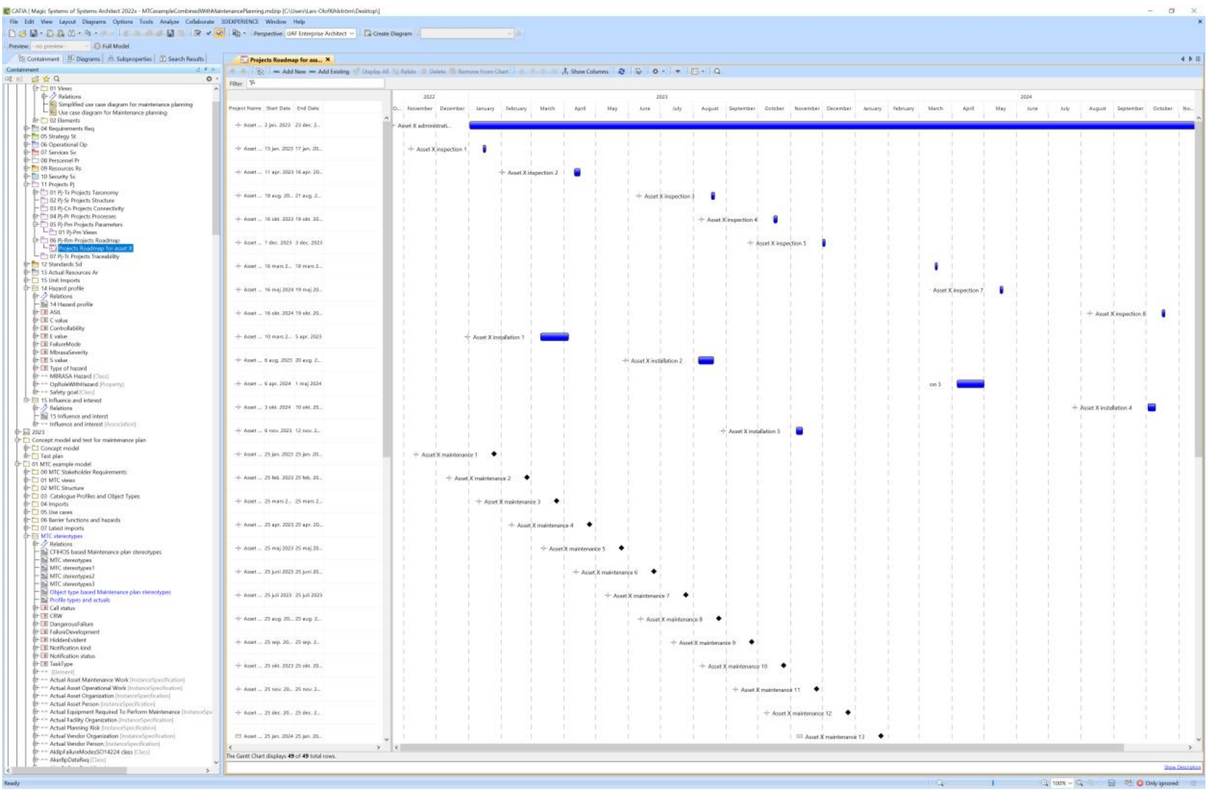

Figure 10: Portion of Gantt Chart Generated by the Planning Model.

Failure Rate Considerations and Impact on a Maintenance Plan

During the operational phase, which encompasses testing and maintenance activities, operational experience serves as valuable insight for refining and updating maintenance procedures in accordance with deviations or compliance with set performance targets.

Follow-up parameters, such as failure rates, are influenced by different factors. As such, they must be monitored during the operation phase to maintain and ensure conformance with design parameters. In the case of deviations, appropriate measures should be implemented accordingly.

The process for updating failure rates for equipment groups is outlined in (Håbrekke et al., 2023). Two methods are discussed:

- Estimating DU (dangerous undetected) failure rate using operational experience only and
- The Bayesian failure rate estimation approach.

According to (Håbrekke et al., 2023), the recommended method for updating the failure rate is the Bayesian failure rate estimation approach, which is also the basis for the parametric analysis in this paper. This approach combines (a priori data) design failure rate or failure rate from the previous observation period with (a posteriori) facility-specific operational experience/data for the current observation period:

1. First, identify an equipment group whose failure rate needs to be updated. The components within this group should, as much as possible, be similar in type, serve the same function, and exhibit comparable failure rates.
2. Next, select an observation period. The length of the period should provide sufficient aggregated operating time to increase the confidence of the updated failure rate.
3. Next, determine the aggregated time in operation and the number of DU failures. This is the sum of the individual time in the operation of each component in the equipment group within the observation period. The following should be considered:
   - Adjust for removed or added components during or after the last period.
   - Exclude components not tested or activated in the period.
   - The operating time contribution from components out of service or in passive standby during the period is excluded.
4. Finally, the uncertainty parameters are calculated, and the failure rates are updated.

The input parameters for updating failure rates are shown in Table 3.

Parameter	Denomination	Description
$\lambda_{\text{DU},i-1}$	per hour	Input failure rate – from design ($i = 1$) or previous period ($i > 1$)
$\lambda_{\text{DU-CE},i-1}$	per hour	Conservative estimate of input failure rate (as a means of expressing failure rate uncertainty)
n_i		No. of tags within equipment group in operation during period i
x_i	-	No. of DU failures within the equipment group during period i
t_i	hours	Length of period i
T_i	hours	Aggregated operating time for period i, $T_i = n_i \cdot t_i$

Table 3: Required Input Data for Updating Failure Rate (Håbrekke et al., 2023)

The estimate for the updated failure rate for period i is (Rausand & Høyland, 2004):

$$\lambda_{DU,i} = \frac{\alpha_i + x_i}{\beta_i + T_i}$$

Where the uncertainty parameters β_i and α_i are (Vatn, 2006):

$$\beta_i = \frac{\lambda_{Du,i-1}}{\left(\lambda_{DU-CE,i-1} - \lambda_{Du,i-1}\right)^2}$$

and

$$\alpha_i = \beta_i \cdot \lambda_{DU,i-1} = \frac{\lambda_{DU,i-1}^2}{\left(\lambda_{DU-CE,i-1} - \lambda_{DU,i-1}\right)^2}$$

Suggested choices for $\lambda_{DU-CE,i-1}$ are:

For period i = 1:

$$\lambda_{DU-CE,0} = 2 \cdot \lambda_{DU,0}$$

For period i>1:

$$\lambda_{DU-CE,i-1} = \lambda_{DU,i-1}^{90U} = \frac{z_{0.9,2(\alpha_{i-1}+x_{i-1})}}{2(\beta_{i-1} + T_{i-1})}$$

$\lambda_{DU,i-1}^{90U}$ is the upper bound of the 90% one-sided credibility interval for $\lambda_{DU,i-1}$

$z_{0.9,v}$ is the upper 10% percentile of the chi-squared (χ^2) - distribution with v degrees of freedom.

Determining the actual values can be done using parametric diagrams and simulation and adding the appropriate data.

Figure 11 shows a block definition diagram comprising the main blocks in the model using Magic Draw Systems of Systems Architect.

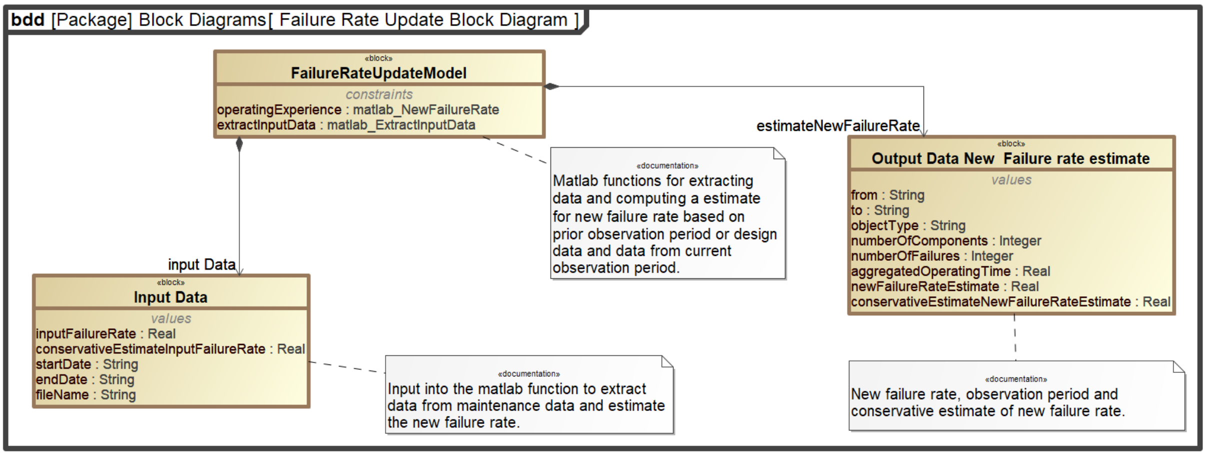

Figure 11: Block Definition Diagram for Failure Rate Update Model (Dan, 2024)

- *FailureRateUpdate Model* - Matlab functions for extracting data and computing an estimate for new failure rate based on prior observation period or design data and data from the current observation period.
- *Input Data—The MBSE tool specifies input data* for the Matlab functions to extract data from maintenance data and estimate the new failure rate.
- *Output Data/New Failure Rate* stores the evaluation's output from Matlab. This includes the equipment group (object type), observation period (start date and end date), number of equipment in the group within the observed period, number of observed DU failures, aggregate time in operation, estimates for the new failure rate, and a conservative estimate for the new failure rate.

Figure 12 shows the parametric diagram. In the diagram, the value properties of the *Input Data* block are connected to the appropriate ports of the Matlab constraint blocks, and the output from the constraints block is connected to the value property of the *output data* block.

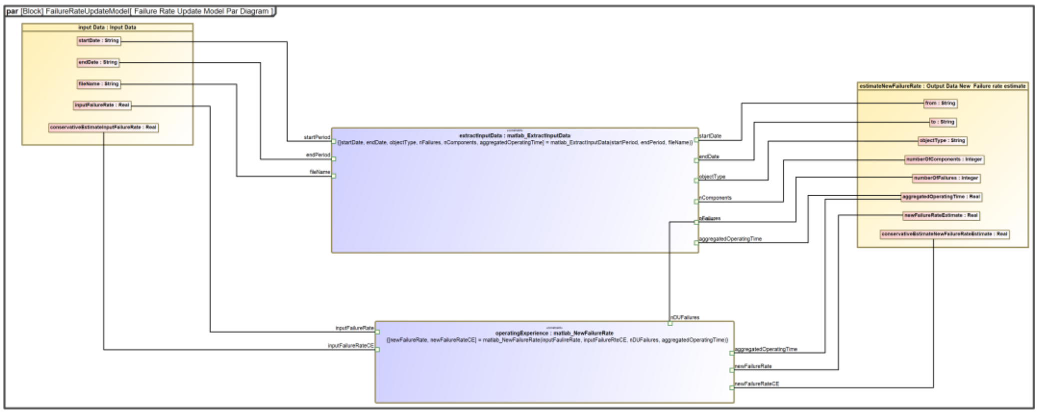

Figure 12: Parametric Diagram for Failure Rate Update Model (Dan, 2024)

The following presents a step-by-step process for using the model to estimate an update for failure rate of a selected equipment group:

1. Step 1 - Select a facility (Main Asset) and equipment group (object type).
2. Step 2 - export the maintenance/test result for the selected equipment group from the enterprise maintenance system.
3. Step 3 - Create an instance of the 'Failure Rate Update Model' with all its parts and constraints properties. A diagram may be created to visualize the evaluation (Figure 13).

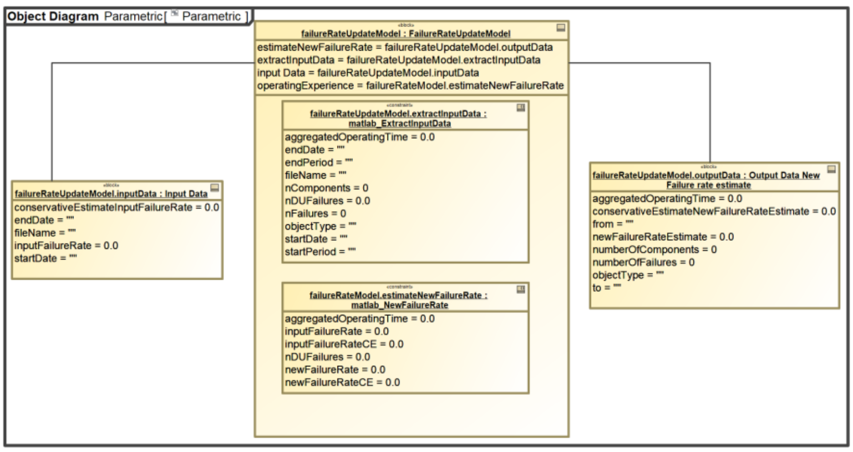

Figure 13: Instance Block for Failure Rate Update Model (Dan, 2024)

4. Step 4 - Provide desired input to the input block:
    - startDate – the desired start of an observation period. The default is "01-January-1900."
    - endDate - desired end of the observation period. The default is today’s date.
    - fileName - path to the exported test result.
    - inputFailureRate - design failure rate or failure rate from the previous observation period if available.
    - inputFailureRateCE – a conservative estimate of the design failure rate or the estimated conservative estimate from the previous observation period if available. The default is 2*inputFailureRate.

5. Step 5—Run the *FailureRateUpdate Model*. The results are displayed in the ’Variables’ pane. They can be exported to the created instance to display on the main display area.

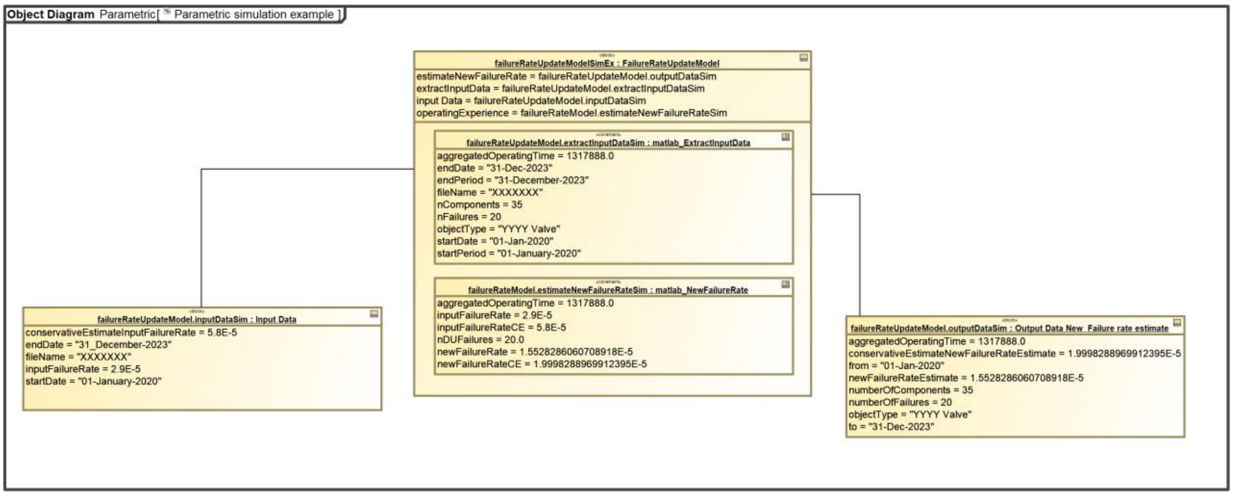

Figure 14: Simulation Example (Dan, 2024)

Figure 14 shows the updated failure rate, the estimate for the conservative failure rate, and other information for the selected equipment group.

After updating the failure rate, a new inspection interval is obtained based on the new failure rate, which is fed back into the overall maintenance planning.

Conclusions and Recommendations

Model-Based Systems Engineering (MBSE) is a structured methodology that leverages models to support system development across design, testing, and maintenance domains. In the context of maintenance planning, MBSE delivers measurable economic benefits by improving efficiency, reducing operational costs, and enhancing system reliability. It enables predictive maintenance, informed resource allocation, and effective cost optimization through improved system visibility and early issue identification. By supporting data-driven decision-making and clear communication across disciplines, MBSE serves as a critical enabler of financially sound, technically robust maintenance strategies in complex system environments. MBSE is not fully established in the oil and gas industry and this paper illustrates an example of how MBSE can be used in in the context of maintenance planning. Using MBSE is a way to strengthen a strategic maintenance agenda by creating a maintenance planning model that eventually can allow the implementation of an integrated maintenance plan with the help of MBSE. Based on what has been gathered from the theoretical framework and empirical results, the following areas have been deemed relevant and crucial, respecting both objective and research questions. In order to adopt an MBSE methodology to develop a data-driven integrated maintenance planning approach, several factors must be considered. For instance, understanding the concepts and principles of systems engineering, MBSE, maintenance planning, planning, integrated planning, and risk is key, as each concept brings various potential benefits and challenges. Understanding the dynamics among all concepts is also essential, as this can provide suitable, beneficial decisions. Additionally, the involvement of the right stakeholders is imperative as it can allow for good communication, knowledge transfer, and the ability to capture essential information to understand what is necessary for a successful implementation.

The goal of this paper was to show an integrated maintenance planning model where data from different data sources related to relevant planning risks, maintenance activities, and requirements can be integrated into a plan. The ability to further add evaluation of failure rates for different elements (here exemplified by using data concerned with on/off valves) can be used to directly influence the development of the maintenance plan as on part of the overall data made use as part of the planning. This can enable improved forecast and predictability to support planners, schedulers, and all relevant stakeholders. Overall, the planning model can gather a vast amount of data, which is constantly updated as changes are made and information gets exchanged. This can make the plan more dynamic and, at the same time, provide stakeholders with early risk visualization.

It is suggested that adopting an MBSE approach can significantly affect an organization's strategic maintenance planning agenda. The main perceived benefits of this research are early risk visualization thanks to how the risks have been implemented in the model, increased traceability, easy information exchange, effective and regular communication of progress, and stakeholder accountability. The further development of the model would be beneficial as it can improve data quality and information exchange, and even though there was manual import with Excel to obtain the information needed to create the planning model, the idea is to make a dataflow that does not require a manual import.

Further model development and a strategy with data are needed to mature this model-based approach to maintenance planning.

- The organization needs support at various levels, especially the maintenance and planning department.
- Identify a strategy for maintenance planning, data quality and governance that aligns with the ongoing work on data management specification used in the organization.
- Mature further interfaces and alignment of the initial planning model with technical life extension planning.
- Mature interfaces and alignment of the initial planning model with asset-integrated planning.
- Develop a close relation to data governance.
- A pilot project: All the above aspects can be considered in further developing the model applied to one asset, including testing and executing the model with actual data already subjected to quality control and governance. This will provide insights on how to capture all the data and information from the different disciplines, allowing the sharing of information among all stakeholders.
- Technical aspects must be considered, including interoperability among the different software, data formats, and data availability.
- Support from relevant leaders at the different levels is needed to conduct the above-proposed tasks.

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Biography

Glenda Jensen. Glenda Jensen holds an MSc in International Business and an MSc in Risk Analysis and Governance. She works at Aker BP ASA with core expertise in maintenance planning, project execution, resource management, and continuous improvement. She has supported major energy projects by optimizing planning processes and integrating tools such as SAP and Primavera to enhance asset management and execution efficiency. Her work includes applying Lean methodologies, coordinating cross-functional resources, and improving operational workflows. She also has experience in business continuity planning and emergency preparedness. Her work focuses on applying model-based systems engineering (MBSE) principles to areas such as maintenance, resource coordination, and continuity planning, with an emphasis on aligning operational planning with systems thinking to enhance efficiency and resilience.

Emefon Ekerette Dan. Emefon Dan holds an MSc in Reliability, Availability, Maintainability, and Safety (RAMS) Engineering from the Norwegian University of Science and Technology (NTNU) and is currently pursuing a PhD within the same field, with a research focus on condition-based maintenance optimization also at NTNU. His work explores failure modeling, condition-based/predictive maintenance strategies, and data-driven decision-making to improve asset performance and lifecycle management. With expertise in system reliability, maintenance management, and risk analysis, Emefon specializes in prognostics, optimization of maintenance strategies, and performance assessment of production and safety critical systems. His interests lie at the intersection of engineering, digitalization, and reliability, with a strong focus on applying systems thinking and predictive analytics to improve safety, efficiency, and resilience in industrial operations.

Edmary Altamiranda. Edmary Altamiranda has the degrees of Systems Engineer (Process Control Systems), Master of Science in Control Engineering, Doctor in Applied Sciences (Intelligent Control Systems) from Universidad de Los Andes Mérida-Venezuela. She has held positions in Oil & Gas since 1994 within Process Control Engineering and Automation Engineering in the Petrochemical Industry and since 2006 within Systems Engineering, Control Systems & Technology in the Subsea Upstream Industry. Edmary has combined scientific and applied research with industrial experience throughout her career. She has also held positions as Assistant Professor / Senior Researcher and Postdoctoral Researcher in the Control System and Artificial Intelligence fields. Edmary is currently working as Control Systems Lead - Technology, R&D at Aker BP ASA since November 2018. In this role she is involved in various R&D, technology projects and Joint Industry Programs with various industrial and academic partners with focus on Subsea Technology, System of Systems Engineering and Digital Twin Technology including Model Based Maintenance & Test Concepts in this context.

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Lars-Olof Kihlström. Lars-Olof Kihlström is a principal consultant at CAG Syntell where he has worked since 2013, primarily in the area of MBSE. He has been a core member of the UAF group within the OMG since its start as the UPDM group. He was involved in the development of NAF as well as MODAF. He has worked with modelling in a variety of domains since the middle of the 1980:ies such as telecommunications, automotive, defence as well as financial systems. He is specifically interested in models that can be used to analyze the behavior of system of systems**.**

Matthew Hause. Matthew Hause is a principal consultant at SSI, a Chair of the UAF group, and a member of the OMG SysML specification team. He has been developing multi-national complex systems for over 45 years as a systems and software engineer. He worked in the power systems industry, command and control systems, process control, Oil and Gas, SCADA, military systems, and many other areas. His role at SSI includes consulting, mentoring, standards development, specification of the UAF profile and training.