Operational Analysis Based on the MBSE Grid for the Implementation of Hydroelectric Group Health Monitoring and Management Unit

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Abstract— Any study or project within the framework of system design has chosen to start the modeling phase with the model-based systems engineering approach (MBSE), it will encounter decision-making difficulties of the approach. to adopt. During the last two decades, many MBSE methodologies have been developed, but the majority of them present an incomplete or abstract architectural framework for organizing the modeling work.

The MBSE Grid based Systems Modeling Language (SysML) approach has made the modeling task easier for system engineers. Indeed, SysML constitutes a powerful tool, using its diagrams, to model the points of view according to the principle of development of requirement, behavior or structure of the system. This paper summarizes the MBSE methodologies most used in research work and development projects. In the context of our study, the MBSE Grid approach is adopted with slight modifications concerning the names of the domains of the grid. By combining with Bombardier Transport SysMM's MBSE methodology, which consists of three main phases, the proposed MBSE grid presents a modeling approach by analysis: operational, functional and technical of the system. The purpose of this work is to conduct an operational analysis, for the implementation of a Health Monitoring and Management Unit (HMMU) of a hydropower group.

Keywords—MBSE, MBSE Grid, Operational Analysis, SysML Hydroelectric group.

I. INTRODUCTION

Systems Engineering (SE) is an interdisciplinary methodological approach to master the design of complex systems and products. The practices of this approach are now listed in standards, carried out using methods and supported by tools.

Systems Engineering Methods provide technical approaches based on Model-Based Systems Engineering (MBSE) to carry out these general activities. The implementation of processes and methods is assisted by a language and modeling tools, now computerized.

Any MBSE approach promises to facilitate communication between different engineering disciplines [1]. Therefore, it should support different architecture views for a single model, offering guidance on how to start modeling the system, how to create the model structure, which views to create, and in what order [2], [3]. To meet this challenge, the approach is obliged to implement the appropriate framework and process, the language, as well as the specific software tool. To ensure a successful implementation of MBSE, the modeling language must be combined with the methodology to become useful [4]. Recent MBSE approaches adopt the Systems Modeling Language (SysML), but it does not provide guidelines or recommendations on the modeling process [5], [6].

The systems engineering community has recognized and used many MBSE methodologies over the past two decades. The most popular among them are IBM Harmony, OSEM, Vitech, SYSMOD and Enterprise Architecture Frameworks (EAF) for systems engineering, such as DoDAF / MODAF, TOGAF, NAF. A new approach called MBSE Grid, was proposed in 2015 by [2]. It is a grid organized in a Zachman style matrix [7], where rows represent viewpoints, columns represent pillars of systems engineering, and cells represent different views of the system model. . The MBSE Grid offers a simplified approach and gives unambiguous guidelines for the modeling process using SysML.

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The number of methods available for the MBSE is not large and not significant. Most of them provide an incomplete or abstract architectural framework for organizing the modeling work. In this paper, the MBSE Grid approach is adopted, the objective of which is to focus our study on the operational analysis of the process for the implementation of a health monitoring and management unit (HMMU). through a vibratory signature of a hydroelectric group installed in the 90s, and today has cracks. The precise definition of the mission of the HMMU unit, the services it offers and the relationships (requirements) with its environment (Hydroelectric group, User, control room, etc.) is one of the most important phases and critiques of the design of complex systems [3], [8]. In fact, more than 80% of the faults in a system or product come from the requirements definition stage [9].

We start our article in section II with a presentation of the work modeled by the different MBSE methodologies. Section III is devoted to the operational analysis by the MBSE Grid approach, for the implementation of the unit for monitoring and managing the state of health of a hydroelectric group. In section IV, conclusions are drawn and future goals are revealed.

II. MBSE APPROACHES

The review of the different MBSE methodologies has been presented in [2], and this section describes and analyzes the most used.

A. MBSE methodologies

- *IBM Rational Harmony for SE*. The process of system development is represented by the classic "V" waterfall diagram (Figure 1), where the flow is iterative for several cycles. The left branch describes the design from top to bottom, while the right side shows the implementation and testing phases from the bottom up to system acceptance [10].

- *Object-Oriented Systems Engineering Methodology (OOSEM)*. It is a design approach based on systems engineering models with object oriented techniques (Figure 2). OOSEM developed in 2010 by INCOSE, it aims to reconcile the processes practiced by any project or organization for the development of a system [11].
- *Vitech MBSE Methodology*. Vitech's MBSE methodology comprises four main systems engineering activities: requirements analysis, behavioral analysis, architecture and verification and validation [13]. SE activities are linked to four areas: Requirements, Behavior, Architecture and Verification and Validation [14]. The four domains are all executed at a given level of detail before a transition to the next layer takes place (Figure 3).
- *JPL State Analysis (SA)*. Methodology developed within the California Institute of Technology by the Jet Propulsion Laboratory (JPL). It provides activities for modeling the behavior of the system as a function of state variables. Models show how the state evolves (Figure 4) [16].
- *Systems Modeling Toolbox (SYSMOD)*. Based on the SysML language, it begins the modeling with the description of the context of the project, to reach at the end the internal structure of the system and these parameters, simultaneously performing the steps of: elaboration of requirements; definition of the context of the system; specification of use cases and process modeling.

The MBSE methodologies described above solve different missions of the systems engineering process [18], [19]. They use step-by-step iterations for data collection. However, this does not provide considerable support for identifying levels of abstraction, which can become an obstacle in assigning responsibilities to stakeholders.

Figure 1 Classic V diagram of IBM Rational Harmony for SE

Source: F. Chadburn, 2017 [10]

Figure 2 Top-down diagram of OOSEM

Source: K. Pietruszewicz, 2019 [12]

Figure 3 Vitech MBSE Methodology Domains

Source: A. L. David and B. S. Zane, 2011 [15]

Figure 4 JPL State Analysis (SA) Methodology

Source: J. A. Estefan, 2008 [17]

B. Enterprise Architecture Frameworks

The process of analyzing a system by iterations, from viewpoints (layers of abstraction), also has its origins in several Enterprise Architecture Frameworks (EAF). We can distinguish two categories of FAEs: those oriented towards defense and those oriented towards industry.

The Ministry of Defense Architecture Frameworks (DoDAF/MODAF) and the NATO Architecture Framework (NAF) are standardized frameworks for defense architectures, allow modeling in different levels of abstraction. These frameworks are similar and use the same modeling language, developed by the OMG, called Unified Profile for DoDAF and MODAF (UPDM) [20].

The TOGAF, FEF and Zachman architectural frameworks are particularly used in scientific research work and considered more oriented towards industrial architectures [21], [22]. They are based on UML languages. Lack of protocol for the exchange and storage of information is a handicap of industrial AAFs, unlike defense AAFs

The latest UPDM 3.0 version has been renamed to UAF 1.0 (Unified Architecture Framework), to support the needs of areas, like civil engineering, for security support, human-machine integration, etc.

Other architectural frameworks exist in the world of transportation and defense industries such as BT SysMM and KDA. The BT SysMM (Bombardier Transport System Modeling Method) consists of three phases to analyze and model the system of interest (Figure 5). The operational analysis phase aims to specify the relationships between the system and its environment, the second functional analysis phase aims to explain the functioning of the system, while the technical analysis phase defines how the physical components are organized. (Hardware, Software) to implement the system [23]. Another methodology applied to Kongsberg Defense and Aerospace (KDA). This approach depicted in Figure 6 is carried out in two stages: specification and design. The design stage takes place from a functional, logical and physical point of view [24].

Figure 5 BT System Modeling Method

Source: O. Naas et al., 2015 [23]

Figure 6 KDA System Architecture Framework

Source: S. E. Soegaard, 2016 [24]

EAFs methodologies present several problems which are summed up in the complexity of the model and the less clear relationships between the different layers (Specification, Design and Structure). EAFs are very powerful for building the framework of enterprise architectures, but not quite suitable for systems, they are relatively complex for systems engineers. It is for this reason a new MBSE approach based on the strengths of existing methodologies and which should be oriented to the modeling of systems.

C. MBSE Grid

The initial MBSE Grid approach applied in 2015 by [2] briefly describes all of the nine cells making up the matrix by specifying the four main pillars of systems engineering (Requirements, Behavior, Structure and Parameters of the System) and how to manage the different abstraction layers (Concept, Problem and Solution).

Adjustments were applied by [25] applied to the Concept and Problem Abstraction Layers (Figure 7). The changes relate firstly to the two cells "C1 User Needs" and "P1 System Requirements" which have been renamed respectively to "C1 Stakeholder needs" and "P1 Goals and Objectives", secondly the merger of the "Concept C4 Layer Effectiveness Measurements with Problem Layer P4 Cell".

	Pillar				
Layer of Abstraction		Requirements	Behavior	Structure	Parametrics
	Concept	C1 Stakeholder Needs	C2 Use Cases	C3 System Context	C4-P4 Measurements of Effectiveness
	Problem	P1 Goals & Objectives	P2 Functional Analysis	P3 Logical Subsystems Communication	
	Solution	S1 Component Requirements	S2 Component Behavior	S3 Component Assembly	S4 Component Parameters

Figure 7 MBSE Grid [25]

Another work carried out by [26] where the initial MBSE grid is kept with two adjustments made (Figure 8). The first modification concerns the name of cell C1, renamed to "C1 Stakeholder Needs". The comparison made by the authors with existing EAF frameworks, reveals two main points of view in harmony with the MBSE grid, to manage the abstraction layers, one area to define the problem and another to propose a solution. The proposed grid has two areas: the problem and the solution. The first "problem" domain, first describes the system as a whole (Need of Stakeholders, Use Case of the System and its context and the measurement of parameters), then the expected behaviors of the subsystems, these two tasks are designated respectively "Black Box" and "White Box".

To facilitate the modeling task, the authors developed a SysML MBSE grid by the method of instantiating each of the nine views (cells) of the system model by SysML diagrams (Figure 9).

D. MBSE Grid adopted

For the purposes of this paper, the MBSE Grid approach updated by [26] is adopted with slight modifications concerning the domain names of the grid. Combining with Bombardier Transport SysMM's MBSE methodology which takes place in three main phases by analysis: operational, functional and technical. In our modeling approach, we also use these three main analysis approaches (Figure 10):

- **Operational Analysis:** its purpose is to define the mission of the system, the services it offers and the relationships with its environment;
- **Functional Analysis:** it aims to explain the logical functioning of the system;
- **Technical or Structural Analysis:** it presents how the physical components (Hardware, Software) are structured for the proper functioning of the system.

The purpose of the study is to conduct an operational analysis of the MBSE Grid approach adopted, to implement a Health Monitoring and Management Unit (HMMU) of a hydroelectric group.

	Pillar					
Layer of Abstraction			Requirements	Behavior	Structure	Parametrics
	Problem	Black Box	Stakeholder Needs	Use Cases	System context	Measurements of Effectiveness
		White Box	System Requirements	Functional Analysis	Logical Subsystems Communication	MoEs for Subsystems
	Solution		Component Requirements	Component Behavior	Component Assembly	Component Parameters

Figure 8 MBSE Grid framework [26]

			Pillar			
Layer of Abstraction			Requirements	Behavior	Structure	Parametrics
	Problem	Black Box	Stakeholder Needs: <ul style="list-style-type: none"> Requirements diagram Requirements table 	Use Cases: <ol style="list-style-type: none"> Use Case diagram Activity diagram 	System context: <ul style="list-style-type: none"> Internal block diagram 	Measurements of Effectiveness: <ul style="list-style-type: none"> Block definition diagram
		White Box	System Requirements: <ul style="list-style-type: none"> Requirements diagram Requirements table 	Functional Analysis: <ul style="list-style-type: none"> Activity diagram 	Logical Subsystems Communication: <ol style="list-style-type: none"> Block definition diagram Internal block diagram 	MoEs for Subsystems: <ul style="list-style-type: none"> Block definition diagram
	Solution		Component Requirements: <ul style="list-style-type: none"> Requirements diagram Requirements table 	Component Behavior: <ul style="list-style-type: none"> State machine diagram Activity diagram Sequence diagram 	Component Assembly: <ol style="list-style-type: none"> Block definition diagram Internal block diagram 	Component Parameters: <ul style="list-style-type: none"> Parametric diagram

Figure 9 MBSE Grid mapping to SysML [26]

			Pillar			
Layer of Abstraction			Requirements	Behavior	Structure	Parametrics
	Operational Analysis		Stakeholder Needs	Use Cases	System context	Measurements of Effectiveness
	Functional Analysis		System Requirements	Functional Analysis	Logical Subsystems Communication	MoEs for Subsystems
	Technical Analysis		Component Requirements	Component Behavior	Component Assembly	Component Parameters

Figure 10 MBSE Grid framework adopted

III. OPERATIONAL ANALYSIS OF THE HMMU UNIT

A. Description of the hydroelectric group

The hydroelectric group object of our study consists of (Figure. 11):

- A turbine designating the device whose mission will be to convert the hydraulic energy of the fluid entering the group into mechanical energy;
- An alternator which consists of converting the mechanical energy supplied by the turbine into electrical energy, through the stator and the rotor;
- Adjustable valves, called guidelines, regulating the flow of the fluid at the inlet of the turbine valves;
- The blades of the turbine which transforms the hydrodynamic energy of the fluid into rotational driving energy;
- A common axis of rotation of the turbine and the alternator, the purpose of which is to drive the generator (Alternator).

Figure 11 Components of a hydroelectric group

Source: M. Bouaicha et al., 2021 [28]

The Table I list the properties of the hydroelectric group.

TABLE I
CHARACTERISTICS OF THE HYDROELECTRIC GROUP [27], [28]

Type	Francis
Axis	Vertical
Rotation speed	333 rpm
Power	80 MW
Number of blades	17
Number of guide bearings	2
Number of bearing or pivot bearings	1
Number of directors	24
Number of poles	18
Alternator bearing clearances	460 μm
Intermediate level clearances	460 μm
Turbine bearing clearances	420 μm

The 80 MW hydroelectric group is operated alternately with other groups in the plant, which depending on the network, start or stop the production of electrical energy. Installed for three decades, the unit now has cracks in certain welds of the braces. To assess this defect, two studies were carried out by [27], [28] in partnership with a service provider specializing in condition-based maintenance of rotating machines using vibration analysis, the objective of which is to find out whether the vibrations are at the origin of these cracks.

The group's axis is carried by 3 bearings which ensure the rotational guidance of the turbine and the alternator: an upper alternator bearing (PAS), a turbine bearing (PTU) and a lower alternator bearing (PAI). On these bearings are installed the sensors for the measurement of vibrations and the movements of the axes of the bearings.

Figure 12 Arrangement of measuring points on the bearings

Source: M. Bouaicha et al., 2021 [28]

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The diagnosis was carried out by performing tests in several operating modes to determine the types of faults that the group shaft may have. The identified faults are: unbalance, angular misalignment of the upper alternator bearing, and high displacements of the centers of the turbine and upper alternator bearings, the values of which place them in critical areas. The summary that emerged during the study [28] provides for permanent monitoring of the bearing clearances, the objective of which is to predict the horizon for exceeding the thresholds of the standardized global vibration levels and the bearing clearance limits recommended by the manufacturer. With this in mind, a unit, of great importance, which deals with the monitoring and management of the state of health (HMMU) of the hydraulic unit will have to be installed.

B. Operational Analysis of the HMMU

The first step in the business analysis phase is to define Stakeholder needs, including guidelines related to regulations, standards, etc. The SysML requirements diagram (req) is best suited to express the needs. Each specified need is manifested by a requirement. All the needs can be expressed in a diagram view.

In the case of the HMMU unit, two needs are analyzed in depth:

- SN1: Unit Management Modes - The unit must be able to monitor the machine in modes: Offline or On-line.
- SN2: Data Type - The unit collects and analyzes vibration signals and displacement measurements of the bearing pins.

These needs are expressed and represented in the SysML requirements diagram (Figure 13). These requirements are then refined and analyzed. The "Unit Management Modes" requirement is refined by the "Monitor and Manage Machine Health" use case (uc) (Figure 14). Use cases (uc) express the actions or tasks performed by the actors and the unit. The use case diagram must be developed according to the context of use of the unit, thus Figure 14 details the use case "Monitor and Manage Machine Health" in the context "Machine On or In Maintenance Intervention".

A use case is clarified by a flow of actions in the form of a scenario of exchanges between the actors and the system. This scenario is represented by the SysML activity diagram, where the actors and the system are modeled by channels. Figure 15 details the "Monitor and manage machine Health" use case scenario, where unit activities are considered top-level functions.

Subsequently, the definition of the context of the system is necessary to show how the HMMU unit interacts with its external environment (User, Machine, D.B Storage, Control Room, etc.). The SysML internal block diagram (Figure 16) is used as well, in order to manifest these interactions in the context of "Machine On or In Maintenance Intervention".

The final step of the analysis is the specification of the non-functional objectives of the stakeholders submitted digitally. This step is called "measures of effectiveness". A separate block will be created to manifest these operational parameters of the HMMU unit, shown in the SysML block definition diagram (Figure 17).

Figure 13 Stakeholder needs expressed in requirements diagram

Figure 14 Diagram Unit Use Cases

Figure 15 Use Case Scenario

Figure 16 Unit System Context

Figure 17 Measurements of Effectiveness

The relationships between the diagrams (Traceability) make it possible to organize the models, and to follow the steps of the MBSE process throughout the system modeling process.

The relationships made during the development of diagram models (Requirement, Use case, etc.) are illustrated in figure 18.

Figure 18 Relationships between MBSE models

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IV. CONCLUSION AND PERSPECTIVE

Many systems modeling approaches have been proposed and used in case studies or real projects, in the field of engineering or in the context of enterprise architecture. Most of them are particularly conceptual and offer a complex or even ambiguous approach, difficult to implement and it does not rely on a modeling language based on models. The most recent is the MBSE Grid methodology based on viewpoints (abstraction domains). It has been adopted and adjusted by perspectives of behavioral, functional and technical analyzes, which will be represented using the diagrams of the SysML language.

The successful implementation of this approach on real projects prompted us to use it in our modeling approach for the implementation of a monitoring and surveillance unit for the health of the hydroelectric group, within the framework of a maintenance management policy using a predictive strategy. The operational analysis process deployed, including the partial results presented in this paper, has proven its effectiveness in modeling systems. Our short-term objective is to continue our implementation project of the HMMU unit by proposing the modeling suite by the two phases of functional and technical analyzes allowing respectively to explain the operation of the system and how it will be its future structure. .

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