International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

June 2024	Issue 59	Volume 16	Number 2	Pages 151-161

MODEL-BASED FUNCTIONAL SPECIFICATION PROCESS - A CASE STUDY FOR INTEGRATION OF HMMU IN CONTROL SYSTEM OF HYDROELECTRIC GROUPS

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Abstract- Systems engineering is a study framework made up of different system modelling activities that can be carried out using different approaches. The "MBSE Grid" approach presented and adopted in the work carried out in article [1], of which I was principal author, takes place in 3 phases: operational, functional, and technical. During the operational analysis process carried out during this study [1], the concepts manipulated within each activity of this process: Elicitation of stakeholder needs, Expression of use cases and scenarios, Description of the context and the definition of the parameters for measuring the effectiveness of the "HMMU" unit were detailed. SysML was selected as the appropriate activity modelling language. In the present paper, we continue the system engineering study based on the "MBSE Grid" approach, through a functional specification process, for the integration of Health Monitoring and Management Unit (HMMU) of a dam's hydroelectric groups. The classic functional analysis methodology, consisting of both external and internal viewpoints, presents several challenges, which can be summed up in the ambiguity of the procedure for elaborating the relationships between the specification and design layers of system. The functional specification process, considered as the second phase of the "MBSE Grid" approach implemented in this article, thus makes it possible to build models representing the requirements analysis of the "HMMU" unit, identify its functions and explain their logical organization independently of the way in which they will be realized.

Keywords: Functional Specification Process, SysML, MBSE Grid.

1. INTRODUCTION

The System engineering originated in the USA in the 1960s [2]. Those who initiated its development were the owners of complex artifacts such as aircraft, weapons systems, telecommunications networks, large software packages and so on. They assumed that systems thinking would provide useful concepts for better structuring and management of projects involving many contractors with a wide range of skills. Several scientific, normative, and industrial communities propose different definitions of systems engineering. This is the case for those proposed by INCOSE (International Council on System Engineering) [3] and AFIS (French System Engineering Association) [4]. These differences lead to confusion between system engineering (the framework for studies) and system design (the activities carried out by engineering disciplines). Systems engineering is a framework that encompasses all the activities of engineering disciplines. This multidisciplinary framework defines the perimeters of the disciplines' studies. It is defined as a cooperative, interdisciplinary methodological approach encompassing a set of activities appropriate to design, develop, and test a set of products, processes and human skills. This whole is integrated into a system in a context of balance and optimization, providing a cost-effective, high-performance solution to the needs of stakeholders that is acceptable to all (IEEE 1220 [5]).

The various engineering disciplines develop models. These models are the central object of scientific problems in engineering disciplines. The nature of a model depends on the framework used: mathematical, computational (language, algorithm) or graphical (behavioral, structural representation, etc.). In systems engineering [6], a model is an abstraction of a real or studied system. It is based on a framework adapted to a set of objectives and representations defined by a point of view. Systems engineering approaches produce technical methods based on MBSE models to carry out its general activities. MBSE methods are designed to support communication between different engineering fields [7]. It suggests how to model systems, create their structures, and specify the order in which they are to be used [8, 9]. To guarantee successful operationalization of the system modeling, the metamodel language must coordinate with the methodology MBSE to be effective [10]. It specifies the semantics (Study of signified) and syntaxes used to build models. In the last decade, MBSE methods have adopted the SysML modeling language, but they do not offer recommendations or guidelines during the modeling process [11].

Registered: 230820 Article Info: 1791 Accepted: 240518
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Main system engineering standards such as IEEE 1220 [5], EIA 632 [12] and ISO 15288 [13] specify the processes applied during the system development cycle. The information structured during the expression of stakeholder needs is essential for the definition of system requirements and architecture. According to the MBSE Grid approach adopted by [1], this system architecture can be broken down into 3 visions: Operational, Functional and Technical. The operational view represents the description of stakeholders' needs in terms of the services provided by the system. This view defines the requirements relating to the system's potential operators, the system's life cycle, and the performance and context in which the system is to be used. The functional view identifies the system's functions and explains how they are organized (logical operation), independently of how they will be realized. In the context of these two visions, a study is proposed in [14], where the authors propose an operational and functional analysis for the management and control of production at a phosphate mining site. Whereas the technical (or organic) vision defines the way in which the system is concretely realized, in other words, the organization of hardware and software components.

In this paper, we continue the system engineering study carried out by [1], of which I was principal author, during the first phase of operational analysis for the integration of a Health Monitoring and Management Unit (HMMU) for the hydroelectric units of a dam. Beginning with a description of the HMMU's mission and culminating in the precision of the parameters for measuring its effectiveness were detailed. The second phase is the functional vision based on the functional analysis process. The aim of this process, which was carried out in this paper, is to provide an understanding and answer to what is expected, rather than already providing a design for the unit. The functional description should not cover the physical architecture of the system.

A 3rd phase of technical analysis at a later stage could propose several alternative solutions. Within this framework of system control unit design and implementation, the authors of paper [15], carry out a design and integration study of a photovoltaic energy monitoring system for a telecom power station. We begin this paper, in Part 2, by outlining the requirements set out in the standards governing systems engineering, such as IEEE 1220 [5], EIA 632 [12] and IEC 15288 [13]. Section 3 is devoted to functional analysis using the MBSE Grid approach, to define how the unit (HMMU) works, and how it behaves to deliver the services described in the operational vision [1]. In Part 4, conclusions are revealed, and prospects are mentioned.

2. REQUIREMENTS DEFINITION PROCESS

2.1. Requirements Definition and Classification

There are many classifications of requirements. These classifications are primarily presented and used to organize requirements definition and validation activities.

So, whatever the categories used, the same mechanisms or relationships will always come into play when defining requirements: decomposition, refinement, and derivation [16]:

- Decomposition relationship: This consists in splitting a requirement into 2 or more sub-requirements. This is the main mechanism for defining requirements. Based on the needs expressed, it enables us to build up a requirements repository of sufficient detail for the other system engineering activities: functional analysis and organic breakdown of the system.
- Refinement relationship: This consists of detailing the definition of a requirement, by modifying the requirement or associating a property with it. Indeed, IEEE standard 1220 [5] and IEC 15288 [13] refer to the need to express requirements as clearly as possible when defining them, if necessary, using properties formulated in a specific business language: formal descriptions, computer algorithms, mathematical equations, electrical diagrams, etc.
- Derivation relationship: This represents the relationship that links a requirement A to a requirement B, when B exists as a result of compliance with A in a particular context. For example, when a technical requirement exists by application of a normative requirement, there is a derivation relationship between these two requirements.

Several classifications of requirements are dictated by the standards governing systems engineering. The EIA 632 standard [14], for example, proposes 33 very specific categories for classifying requirements. Table 1 illustrates a requirements classification specific to IEEE standard 1220 [5]. The 15 requirements definition steps detailed in this figure are associated according to a particular hierarchy which illustrates the levels of precision and refinement of the requirements. The first 4 steps, numbered 1 to 4, correspond to requirements that emerge directly from the expression of stakeholder needs. These stages will therefore be carried out very early on and will consist of formalizing in the form of requirements the expectations formulated during the elicitation of needs.

Table 1. Requirements definition and classification [5]

1. Expression of stakeholders' needs	1. Define the aspirations of stakeholders
	2. Define the constraints of the project and the company
	3. Specify external constraints (standards, etc.)
	4. Establish operational scenarios
2. Refinement of stakeholder requirements	5. Define system limits
	6. Specify system interfaces
	7. Specify the usage environment
	8. Specify the system life cycle
3. Defining functional requirements	9. Define system requirements
4. Definition of performance requirements	10. Define component requirements
5. Refinement of functional and performance requirements	11. Define system limits
	12. Define system interfaces
	13. Define user environment
	14. Define the system life cycle
6. Definition of requirements framework	15. Organize the requirements defined in the previous stages: operational, functional, and organic

Steps 5 to 8 refine the previous requirements by going beyond the level of detail developed during the need's elicitation. Step 9, "Define functional requirements", formalizes the functional analysis into system requirements. Step 10, "Define performance requirements", relates to the system description. Defining these requirements has an impact on the choice of system components. Similarly, design choices and constraints may require a review of these requirements. The final steps, numbered 11 to 14, involve refining functional requirements (9) and performance requirements (10). Finally, step 15 corresponds to the organization of the requirements defined through all the steps described above, according to the three categories of requirements.

2.2. Requirements Validation

To ensure the quality of written requirements, a related activity to requirements definition is requirements validation. According to the previously cited system engineering standards IEEE 1220 [5], EIA 632 [12] and IEC 15288 [13], requirements validation consists of two distinct aspects:

- The complete requirements repository must be coherent. The requirements must respect the constraints defined during the expression of needs and transcribe all the elicited needs. This aspect represents a sub activity of requirements definition, generally carried out at the end of the process.
- The requirements repository as part of the project must be consistent with the rest of the project information. This is a consistency control activity for the project, verifying that the requirements are indeed respected in the rest of the system specification. This step is more a validation of the system against the requirements than a validation of the requirements.

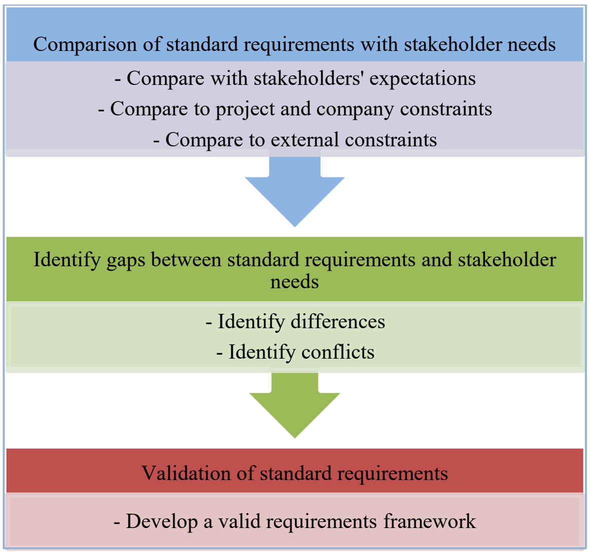

Figure 1. Requirements validation [5]

Requirements validation therefore corresponds mainly to the first aspect described above. The diagram in Figure 1, taken from the IEEE 1220 standard [5], represents the validation of requirements.

The requirements defined in the repository are the input to the activity validation process. After comparison, in the event of conflicts or differences, the validation activities loop back to the requirement definition activities to correct any discrepancies. The requirements are validated individually, and then the process continues with activities to check that all the requirements are consistent with each other and with the rest of the project.

The importance of the link between requirements and system description entities is such that it facilitates control and validation activities. Two types of relationship may be involved:

- Satisfaction relationship: this relationship is used to define the entities that satisfy a particular requirement. For example: a bicycle wheel considered as an entity (component) can satisfy an operational requirement of wheel diameter.
- Verification relationship: this relationship is used to define the entities used to test compliance with a requirement. For example: the description of a mechanical power test enables verification of a motor performance requirement.

These relationships enable requirements validation activities to be carried out for the project. Validation can check that all requirements are satisfied and verifiable.

2.3. Requirements Representation in SysML Language

Based on the SysML (OMG 2012) standard [17], we can define the necessary and sufficient SysML mechanisms for carrying out the requirements definition and validation activities described above. The SysML standard (OMG 2012) [17] contains a modelling element (model) specific to the representation of a requirement and a set of dedicated relationships. These include the requirement definition relationship elements: decomposition, refinement, and derivation. Other elements of the requirements validation relationship are verification and satisfaction.

Table 2 shows graphical symbols in SysML for requirements and useful hierarchical and traceability relationships.

Table 2. Representing requirements and their relationships in SysML language [17]

Concept	Element	Graphic entity
Requirement	Requirement	« Requirement » Requirement Name
Decomposition	Containment	⊕————
Refinement	Refine	« refine » - - - - - ->
Derivation	DeriveReqt	« DeriveReqt - - - - - ->
Verification	Verify	« Verify » - - - - - ->
Satisfaction	Satisfy	« satisfy » - - - - - ->

The requirement is represented as a rectangle bearing the "Requirement" header and the requirement name. A requirement in SysML has two main properties: "id" and "text". The "id" property assigns a unique identifier to each requirement, enabling it to be traced. The "text" property corresponds to the requirement's designation in natural language.

The "decomposition" relationship between two requirements is used to structure the requirements hierarchy. The "refine" relationship corresponds to the need to describe a requirement with various entities outside the pure definition of requirements. As such, it always links a requirement at the tip of the arrow with any other element, including another requirement, that refines the requirement. The derivation relationship highlights the connection between two requirements. The SysML relationship "deriveReqt" thus connects two requirements: the origin of the arrow represents the requirement that exists because of the requirement at the tip of the arrow. Requirement satisfaction is represented by a "satisfy" arrow whose origin represents any entity that satisfies the requirement at the tip of the arrow. Finally, the "verify" relationship links any entity at the origin of the arrow that enables verification of the requirement to which the arrow points.

3. FUNCTIONAL ANALYSIS OF HMMU

3.1. HMMU Operational Analysis

The HMMU operational analysis process, as described and elaborated in [1], is carried out in 4 essential steps:

- Express stakeholder needs: this involves expressing the requirements gathered from the system's various stakeholders.
- Define the unit's use cases: Represent the refinements of stakeholder requirements. Every use case outlines the objectives users aim to accomplish while utilizing the system. It also encompasses scenarios that delineate the sequences of actions within use cases.
- Define the context: This is the environment in which the system will evolve. Within the boundaries of this context, the system interacts with its various stakeholders.
- Measuring system efficiency: Describes the non-functional objectives set by the user for the system, expressed in numerical form.

Figure 2 summarizes the steps in the operational analysis process, where they are modeled by SysML diagrams. The initial phase in the operational analysis process involves delineating stakeholder requirements, encompassing regulatory directives, standards, and so forth. The SysML requirements diagram (req) is most suitable for articulating these needs. Every specified need is manifested through a corresponding requirement. In the subsequent phase, the specified requirements undergo thorough analysis and refinement within use case diagrams (uc). These diagrams effectively illustrate the actions or tasks carried out by both actors and the system. It is imperative that the use case diagram is tailored to the specific contextual usage of the unit.

A use case is elucidated through a sequence of actions, constituting an exchange scenario between the actors and the system. This scenario is visually captured through the SysML activity diagram, where actors and the system are depicted and interconnected by corridors.

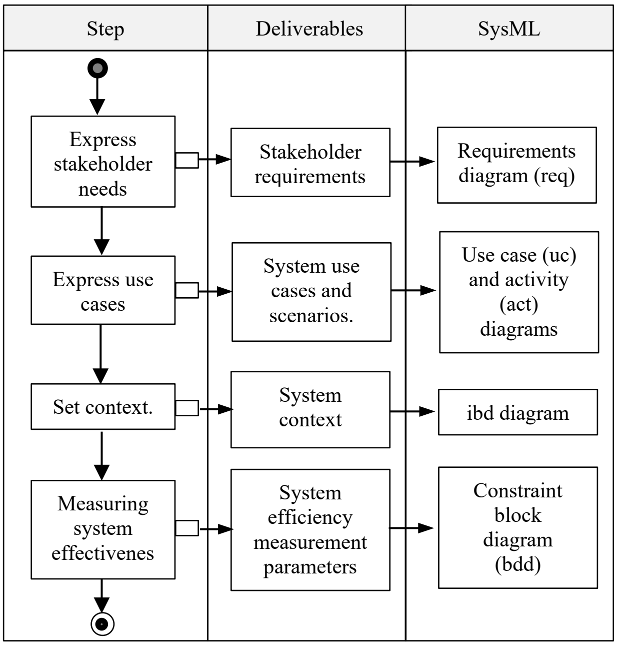

Figure 2. Summary of the operational analysis process.

Following this, the system context is established to illustrate the interactions between the HMMU and its external environment (Users, Machines, Database Storage, Control Room, and others). The internal block diagram is employed to depict these interactions specifically within the framework of "Machine On or in maintenance intervention". The concluding phase involves detailing the non-functional objectives presented by stakeholders in a quantitative format, termed as "effectiveness measures". A distinct block will be established to articulate these operational parameters of the HMMU, as illustrated in the block definition diagram.

The HMMU operational analysis process deployed in [1], whose partial results are represented by SysML diagrams, is illustrated in Figure 3. The relationships between the diagrams (Traceability) make it possible to organize the models and follow the steps of the methodology MBSE throughout the unit modelling process.

3.2. HMMU Functional Analysis

3.2.1. MBSE Grid Functional Analysis Process

The classic functional analysis methodology (Figure 4), which relies on both external and internal points of view, presents several problems that can be summed up in the ambiguity of the procedure for elaborating the relationships between the specification and design layers of the system. It is best suited to systems engineering activities for the specification and design of simple products, but not entirely suitable for complex systems.

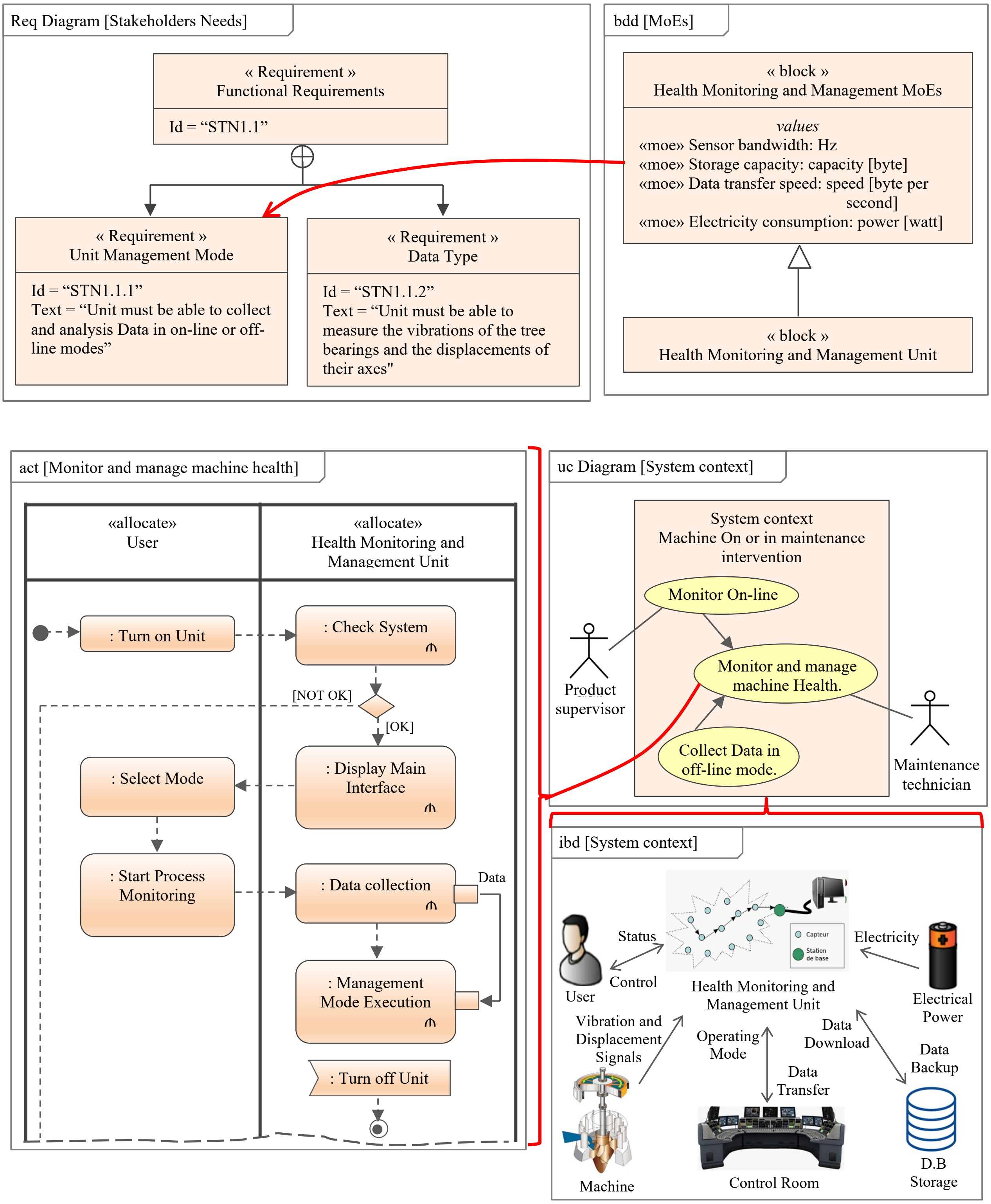

Figure 3. Synthesis of the "MBSE" models developed during the operational analysis of the HMMU unit [1]

The process of functional analysis according to the "MBSE Grid" methodology will take place after the previous process of defining the requirements or needs of stakeholders through operational analysis has been initiated. These established requirements thus constitute the inputs to this process. The continuity and coherence of all these activities must be ensured by correspondence between the different entities handled. We have already presented the relationships specific to requirements, which enable them to be validated and controlled (satisfaction, verification, etc.). During functional analysis, a new relationship useful for traceability is introduced: functional allocation.

This relationship describes the link between the function defined during the functional analysis and the component described during the technical analysis activity (organic description) which performs this function. A function can be allocated to several components, and several functions can be allocated to a single component or to an embedded unit of components. The level of detail when describing system functions can vary from one user to another.

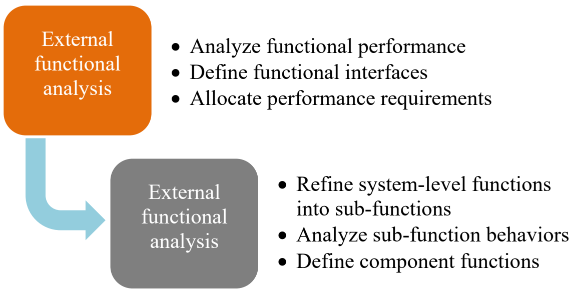

Figure 4. Summary of the operational analysis process

The second stage in methodology "MBSE Grid" to HMMU modelling is the functional specification. The procedural aspect of this functional analysis phase enhances the depth of the conducted operational analysis. The aim of this process is to describe and explain the logical operation of the unit.

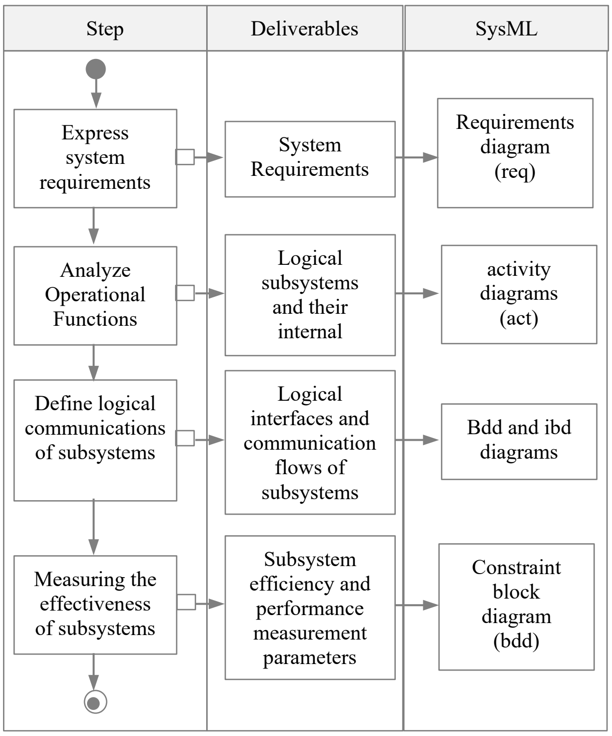

Figure 5. MBSE Grid functional analysis process.

The functional analysis process, as described in the "MBSE grid", consists of 4 essential steps:

• Express system requirements: Through the analysis of stakeholder needs, identify and define the specific system requirements.

• Analyze operational functions: This constitutes a further iteration in the enhancement of use cases, employing activity diagrams for refinement. At a more elevated level of abstraction, operational functions are identified and need to be refined. This stage is also instrumental in the identification of logical subsystems tasked with executing a set of functions.

• Define logical subsystem communications: Used to identify how the system communicates with logical subsystems.

• Measuring subsystem effectiveness: Define Measures of Effectiveness (MoEs) and Performance (MoPs) for subsystems and establish methodologies for their evaluation.

Figure 5 summarizes the steps in the functional analysis process of the MBSE Grid approach.

3.2.2. SysML Modelling Approach

The system requirements are directly tied to operational analysis specifications and are systematically derived from stakeholder needs during the development of logical subsystem communication views. The example in figure 6 illustrates the derivation of the system requirement (SysR1: System Requirement) "Data collection and processing" from the Stakeholder Requirement (STN1.1.1: Stakeholder Needs) "Unit Management Mode". The latter was expressed in the requirement diagram in figure 13 of paper [1].

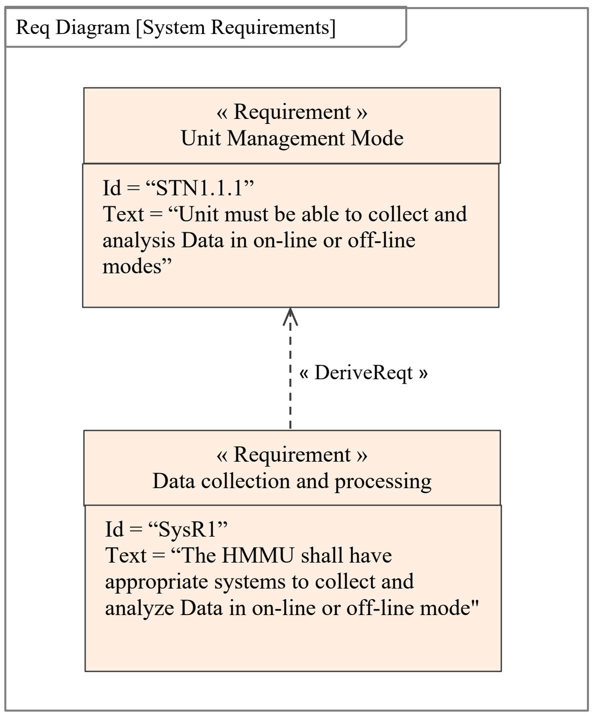

Figure 6. Deriving a system requirement from the needs of stakeholders

In the second phase of functional process, there is a continued refinement of use cases through the utilization of activity diagrams. Once the system's high-level functions have been identified as operational functions, they can be refined. For every system function, it is essential to generate an activity diagram. The "MBSE Grid" methodology enforces specific refinement rules to maintain consistency across hierarchical levels. for instance, the swim lanes depicted in the activity diagram must accurately represent logical subsystems.

Figure 7 illustrates an activity diagram depicting the "Management Mode Execution" function. The diagram includes two swim lanes, with one representing the "Data Transfer Group" subsystem and the other representing the "Analyzer Group" subsystem. Following this, each identified function with symbol ⋔ can either:

• Undergo further refinement through the creation of a new activity diagram.

• Refine a System Requirement, for instance, the "Analysis Data" refines SysR1 "Data collection and processing".

The activity diagram serves as a valuable tool for pinpointing logical subsystems. The next step is to define the connectors and interfaces that facilitate communication between them.

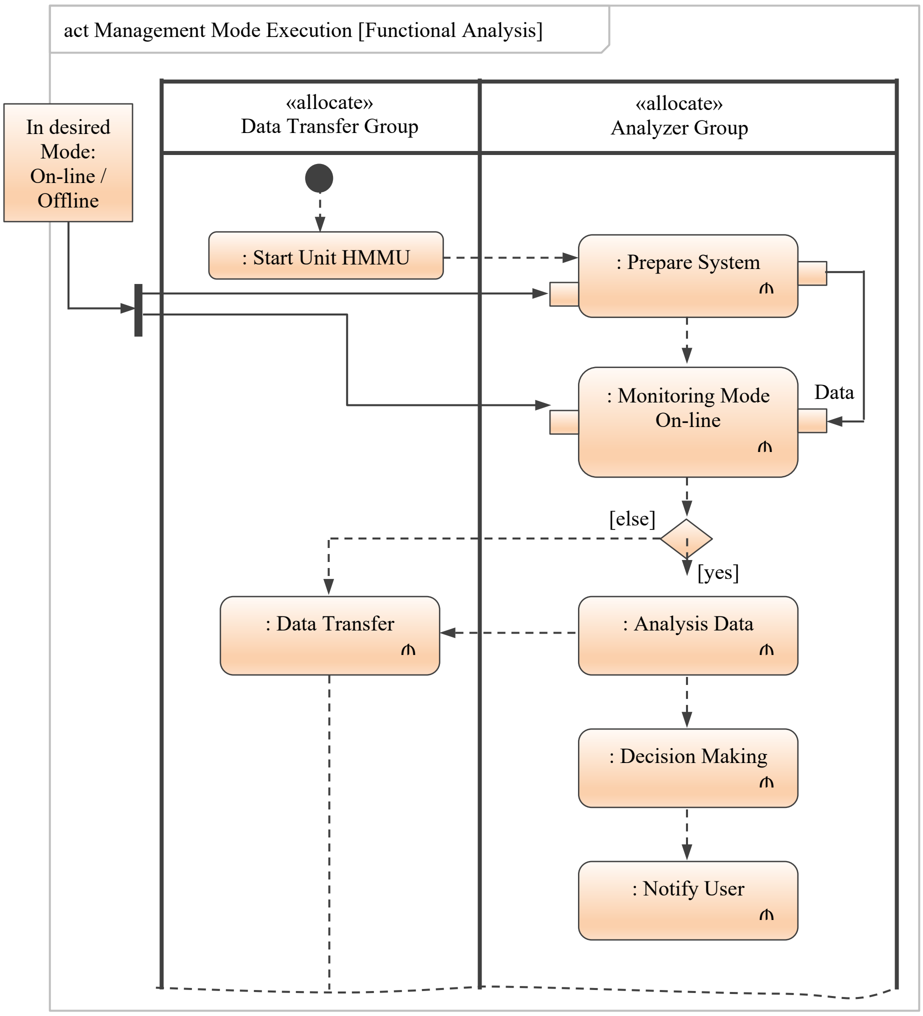

Figure 7. Refinement of an operational function

As per the MBSE grid, during the third step of defining logical subsystem communications, an initial block definition diagram is crafted for the entire system (Figure 8), followed by the creation of individual block definition diagrams for the logic subsystems. Following that, an internal functional diagram is established for the system. The objective is to form connections between the subsystems through interfaces. Figure 9 shows the internal block diagram for the Health Monitoring and Management Unit (HMMU). The diagram illustrates the communication flow of the "Analyzer Group" subsystem with other subsystems, notably the "Data Transfer Group".

The concluding phase involves specifying Measures of Effectiveness (MoEs) for the subsystems and outlining evaluation methods for them. The assessment procedures for MoEs are established using constraint blocks, and it is advisable to ensure that MoEs have detailed relationships with System Requirements. Traceability between the models of the views relating to the operational and functional analysis phases is a crucial view of the methodology MBSE. Figure 10 shows an extract of the relationships between the requirements and functions of the HMMU in our study, carried out during the development of the diagram models at each level of operational and functional abstraction.

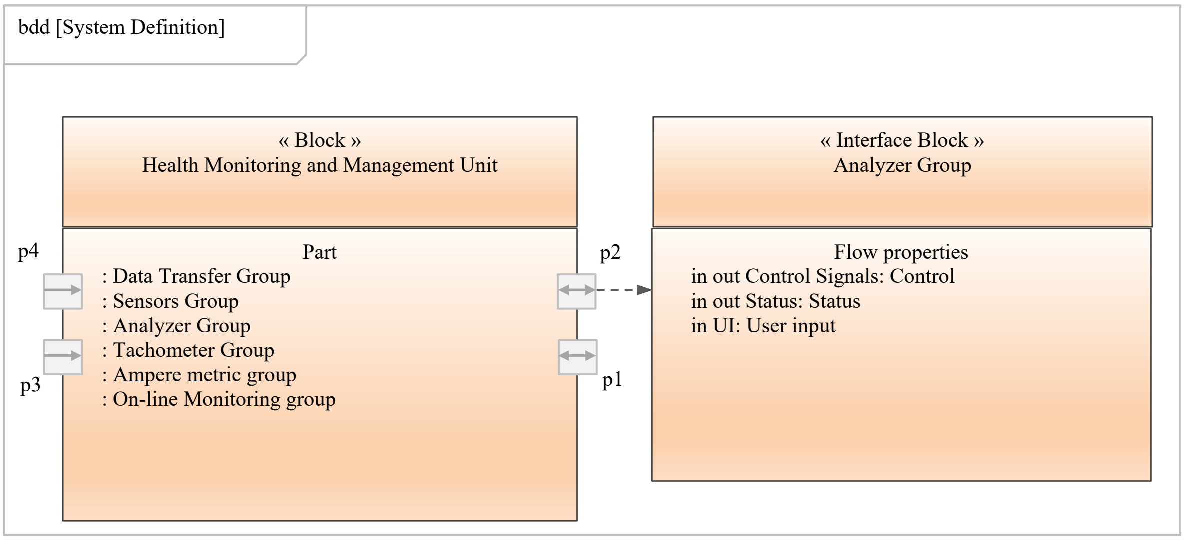

Figure 8. System definition diagram

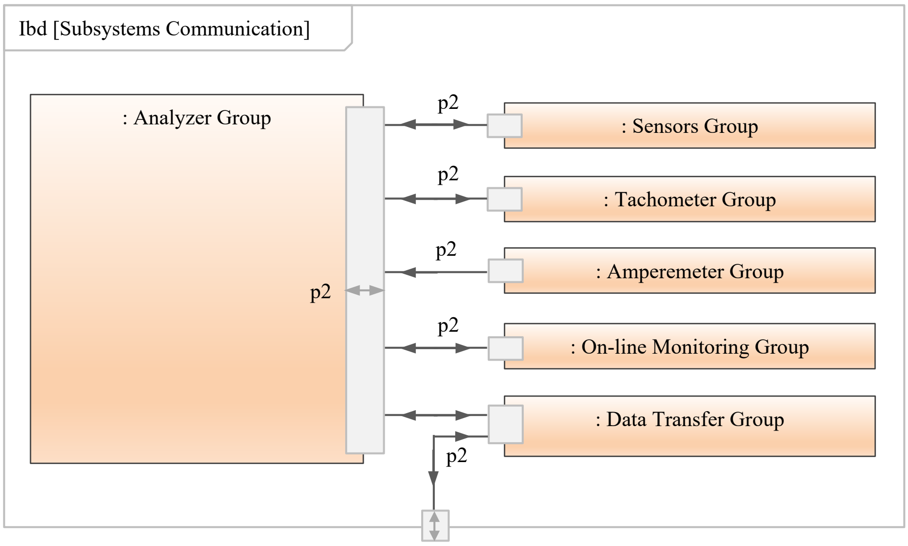

Figure 9. Subsystems communication

4. CONCLUSIONS

As part of our predictive maintenance strategy, we conducted a system engineering study to facilitate the integration of a Health Monitoring and Management Unit (HMMU) into the hydroelectric groups of a dam. The approach adopted is "MBSE Grid", whose first phase of operational analysis was carried out by [1]. In this article, the focus is on the modelling activities that are carried out as part of the functional analysis process in the MBSE methodology. The goal of this process is to understand how the "HMMU" communicates with logical subsystems. This understanding is achieved by examining the control and resource flows within the system. The article provides a description of the steps involved in this process, highlighting the importance of accurate modelling to effectively analyze the system's functionality.

The results of these activities are modeled using a wide range of SysML diagrams, and consistency between the established IS models is also illustrated by a set of allocation and traceability relationships. This provides the basis for system modeling based on the "MBSE Grid" approach, so that in a forthcoming paper, the "HMMU" implementation project can continue with the final phase of technical analysis to establish the unit's physical architecture, and how it will be structured in the future.

NOMENCLATURES

1. Acronyms

MBSE	Model-Based Systems Engineering
HMMU	Health Monitoring and Management Unit
SysR1	System Requirement No. 1
STN1.1.1	Stakeholder Needs No. 1.1.1

2. Symbols/Parameters

$p1$, $p2$, $p3$, $p4$: Parameters

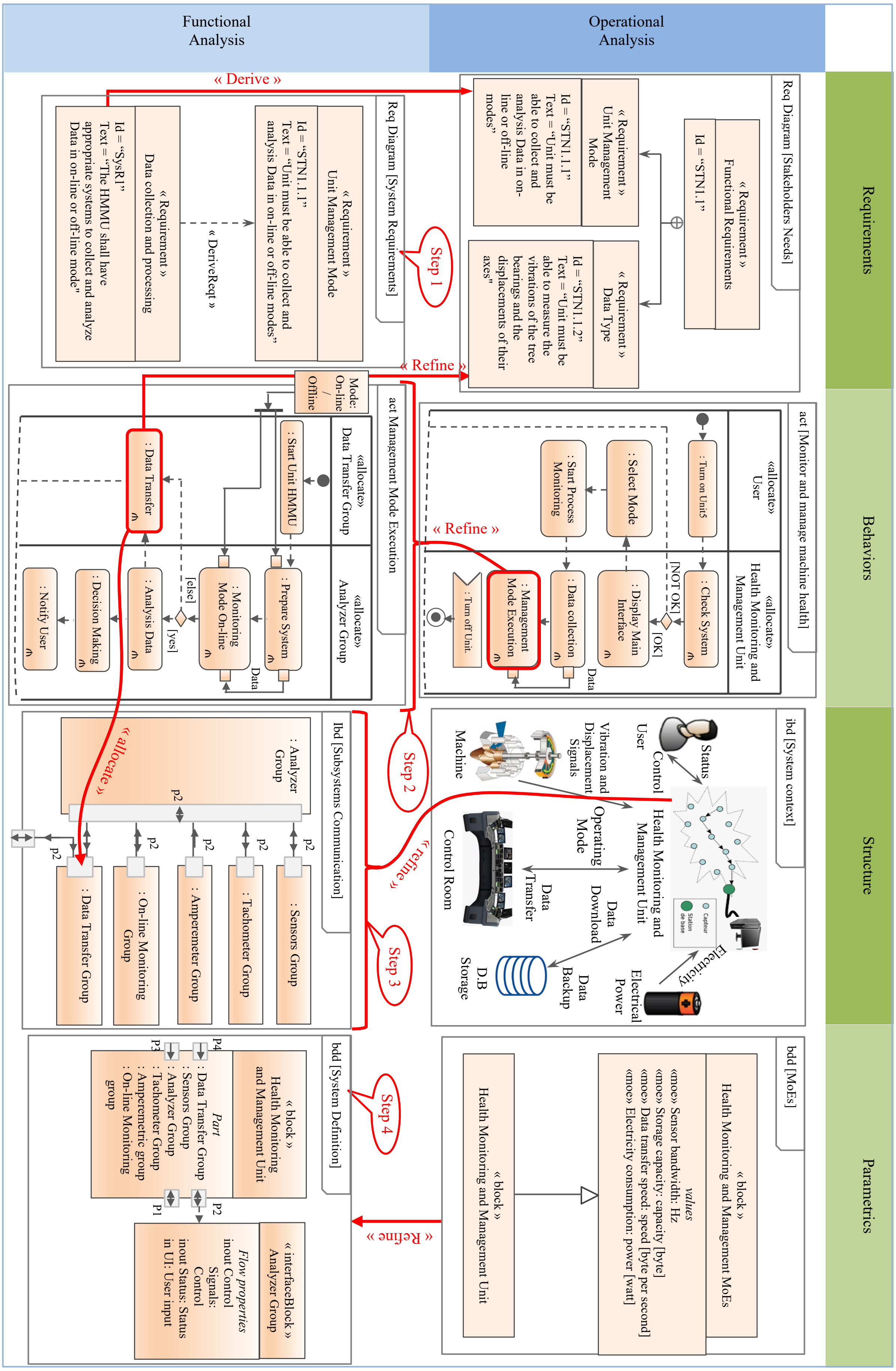

Figure 10. Extract of traceability in the HCMU

Figure 10. Extract of traceability in the HCMU MBSE grid

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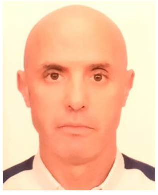
BIOGRAPHIES



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