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MODEL-BASED OPERATIONAL AND FUNCTIONAL ANALYZES FOR COMPLEX MULTIDISCIPLINARY SYSTEM: A CASE STUDY FOR A MINING PRODUCTION CONTROL SYSTEM

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Abstract- Many conceptual models have been presented and applied in various manufacturing domains. However, few works were devoted to the mining sector. Indeed, Open pit mines by their very nature present several challenges in terms of controlling the various operations and processes that govern their overall operation. Among these challenges and constraints, we cite mainly the heterogeneity of their hardware and software infrastructures, the complexity both in terms of the physical systems that constitute their physical environment and the management systems that define their managerial environment. This paper presents an operational and functional analysis of a mining site which is considered to be a complex system using the Model Based Systems Engineering (MBSE) approach and framed by the CESAM method, illustrated by a case study on the production control system of the fixed installations of a phosphate open-pit mine. These analyzes were performed with the help of managers and operational staff within a mining phosphate company and allowed us to identify lifecycle, stakeholders, needs, use case and requirements of the system of interest. The conceptual models produced in this article are performed with the Systems Modeling Language (SysML).

Keywords: Complex System Engineering, Mining Indusry, Model-Based System Engineering (MBSE), SysML, System Modeling.

1. INTRODUCTION

Manufacturers increased their production and improved their performance thanks to the industrial revolution and stronger competition; which has reduced costs, improved economic performance and provided business opportunities [1], [2]. The mining industry has not escaped this revolution and competition and in particular surface mines which face several challenges and constraints in the management of mining operations and processes.

Open pit mine is a mining process that involves extracting minerals from the ground. It is a technique accepted and applied by industrialists which is used when the mineral deposit is near the surface, therefore not requiring tunneling [3].

Indeed, the phosphate open-pit mine encompasses a complex system comprising two types of installation: mobile installation and fixed installation. Each installation represents a system and has its own subsystems that interact with each other and the two installations themselves interact. In this paper, we will focus on fixed installations (FI), these subsystems and their interactions. The mine's FI is a complex multidisciplinary field which includes chemistry, process engineering, electrical engineering, mechanical engineering, etc. To manage this complexity in constantly changing circumstances, systems engineering (SE) approach, especially MBSE, is necessary to define the system using System Modeling Language (SysML). The combination of this language with appropriate methodologies and tools such as the MBSE approach, can be considered as a formal and detailed industry standard for the modeling of complex systems [4].

The objective of our study is the design of a production control system for an open pit mine by applying the MBSE approach. This approach will model our system in order to define its life cycle, to identify its stakeholders, to define its context and finally to describe its functional and non-functional requirements. We will use a framework inspired by the CESAM method (CESAMES Systems Architecting Method). Given the complexity of our system of interest, this paper does not present the complete design, but focuses on the operational and functional analysis by presenting non-exhaustive examples in the case study.

The paper is structured as follows: Section 2 the system engineering approach focusing on MBSE method, SysML language and CESAM framework. Section 3 presents the result and discussion. This section presents a case study that models and designs the production control system for an open pit mine. Section 4 ends with conclusion and perspectives.

2. MATERIAL AND METHOD

2.1. System Engineering

System engineering is an interdisciplinary approach which consists in developing, developing, upgrading and verifying a set of products, processes and human skills in order to provide a solution that is useful and acceptable to stakeholders [5]. The fundamental concept of SE is to break down complex systems into sub-systems that are easier to identify and develop. It is a methodology that offers the techniques and procedures necessary to support all stages of the analysis and development process (definition, analysis, and specification of requirements, architecture design, integration, and finally verification, validation and qualification of the system). One of the advantages of using the techniques of SE is to apply a holistic approach to the problem in order to have the most complete possible design [6]. Systems engineering mainly uses three standards: IEEE-1220, EIA/ANSI-632:" and ISO/IEC/IEEE-15288.

Complexity of systems forces organizations to apply a model-based approach in System Engineering activities, thereby the MBSE approach is used and it is the new system engineering approach. It uses models for the different activities of the system development process.

2.2. Model-Based System Engineering (MBSE)

MBSE is a process of engineering complex systems consisting in achieving objectives through the absolute application of models. Systems engineering projects are based on models by grouping together various specific tools in a field [7]. The characteristic of the MBSE is the storage of information in a central repository thus allowing the interconnection between the elements of the model and the analysis of the system. [8]. MBSE constitutes a chain linking objectives to requirements, requirements to functions, functions to physical architecture elements, etc. the number of elements linked in this chain depends on the degree of detail desired in the modeling [9]. Several advantages of the MBSE have been established by manufacturers, such as consistency of reasoning, management of complexity or the guarantee of exhaustiveness [10].

MBSE is based on three pylons: a specific modeling language, a methodology or framework and a modeling tool. [11]. A complete review of MBSE methodologies is provided in [12].

This article uses SysML modeling language, Cameo Systems Modeler software, and CESAM method as a framework (methodology).

2.3. SysML Modeling Language

The systems modeling language focuses on the design, analysis and verification of complex systems [13]. It is a diagrammatic modeling language for systems engineering [14]. SysML adopts some part of UML (Unified Modeling Language) and it is based on it. It replaces the modeling of classes and objects by the modeling of blocks for a vocabulary more suited to SE. SysML defines a standard header for each diagram that must contain the type of diagram (act, bdd, ibd, sd, etc.), the elements represented in the diagram (packages, blocks, activities, etc. ....), the name of the modeled element and the name of the diagram or view represented.

The SysML language contains 9 types of diagrams, some of which come from UML and break down as follows; Functional diagrams contains the use case diagram (uc) and the requirements diagram (req). Structural diagrams contain the block definition diagram (bdd), internal block diagram (ibd), parametric diagram (par) and package diagram (pkg) and Behavioral diagrams contains activity diagram (act), the state machine diagram (stm) and sequence diagram (sd). The main purpose of each SysML diagram is explained in [15]. SysML is adopted in various fields, such as avionics domain [16], automotive systems [17], safety information systems [18], mechatronic design [19], systems architecture [20], and in our case, we will use it in the mining industry.

2.4. CESAM Method

An architecture framework is used to provide guidelines and instructions for structuring, classifying and organizing systems architectures [6]. The framework applied in this paper is inspired by the CESAM method. This method is especially suited for the modeling of complex systems.

In order to analyze in a comprehensive way, the system, CESAM method uses three main visions: the operational vision, the functional vision and the physical or constructional vision. Reference [21] illustrates the different visions in CESAM method .

The operational vision specifies the missions of the system. This vision makes it possible to model the interaction of the system with its external environment. So, it sees the system as a black box.

Functional vision models the functions of the system. This vision allows the analysis of the interior of the system. So, it sees the system as a white box.

Constructional vision defines the concrete realization of the system. This vision makes it possible to model the concrete components of the system (hardware, software and human's elements). So, it sees system as a white box.

The generated models of the three visions are interrelated. Indeed, the missions of the system are carried out thanks to the functions and the components: this links the operational vision with the other visions. All the functions of the system are carried out by a set of physical components: this links the functional vision with the constructive vision. Finally, the functions required by the system's missions are activated by the physical components.

The CESAM method proposes five types of SysML diagrams for each vision. They are summarized in Table 1 [21].

Table 1. CESAM Systems Architecture Diagrams from [21]

Operational	Functional	Physical
Needs Architecture	Requirement Architecture	Requirement Architecture
Lifecycle	Functional mode	Configuration
Use case	Decomposition / Interaction	Decomposition / Interaction
Scenario	Scenario	Scenario
Flow	Flow	Flow

3. RESULT AND DISCUSSION

The phosphate open-pit mine is a complex multidisciplinary field (chemistry, process engineering, engineering, etc.) which encounters several problems such as heterogeneity of the processes, heterogeneity of the materials and heterogeneity of the software. In this study, we will focus on the production system of the fixed installation.

3.1. The Fixed Installation Phosphate Mining Process

The fixed installation represents the mechanical treatment of the mine which is divided into three stations:

- De-stoning station: its role is to remove stones from the different layers of phosphate each separately. The phosphate is received by hoppers which pour it into screens: the phosphate less than 90 mm^2 is transported to the storage yard and the phosphate greater than 90 mm^2 feeds a crusher which reduces it to a size between 0 and 300 mm^2 and transported to the sterile storage.
- Screening station: it supplies the hoppers with the stripped phosphate. It is screened a second time: phosphate less than 10 mm^2 is transported to final storage, phosphate greater than 10 mm^2 is sent to the sterile storage. The phosphate is transported by conveyors. The homogeneity of the desired quality is ensured at the level of final storage by horizontal and vertical homogenization.
- Train loading station: the bucket wheel picks up the screened phosphate and feeds conveyors to convey the phosphate to the train loading hopper.

Figure 1 shows the mining process of the fixed installation carried out with the activity diagram.

3.2. Production Control System for the Fixed Installation of an Open Pit Mine

Production control system is an intelligent system that operates production management, production forecasting and long and short-term production planning. This system provides mine stakeholders with the KPIs (Key Performance Indicator) necessary for decision-making. From this perspective, we design and model a production system in a very complex and uncertain environment by analyzing our system according to two visions: the operational vision and the functional vision. These analyzes were carried out with the help of managers and operational staff of a phosphate mining company.

3.2.1. Operational Vision

A static operational vision encompasses the mission of the system, its context, its boundaries and its interactions with its environment. To do this, we must first identify the lifecycle of our system, its stakeholders and their needs.

The definition of a system lifecycle provides a complete view of the system and sets up a methodology to ensure the needs of stakeholders in a structured and efficient way. The establishment of a system life cycle is not universal, each organization adapts to these needs in order to make the job as easy as possible.

For our case study, the lifecycle of our production management system includes five phases: design phase, development and implementation phase, installation and testing phase, usage phase and maintenance phase.

- Design phase: during this phase, the system, the interactions with its environment and the needs of the stakeholders are defined in order to describe the functioning of the system.
- Development and Implementation Phase: During this phase, the system needs defined in the design phase are transformed and translated into a programming language in order to build the system.
- Installation and testing phase: during this phase, the system is installed and commissioned within the company in order to verify it, test it and finally validate it.
- Usage phase: During this phase, the system is put into operation and operated in its environment to meet the services and user needs.
- Maintenance phase: during this phase, the system is maintained and updates are performed.

Figure 2 shows the lifecycle of our system. The operational context is modeled by the use of the block definition diagram for each phase of the system lifecycle. The first step is to identify the stakeholders for each phase. Table 2 shows the stakeholders for each phase. Figures 3 to 7 show the context diagram for each phase.

Table 2. Stakeholders for each phase

Stakeholders	Design phase	Development and Implementation Phase	Installation and testing phase	Usage phase	Maintenance phase
ISA-95 standard	x				
Maintenance system	x	x		x	
Quality system	x	x		x	
Inventory system	x	x		x	
IT engineers		x	x		x
Server		x	x	x	
Communication network			x	x	
Operators			x	x	
Expert engineers	x	x		x	

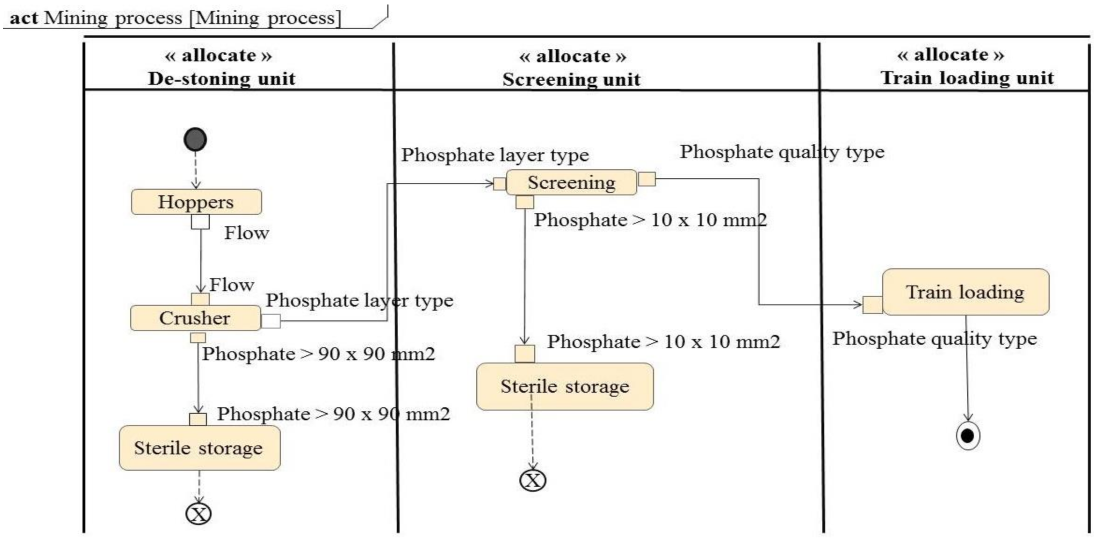

Figure 1. The phosphate mining process of the fixed installation

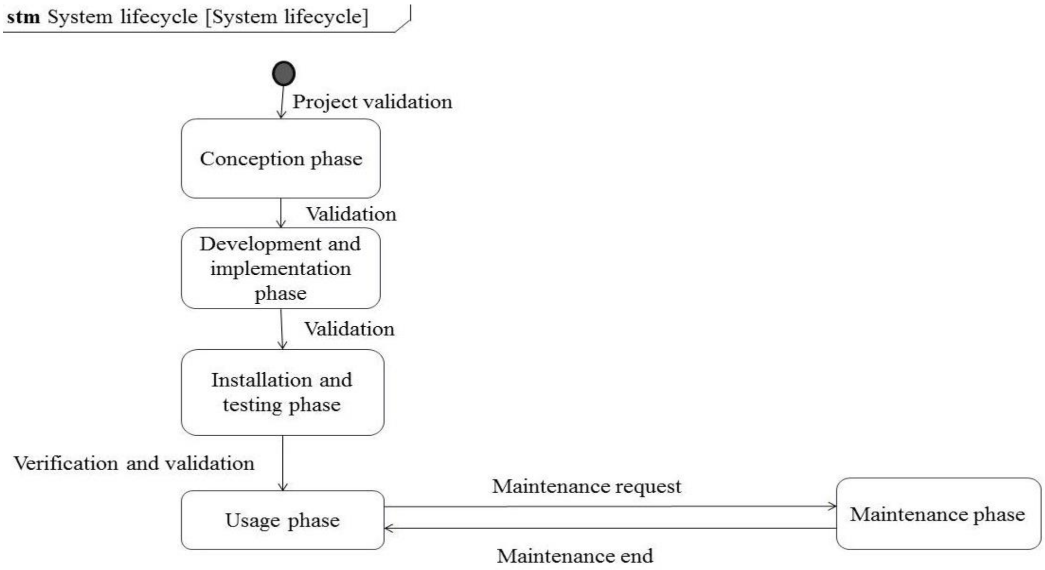

Figure 2. System life cycle

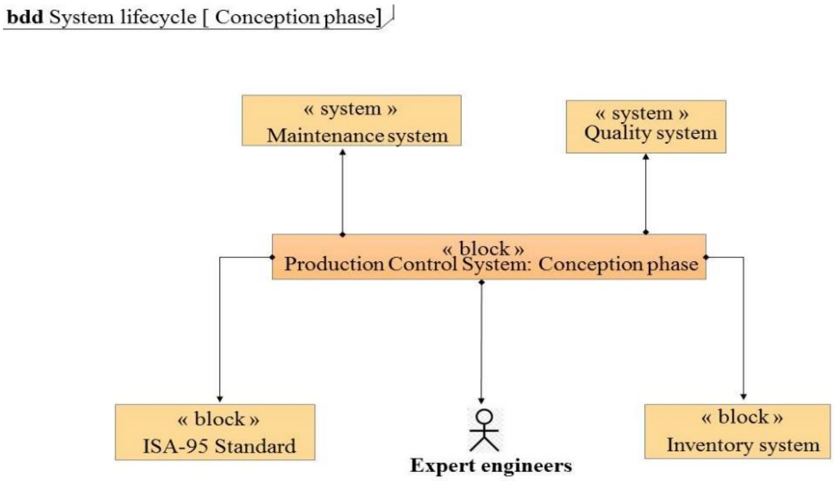

Figure 3. Context diagram - Conception phase

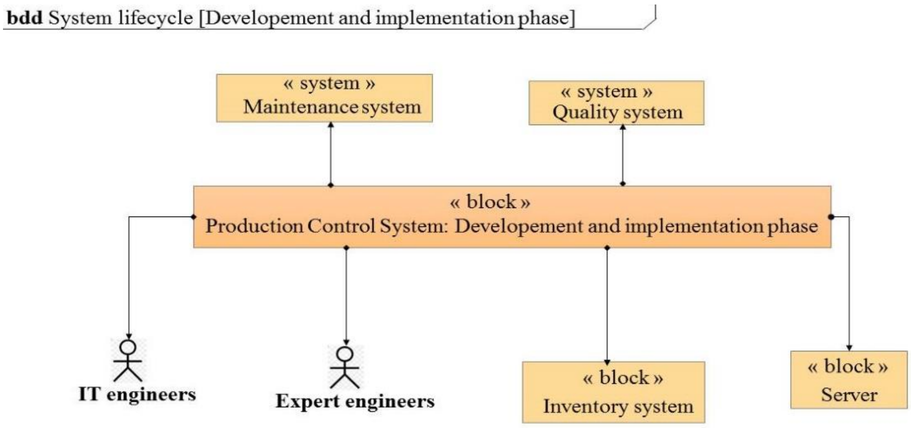

Figure 4. Context diagram - Development and implementation phase

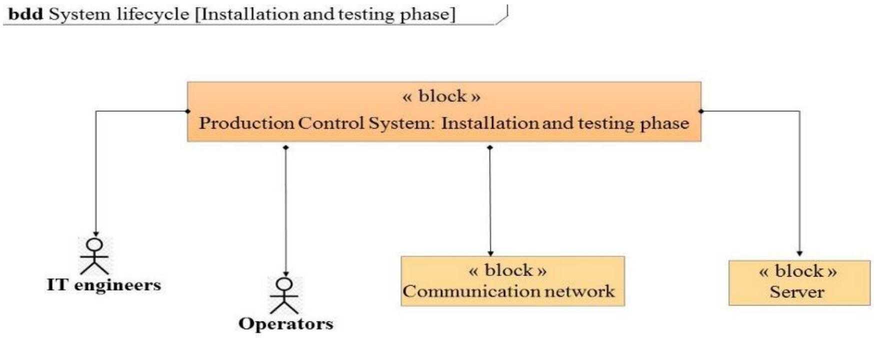

Figure 5. Context diagram - Installation and testing phase

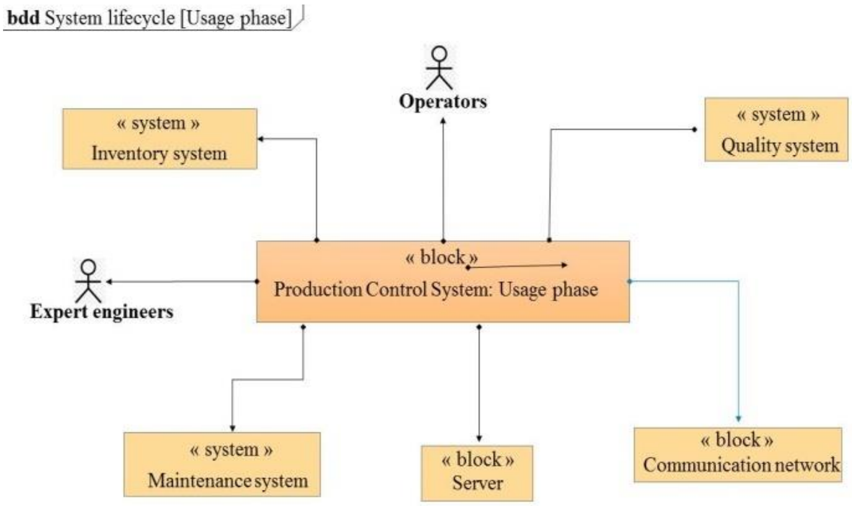

Figure 6. Context diagram - Usage phase

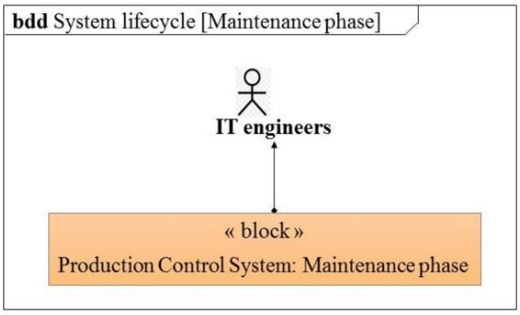

Figure 7. Context diagram - Maintenance phase

Identifying stakeholder needs is very important to ensure the goals of the system under development. Thus, stakeholders must describe the services expected by the users of the system. Its needs can then be translated into requirements. Table 3 shows non-exhaustive examples of stakeholder needs.

Table 3. Some examples of stakeholders need

ID	Needs
01	Define key performance indicators
02	Define the data flow
03	Analyze and process mine data
04	Optimize the production process
05	Optimize long and short-term production planning
06	Forecasting production

Having identified and defined the context of the production control system, we must refine the analysis by introducing use cases that statically describe the external systems involved and the human actors and their interactions with the system of interest. Use cases will help to refine stakeholder expectations and therefore identify system requirements in more detail. In our case, use case from the usage phase is represented as an example in Figure 8.

3.2.2. Functional Vision

The functional vision is characterized by the modeling of the functions of the system which defines the requirements of the system. These requirements are expressed by means of the needs of the stakeholders taking into account the operating constraints of the system [22]. The requirements can be divided in two categories: Functional requirement and non-functional requirement. A functional requirement defines a function that a system should be able to accomplish, what the system should do, and describes the behavioral aspects of a system.

A non-functional requirement specifies properties of the system, such as environmental and implementation constraints, performance, platform dependencies, maintainability, scalability, and reliability. It is necessary to clearly define the engineering requirements and do not forget any requirement to avoid an erroneous concept design and integration. In addition, good requirements engineering will avoid additional costs during the design process. The identification and analysis of the requirements makes it possible to determine the perimeter and limits of the system, to determine the strengths and weaknesses of the prior system in the case where it exists, to ensure that the requirements of the Stakeholders are complete and coherent and elicit the missing requirements of the Stakeholders. Requirements are modeled using the requirements diagram. The latter shows in an explicit way the relations between these requirements. Figure 9 shows some examples of the non-functional of our system of interest. For reasons of figure resolution, the functional requirements of our system are distributed over two figures; Figure 10 (a) and Figure 10 (b).

For the non-functional requirements in figure 10, the system must meet certain non-functional criteria such as ensuring the automatic feedback of data in real time or consulting remotely the control interfaces, etc. These criteria ensure the proper functioning of the system in terms of performance, documentation, operability, readability, etc.

Some examples of functional requirements from Figure 11, the system must control the production by displaying:

- The type of the layer arriving at the unit of the fixed installation (id = "7.4"), and this for the stripping unit (id = "7.4.1) and the screening unit (id = "7.4.2),
- Instructions in the event of anomalies (id = "7.6"); the system gives an instruction to check the layer if the flow rate of the waste rock increases (id = "7.6.1") (in this case, part of the phosphate is lost with the waste rock) and to check the state of the mill if the size grain increases (id = "7.6.2") (in this case, the waste rock is present in large quantities in the phosphate).
- The tonnage of the phosphate produced (id = "7.11").

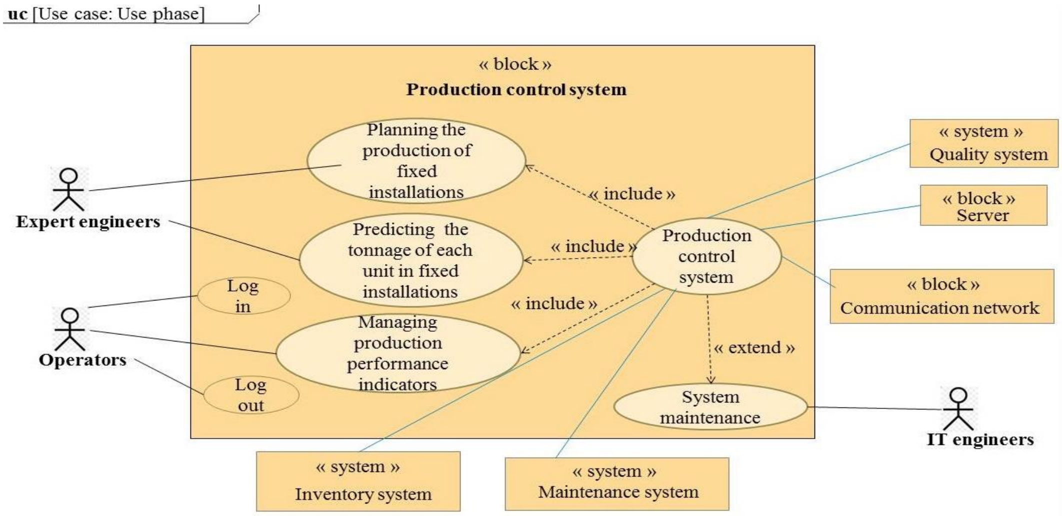

Figure 8. Use case diagram - Usage phase

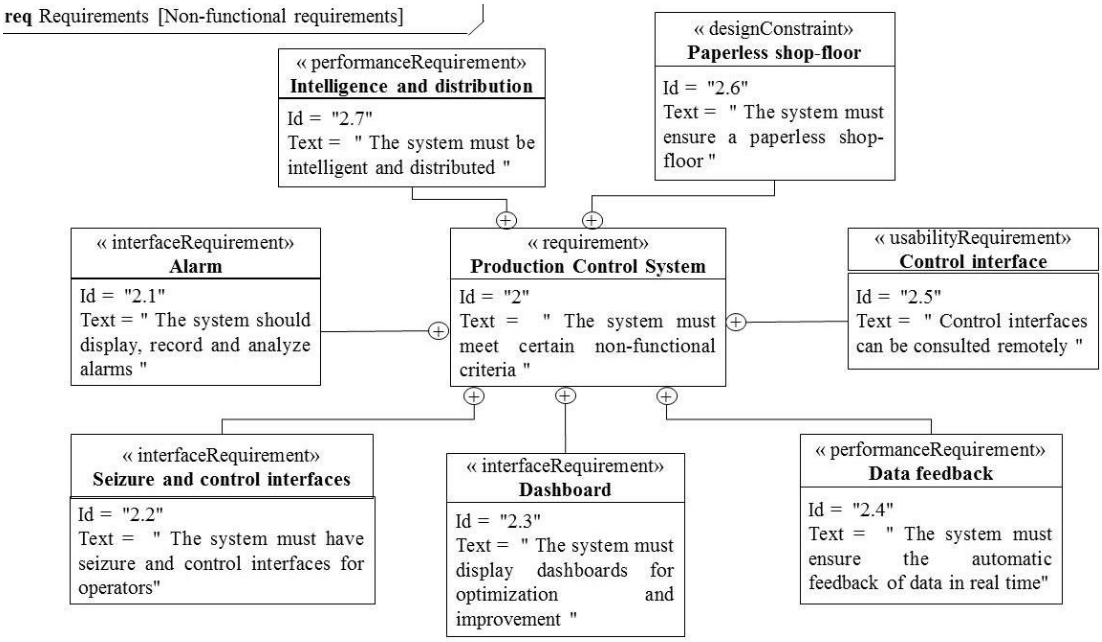

Figure 9. The non-functional requirements of the production control system

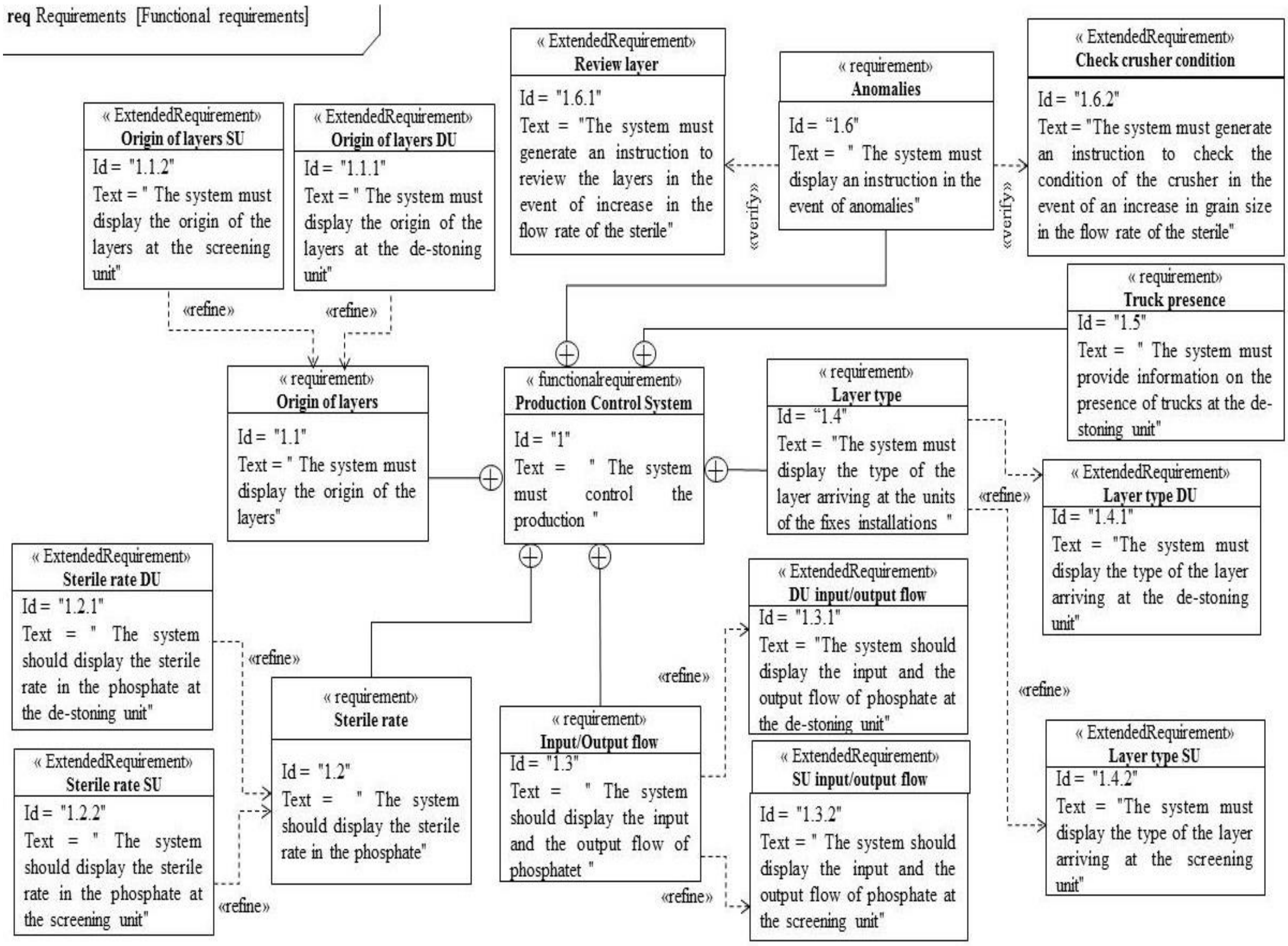

Figure 10 (a). Functional requirements of the production control system

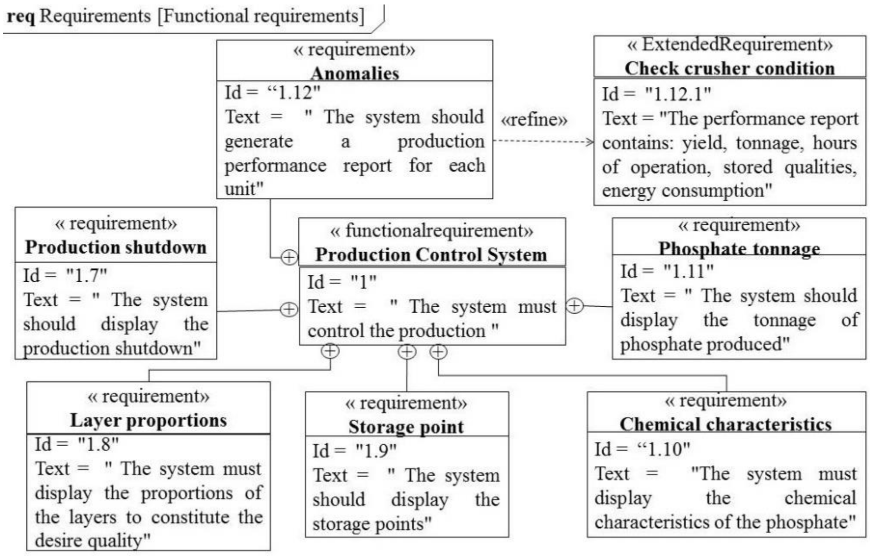

Figure 10 (b). Functional requirements of the production control system

4. CONCLUSIONS

The integration of a production control system in a phosphate open-pit mine offers a better quality of information, facilitates and makes more reliable the performance analysis and allows putting in place corrective action plans more relevant. In view of this, we propose in this article operational and functional analyses through a concrete case study for a production control system. Given the complexity of the system, we adopt the MBSE approach framed by the CESAM method. These analyzes made it possible to determine the life cycle of the system, its stakeholders, its needs and its functional and non-functional requirements. The tool used for modeling is SysML.

Since this paper focuses on operational and functional analyzes, the next step is to complete our design of the production control system of a phosphate open-pit mine with a constructional vision by modeling the components concretely (hardware, software and humans).

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