Digging Into Mining 4.0: Applying Systems Engineering to a Digital Spare Parts Management System

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Abstract—*This article addresses the lack of literature on developing a digital platform for real-time spare parts inventory management in the mining industry. From this perspective, we investigated a holistic and multidisciplinary approach that combines business process reengineering, systems engineering, and software development. The goal was to develop an easy-to-adapt framework for researchers and industry professionals. This research proposed a comprehensive vision of the spare parts inventory management process and provided managers with the ability to monitor the process. The proposed digital spare parts management system was successfully implemented for a Moroccan phosphate company. It was demonstrated that the system could save up to 1.3 million DH annually by resolving spare parts inventory issues and improving customer satisfaction in the mining industry.*

Key words: Digital transformation, mining, spare parts management, systems engineering, volatility, uncertainty, complexity, and ambiguity (VUCA)

I. INTRODUCTION

MINING companies operate within a constantly evolving economic environment, described by volatility, ambiguity, uncertainty, and complexity. To succeed in such an environment, these companies are racing time to navigate various challenges, including fluctuating prices and demand for minerals, growing environmental concerns, social responsibility issues, and the need for technological innovation. Therefore, mining companies are constantly investigating effective strategies that address these challenges, particularly concerning operational efficiency. Unscheduled downtime in industrial operations can be a major source of increased expenses and unsatisfactory operational efficiency, particularly as demand rises [1]. The root cause of these overages often lies in maintenance problems such as equipment failures and breakdowns. Therefore, companies are leveraging technology and analytics to optimize their maintenance processes [2].

All these efforts converge toward the apparition of Mining 4.0, which is the application of research and development activities related to the concept of Industry 4.0 in the mining industry to maintain its competitive advantage [3], [4]. Mining 4.0 is orientated to decision-making through systems that support decisions, improve operations in the mine, enhance the management of human and material resources, and use the technological resources of data and information without undermining the care of the environment [5], the implementation of artificial intelligence, the reduction of uncertainty [6], and the digitization of the mine. As mining companies move toward a digitally enabled maintenance management system within the Mining 4.0 movement, it becomes increasingly clear that effective maintenance processes are critical for success [7]. This includes spare parts management, one of the essential aspects of maintenance [8]. To reduce pressure on capital-intense mining operations [9], a maintenance strategy where the spare parts are continuously monitored can be a challenging initiative toward Mining 4.0 [10]. This leads to intensive investment in developing effective and integrated information systems as monitoring, controlling, and decision-making tools [11].

Our review of the existing literature revealed that while several studies investigated developing efficient frameworks for real-time spare parts management systems in the manufacturing industry, few studies have been conducted on the mining and chemical transformation industries [12], [13]. However, no attention has been given to designing and developing an easy-to-adapt spare part warehousing and inventory management system, considering the specificity of capital-intensive industries. Since they often operate in harsh environments, which can increase the risk of equipment failures and breakdowns. Furthermore, these industries are strongly engaged in conducting regular equipment inspections, performing preventative maintenance, and ensuring that adequate spare parts are always available to avoid any shutdown due to the nature of their products [14]. From both practical and theoretical perspectives, developing an efficient spare parts warehousing management system and framework for the mining industry becomes necessary. This study investigates the current awareness of the advantages of implementing a real-time spare parts management system for a mining company. The discoveries reduce the gap between cutting-edge engineering and research. Moreover, we answer the following research question:

RQ1. How can mining companies ensure efficient real-time spare parts management within volatile, complex, uncertain, and ambiguous environments, such as capital-intensive companies?

To answer the question, the authors assessed the current trends in spare parts management systems within the context of the mining industry. Then, they proposed a comprehensive strategy incorporating modeling, systems design, and business process reengineering methodologies. A real-world case study of a Moroccan phosphate company served as the basis for the proposal and evaluation of an adaptable framework for an effective digital platform fit for the mining industry.

The remainder of this article is organized as follows. Section 2 presents an overview of the related works, focusing on the case of capital-intensive industries and mining companies in particular. The adopted methodology is introduced in Section 3. Insights are explored in Section 4 based on findings from a case study. We list the many theoretical and practical contributions, as well as the constraints, in the last section.

II. Background

A. Recent Advances in Smart Spare Parts Management

Efficient spare parts management systems are crucial for ensuring spare parts availability while minimizing inventory and warehouse operation costs [15]. Such systems include inventory control, demand forecasting, order management, warehouse layout optimization, and day-to-day storing and retrieval synchronization [16].

Manual systems for managing spare parts inventory and warehousing operations can be time-consuming, costly, and prone to errors. These systems face several challenges in ensuring traceability and real-time access to the current status of the warehouse. However, automation can offer several advantages for managing and controlling spare parts warehousing activities. Automated warehousing systems, for instance, can enhance efficiency by automating the movement of parts within the warehouse. This reduces the need for manual handling and transportation, reducing the risk of damage to parts during transit.

Recent research has focused on Industry 4.0 innovations for smart spare parts management, especially those related to inventory control and demand planning [17]. For example, Lin et al. [18] proposed a smart spare parts inventory management system that utilizes real-time sensor data to make better ordering decisions. The authors emphasized the importance of adopting an efficient modeling approach for the degradation process of critical operating components. Keivanpour and Ait Kadi [19] investigated the effect of Internet of Things (IoT) on aircraft spare parts inventory management. They explored different IoT-empowered cooperative strategies on the cost and availability of spare parts. Meanwhile, Zhang and Wu [20] developed a cyber-physical inventory management system that integrates real-time information from machines, shop floors, spare parts databases, and suppliers to make better decisions and establish transparency and flexibility.

In addition, Mukherjee and Dey [21] proposed a decision support system for spare parts management for the process industry based on the analytic hierarchy process. The authors tested and validated an integrated framework for selecting the best warehousing option for business excellence in any manufacturing organization. From a business intelligence perspective, Stefanovic [22] developed data mining applications for spare parts inventory management. The proposed framework uses a unified business intelligence semantic model and a data warehouse to employ data mining technology to provide accurate and up-to-date information about spare part availability.

B. Systems Engineering: Principals, Applications, and Limitations

Systems engineering (SE) is a holistic and interdisciplinary approach that encompasses various fields of engineering and science to incorporate technological breakthroughs into the planning and development stages of a system [23]. The application areas of this approach are broad and diverse, ranging from software development, healthcare, and transportation, to manufacturing [24].

Systems engineering focuses more on defining needs and functionalities early in the development cycle [25]. Therefore, this approach focuses on covering all requirements and creating and validating the right design. One might remember that the settings in which systems engineering is applied are not meant to be completely distinct from one another or mutually incompatible. Moreover, they impact how the general knowledge of the systems engineering life cycle and processes are applied. In fact, systems modeling can be used in various real-life applications such as materials science [26], medical sciences [27], chemical engineering [28], and many more.

Although systems engineering has various advantages in the design and development of complex systems, it also has some limitations. First, successfully applying this approach requires high-quality communication and collaboration among stakeholders. This can lead to misunderstandings, delays, and errors in the design process. Furthermore, the SE approach follows a predefined set of steps, limiting flexibility and creativity in the design process.

C. Research Gap

Mining companies operate in a complex environment, where managing efficiently and effectively a wide range of costly spare parts ensures higher both production and maintenance performances. The mining environment is inherently unpredictable due to, on the one hand, the difficulty in preventing breakdowns and, on the other hand, the cost of nonavailability and warehousing. That requires real-time information sharing, traceability, and higher accessibility. Thus, the necessity to design a tailored information system to be scalable and adaptable, given the dynamic nature of the industry. Nevertheless, the current literature lacks a digital platform framework that addresses these challenges in the context of mining equipment's spare parts management. It is crucial to note that developing an integrated digital platform for spare parts management is only a component of a larger industry 4.0 transformation in the mining industry. Therefore, investigating the design and development of an easy-to-adapt framework based on a systems engineering approach help address the research gap in the field.

III. DP4M Framework Development

To address spare parts warehousing issues for mining companies, it is mandatory to analyze critically and re-engineer the current business processes, design a comprehensive framework for managing spare parts in real time, and confirm results observed from experiments. In this section, we present an overview of the adopted methodology, from business process reengineering to software development.

A. Methodology

The effective management of spare parts is essential for the success of any industry. To ensure that spare parts are available when needed and at the lowest possible cost, a system engineering approach can be followed Figure 1. This methodology involves six phases: 1) assessing available information, 2) defining the problem and establishing objectives, 3) developing system requirements, designing the system, 4) implementing the system, 5) testing and validating the system, and 6) monitoring and improving the system.

- Assess Available Information: Before starting the process, it is important to analyze the current processes of the spare parts management system and the corresponding data architecture governance. This assessment can help to identify pain points and possible improvement areas and prepare for system requirements and design.
- Define the Problem and Establish Objectives: The problem statement and system targets should be defined in light of the assessment. This should contain an in-depth understanding of the scope of the system, the desired results, and the constraints and limitations that must be considered. In order to better understand the scope of the problems based on the initial root cause analysis, we started by creating a clear problem description. All stockholders contributed to the creation of this declaration.
- Establish System Requirements: The system requirements are defined during this stage.

Identifying the system's functional and nonfunctional requirements, such as the types of spare parts to be managed, inventory level goals, ordering and delivery procedures, and reporting and monitoring needs, is part of this process. First, we determined and prioritized the requirements and expectations of each system stakeholder. Then, by determining the many use cases and scenarios the system will handle, we created and categorized the functional requirements for the system. Finally, in order to allow effective communication and collaboration, we specified the interfaces between the various system components.

- Develop and implement the system: The system was then put into service in accordance with the design requirements. This includes installing the required hardware and software, configuring the system, and testing the system to make sure it is functioning properly.
- Test and validate the system: Once the system has been implemented, it needs to be tested and validated to make sure it satisfies the objectives and requirements that have been set forth. User acceptance testing, system testing, and integration testing are all included in this.
- Monitor and improve the system: Finally, to ensure a continuous improvement of the system functionalities, the system must be monitored and improved over time. To do this, data on system performance must be gathered, analyzed, and improvements must be made to the system as needed.

Mining industries can design effective spare parts management systems to support their productivity using the techniques described here. Using a systems engineering method guarantees that each component of the upcoming system is carefully examined and connected, resulting in an improved and more effective system that aids businesses in achieving their tactical, strategic, and operational goals.

B. Business Process Re-Engineering for Real-Time Spare Parts Management

In this section, we outline the redesigned spare parts warehousing and inventory business processes implemented using a reengineering approach. That results from a critical need for highly efficient, reliable, real-time spare parts warehousing and inventory operations that satisfy customers' demands and cut costs.

To re-engineer the spare parts warehousing processes, a number of actions need to be taken:

- Identify the current processes: Finding out what procedures are in place and how they are being used is the first step. Process mapping, which entails recording the steps in each process, can be used to achieve this.
- Analyze the processes: The next stage is to assess the current procedures to find any inefficiencies or potential opportunities for improvement. Process analysis, which entails assessing the efficacy and efficiency of each process, can be used to do this.
- Redesign the processes: Based on the analysis, the next step is to redesign the processes to eliminate inefficiencies and improve their effectiveness. This can involve changing the sequence of steps, simplifying the process, automating certain tasks, or introducing new technologies.
- Implement the new processes: Once the redesigned processes have been developed, the next step is implementing them. This can involve training employees on the new processes, updating IT systems, and ensuring that the necessary resources are in place to support the new processes.
- Monitor and evaluate: The final step is to monitor and evaluate the new processes to ensure they achieve the desired results. This can involve tracking key

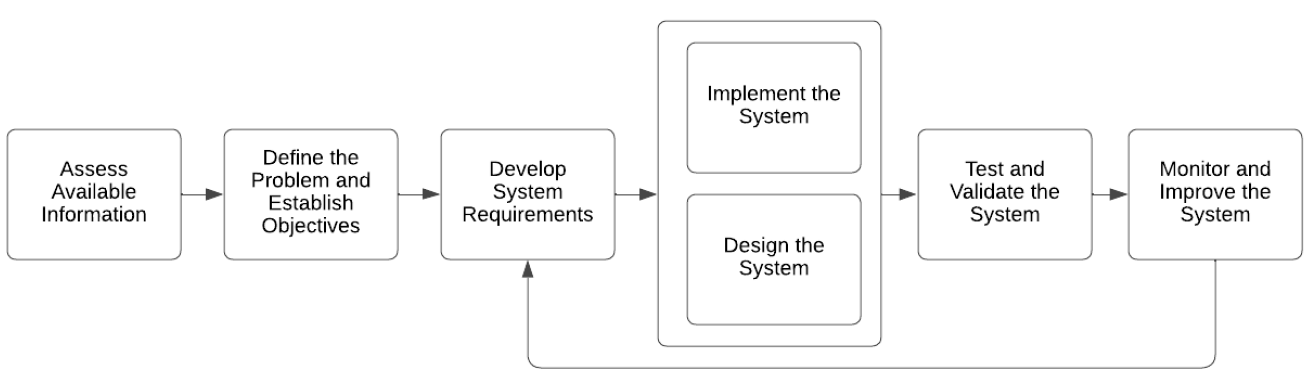

Figure 1. Adapted systems engineering process (adapted from Dahl's work [29]).

performance indicators such as cycle time, inventory accuracy, and customer satisfaction and making necessary adjustments.

C. Design and Analysis Using SysML

Systems modeling language (SysML) enables systems engineers to develop detailed and comprehensive models of complex systems [30]. It has the ability to understand better how different parts of the system interact with one another, identify potential issues or problems, and design solutions that meet the needs of stakeholders. For this reason, we adopt SysML since developing a collaborative spare parts warehousing and inventory management requires the integration of many subsystems such as ordering, tracking, and inventory management of spare parts as well as the performance system. The challenge was to avoid debasing the overall legacy system. However, at the same time, reengineering other interacting subsystems. From this perspective, we have turned to SysML modeling to create system-level diagrams such as block diagrams, use case diagrams, and activity diagrams, as well as more detailed models of system components such as interfaces, requirements, and behaviors [31]. SysML is also used to create models of system architectures, which can help engineers to optimize system performance, improve reliability, and reduce costs.

SysML modeling provides a common language for all stakeholders involved in developing a complex system. That enabled us to understand the system's design and requirements and facilitated communication between different teams and departments [32] for a challenging environment such as mining companies. Furthermore, we used SysML modeling to simulate and test the system under various unforeseen conditions, which can help to identify potential issues and refine the design before the system is actually built.

In this study, we followed a holistic approach combining business process reengineering and model-based systems engineering using SysML [32]. We implemented a proof of concept of the resulting model as a digital platform for real-time spare parts warehousing and inventory management called D4SP.

IV. D4SP in Practice: The Case of a Phosphate Company

A. Background

This research was conducted at a Moroccan firm with one-third of the global market share for exporting phosphate in all its variations. The company has an end-to-end mining and chemical processing process, ranging from extracting phosphate ore to delivering phosphoric acid and fertilizers to the final consumer. The supply chain comprises four mining sites and two chemical complexes spread across three axes: the northern axis, central axis, and southern axis. This study was performed on a trial mine, the latest open pit mine for phosphate. This mine signifies a notable advancement in the company's strategy to adopt Industry 4.0. It is accessible to the scientific community, allowing researchers from affiliated universities to examine practical solutions in crucial domains.

It was observed that our industrial partner's inventory of spare parts and consumables in the main warehouse exhibited consistent growth from 2017 to 2022, with an increase of 18% when adjusted for the level of production, amounting to 4 billion Moroccan Dirhams (DH) in value. This increment had a significant effect on the working capital, with a surge of up to 20% in 2020. As of 2022, the inventory reached almost 1.867 billion DH, with approximately 40% of the stock remaining stagnant for over five years. This posed a considerable risk of potential obsolescence (refer to Figure 2). That was due to a lack of visibility and manual procedures used for traceability.Our industrial partner relies heavily on critical equipment such as excavators and haul trucks to extract, and transport phosphate rocks, and downtime caused by equipment failure can be costly due to the complexity of open-pit extraction. Inefficient spare parts warehousing and inventory management can contribute to this downtime by causing delays in ordering and receiving replacement parts. Thus, we developed digital spare parts warehousing and inventory management platform that streamlines, in real time, the ordering, tracking, and inventory management of spare parts, reducing inventory carrying costs and increasing equipment uptime. The expected benefits include cost savings by 12%, improved equipment uptime, and increased efficiency in the spare parts ordering and delivery process.

B. Current Spare Parts Management Processes Assessment

The current process was modeled based on

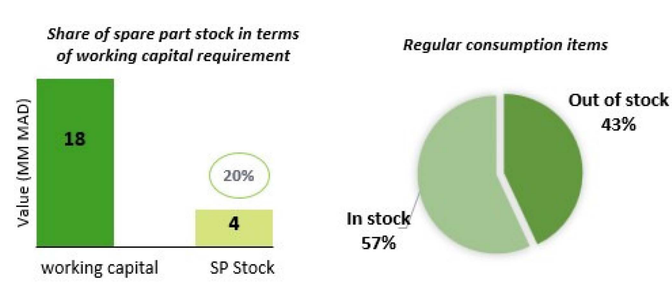

Figure 2. Spare parts management performances before D4SP.

interviews conducted with employees from the maintenance, production, and procurement departments. The procurement process involves four actors: the internal supplier, the purchaser, the storekeeper, and the end user. Three modes of procurement are defined to meet the specific needs of the organization.

The first procurement mode is called “min/max,” and it is mainly applied to critical, systematic, and consumable articles. The minimum and maximum stock levels are defined in consultation with the end users and entered into the system to automatically trigger warnings. The stock is reviewed monthly, and the procurement process is launched once the minimum level is reached. The second procurement mode is the “Scheduled” mode, which is based on the schedule of planned maintenance. Needs expression for year $n+1$ is edited in March of year n. The third mode is “Upon request,” which is dedicated to condition-based maintenance needs reported by inspection reports.

The procurement process for the three modes is described in the business process modeling notation [33] diagram presented in Figure 3. The process starts with the internal supplier grouping the needs by nature and family. Depending on whether the article is under contract or convention, the supplier creates a delivery request (DR) or a purchasing request (PR) and updates the DR or PR status in the system. The purchaser then checks if the delivery deadline is respected and alerts the supplier if necessary. Once the item is received, the storekeeper transfers the documentation to the codifier for archiving and controls the quantity. If the item is compliant, the storekeeper calls the end user for qualitative control. If the control requires a referral, the storekeeper completes it. Otherwise, the end user completes the control. Compliant items are sent for provision, and noncompliant items are returned to the purchaser to inform the supplier.The modeling exercise facilitated the identification of key areas that require attention in managing spare parts procurement. The primary objective of the spare parts management policy is to provide the best quality of service to users while optimizing stock levels, minimizing costs, and reducing supply times. To achieve this objective, the following actions should be taken:

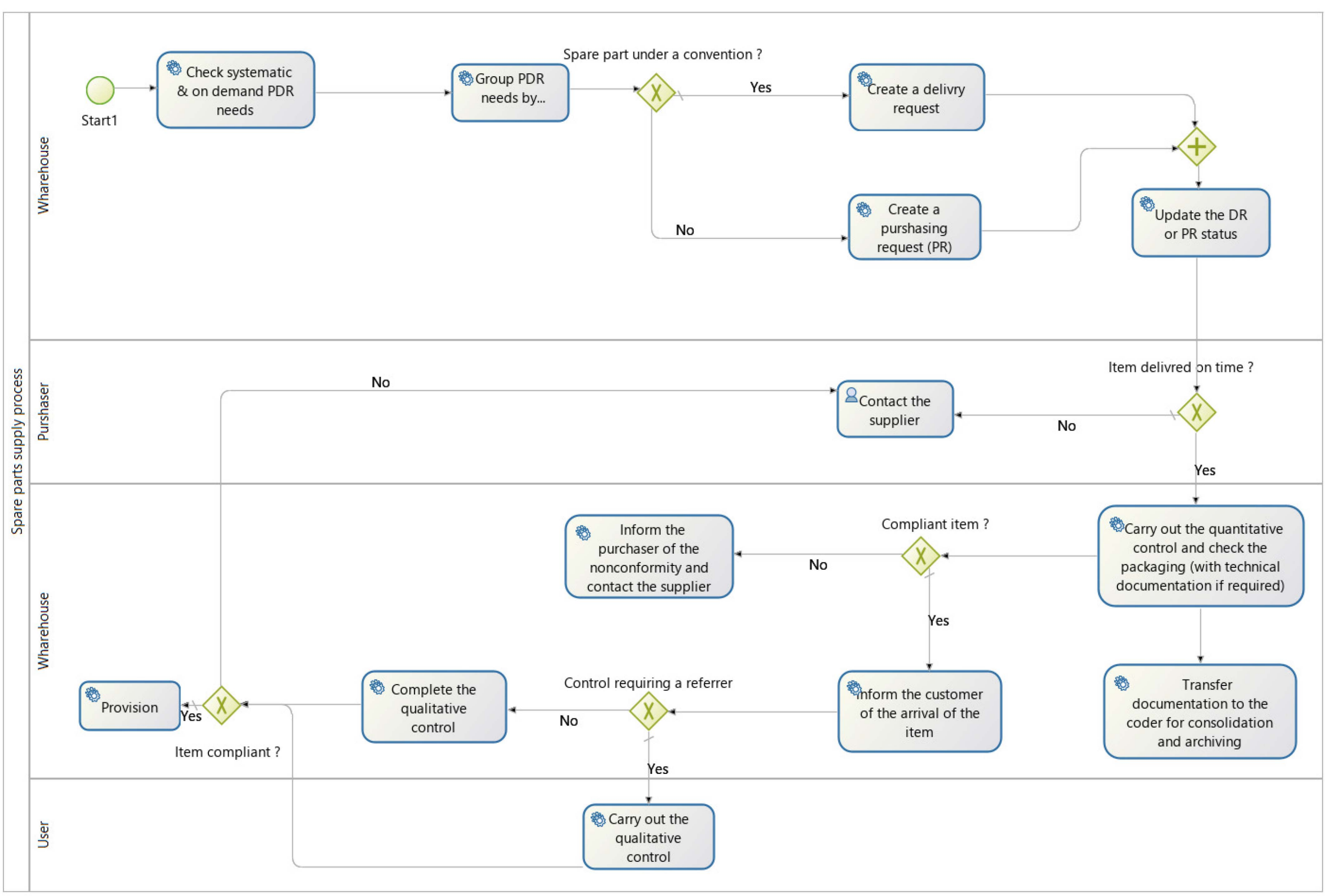

Figure 3. Mine spare procurement process modeling.

- Control and optimize stock to maintain appropriate inventory levels.
- Ensure availability of critical and regular consumption articles for continuous production.
- Reduce supply times, both internal and external.
- Maximize framework agreements and conventions for article coverage.
- Standardize the process of needs expression and stock management.
- Establish an integrated platform for spare parts performance management that will provide real-time monitoring of the availability and status of spare parts.

Improved spare parts management will contribute to the smooth functioning of production operations.

C. Re-Engineering Current Analyzed Processes

The gaps identified in the current business processes related to spare parts inventory and warehousing, here, a new framework for efficient spare parts management is suggested based on re-engineered business processes. The framework involves setting inventory targets, forecasting demand, and optimizing inventory levels. A platform is also developed that displays the available spare parts stock by nature and the minimum and maximum stock levels for optimal spare parts management. These proposed solutions are meant to increase the efficiency and effectiveness of spare parts inventory and warehousing. The new process includes several phases represented in Figure 4:

All the spare parts need of the internal user are submitted on the platform with specifications of the items, quantities, and delivery timelines. On his own, the purchaser works with the storekeeper to develop an inventory plan based on the consumption history that sets minimum and maximum inventory levels, reorder points, and lead times for each spare part. The plan considers demand forecasts, usage patterns, and criticality levels of the spare parts. The storekeeper then uses the platform to monitor inventory levels regularly and compare them to the minimum and maximum levels of the inventory plan. The platform automatically notifies the purchaser once the inventory level of a spare part goes below the minimum level, who will then launch a purchasing order for the required spare parts with the supplier. Once the spare parts arrive, the storekeeper receives and verifies the order against the purchase order and the platform's records. Any discrepancies are reported to the purchaser for resolution. The storekeeper then updates the inventory records on the platform to reflect the new stock levels, and the platform automatically adjusts the minimum and maximum levels for each spare part based on the inventory plan. Finally, the purchaser, storekeeper, and internal maintenance team can use the platform to review performance metrics such as inventory turnover, stock-outs, lead times, and supplier performance. They can identify

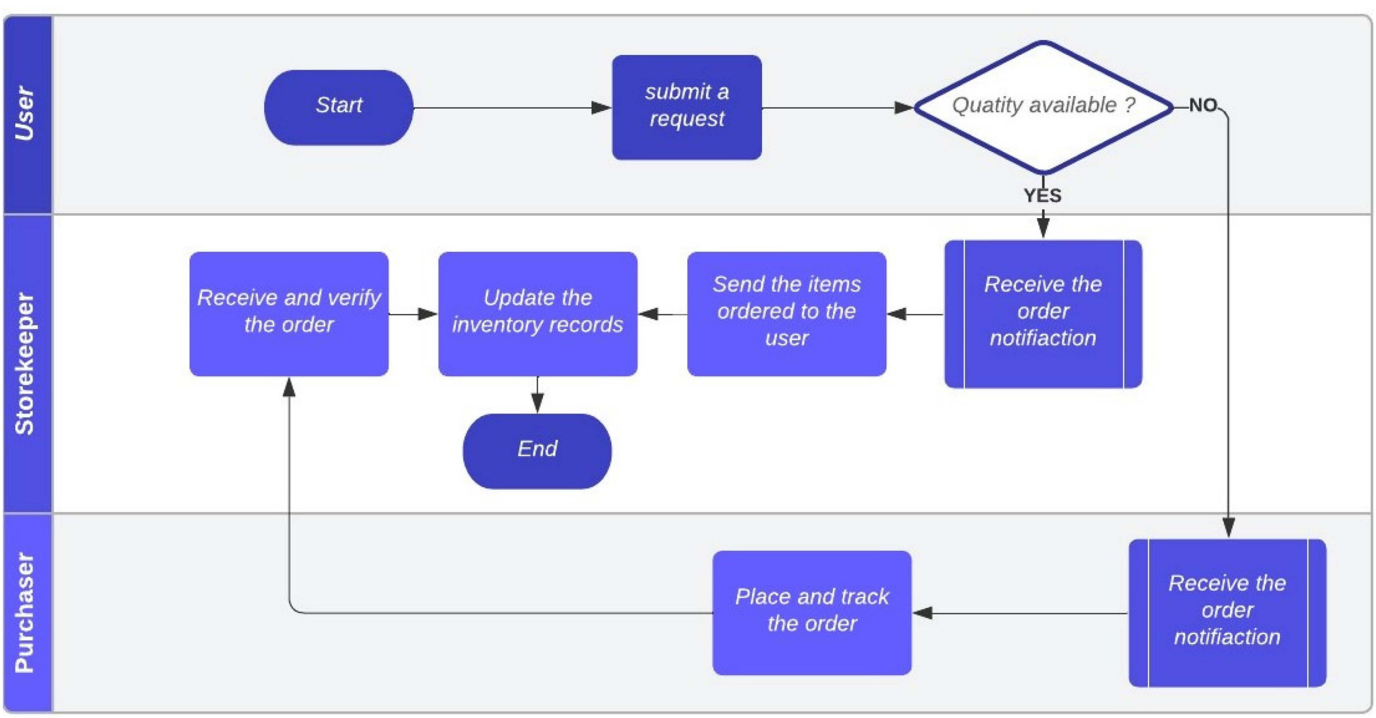

Figure 4. Spare parts management processes re-engineering.

opportunities for improvement, adjust the inventory plan, and communicate any changes to the other stakeholders. By using the platform to streamline the spare parts management process, the re-engineered business process improves operational efficiency, reduces costs, and ensures the timely availability of critical spare parts without relying solely on the role of the supplier.

D. D4SP Development and Deployment

The application has been developed using JavaScript libraries, namely Node JS and React, for server-side and front-end development, respectively. The use of these technologies has resulted in a fast and efficient application that is capable of handling heavy workloads. PostgreSQL has been selected as the database to store and manage data due to its scalability and reliability. This design approach has been implemented with the intention of ensuring that the solution is scalable to meet changing requirements and user needs. The development process has been collaborative, involving stakeholders in the discovery of requirements and the development of solutions.

1) *Functional Requirements and Use Cases:*

A number of functional requirements must be satisfied by the proposed solution. It must, first and foremost, be able to display the stock distribution by the user and by nature. This will clarify how the resources are distributed and allow the user to track and monitor the stock. The second need is the ability of the system to display the value of the stock of each nature in KDH and compare it to the minimum and maximum values, which will guide the users in making consumption decisions, ensuring that they stay within the set established boundaries. Third, the system must be to track regular consumption stock levels according to its exceeding the Min–Max in order to identify any discrepancies and ensure that the stock is being used effectively. The system must, fourth, be able to display the value of the critical consumption stock in kDH and compare it to the minimum and maximum values. Users will be able to anticipate critical shortages and take necessary actions to prevent the issue. Fifth, the system needs to track the quantity of the critical consumption stock and detect any exceeding of the Min–Max. This will enable the user to monitor critical stock levels and be alerted when the minimum threshold is crossed. Finally, the system is required to display the distribution of other consumer items by user request. This will enable users to monitor the distribution of specific items, ensuring they are utilized effectively. In conclusion, the proposed system must be able to meet these functional requirements in order to guarantee effective stock management. These requirements are essential for the successful implementation of the system and will assess the users with all the information they need to make resource-use decisions.

E. Proposed Use Cases

D4SP offers a set of functionalities for the warehouse manager to manage the stock effectively (see Figure 5).The warehouse manager can access the system's main menu after logging in. A donut chart illustrating the stock breakdown by nature, including regular, critical, and other items, is displayed when the "stock distribution" is selected. The "Distribution by User" option allows the user to view a bar graph showing the stock distribution by the user. The "Distribution by Number of Items" option displays a donut chart showing the distribution of regular consumption stock by the number of items. In contrast, the "Regular Consumption Stock" option displays a donut chart displaying the stock value in kDH. The "Distribution by Number of Items" option displays a donut chart showing the distribution of requested stock by the number of items. In contrast, the "Stock Requested by Users" option provides a donut chart displaying the stock value in kDH. The warehouse manager can easily and clearly see the stock situation thanks to these functions, which aid in making optimal decisions concerning inventory management.

Moreover, the system allows the warehouse manager to add and modify items in the stock. The "Add Item" option prompts the warehouse manager to enter the item details and select the stock type. After entering the details and selecting the stock type, the system adds the item to the appropriate stock type. The "Modify Item" option allows the warehouse manager to select the item to modify and display the details. The warehouse manager can modify the item details as required, and the system updates the item data accordingly.

Using D4SP, the warehouse manager can efficiently manage the stock and ensure it is appropriately distributed among different stock types and users. The system's functionalities make the stock management process smooth and straightforward, allowing the warehouse manager to focus on other essential tasks.

1) *Logical Data Model for D4SP:*

To elucidate the adopted data structure, a logical data model, presented in Figure 6, is presented, considering the technological model that will be used for their management. Initially, we introduce the item class, the common point among the other classes. This class encompasses all information related to the item, such as reference, quantity, value in kDH, nature, and others. Subsequently, the

"Procurement" and "Framework agreement" classes represent details of the inventory plan concerning the item, such as minimum and maximum stock level. Additionally, we propose the "Warehouse" class to represent the exact location of the item inside the warehouse. For the screening phase, we assimilated one or more destoning stockpiles to each pile, using the classes (screening,

Figure 5. Use case diagram for D4SP.

screening_pile, layerEpCr). The Train class distributes the screening pile in multiple trains while maintaining the connection and calculating the new content before transferring it to the customer. This structured approach enables the efficient management of the phosphate location, ensuring the accurate representation of the data while catering to the diverse requirements of the stakeholders.

2) Performances Assessment Dashboards:
Performance assessment dashboards are crucial tools that provide manufacturers with the capacity to track spare parts inventory performance and then make data-driven decisions. Such dashboards can be used to monitor key performance indicators (KPIs) related to inventory, such as distribution of items, breakdown of items by amount and nature, stock of regular and critical consumption items, and breakdown of other items by the user. Figure 7 summarizes several key performance indicators (KPIs) related to spare parts warehousing and inventory management and their respective descriptions and measurements. The KPIs cover different aspects, such as distribution, breakdown, and stock levels, as well as regular and critical consumption items. Therefore, Figure 7 provides a useful reference for mining companies that need to track and monitor spare parts warehousing and inventory performance and make data-driven decisions to optimize their current processes.

Figure 8 presents a dashboard view that effectively visualizes the stock value for regular consumption in kDH using a gauge chart. The chart features black needles that serve as indicators for the minimum and maximum stock levels, making it easy to determine whether the current stock level falls within the desired range. Moreover, the current stock level is represented by a green needle, which is positioned to point to the appropriate section on the gauge, providing a clear and immediate visual representation of the stock level for regular consumption in kDH.

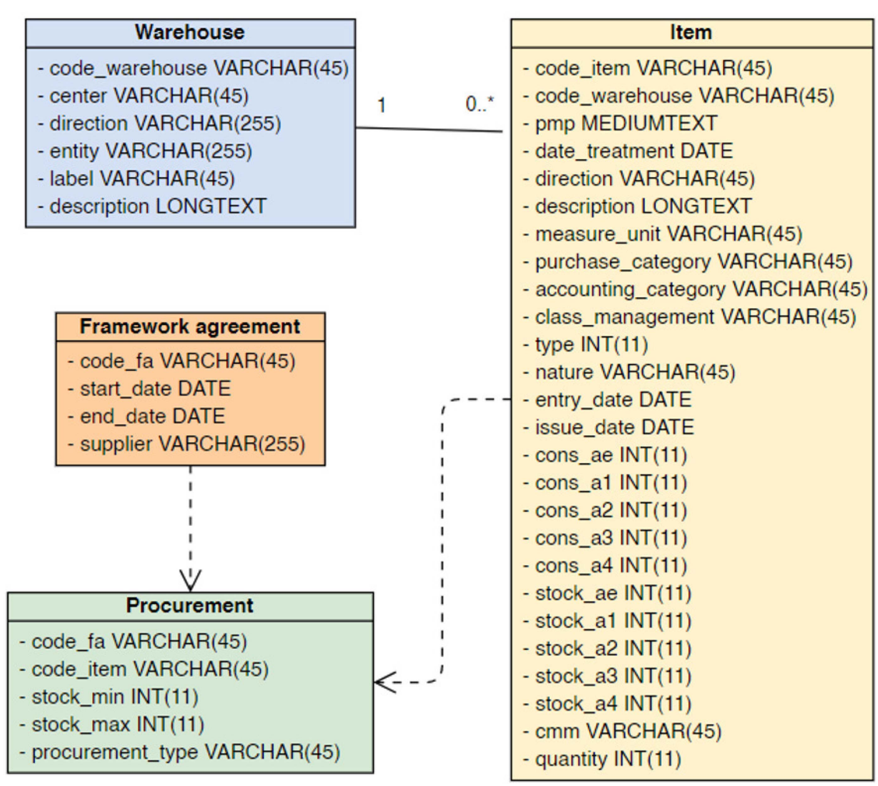

Figure 6. Logical data model for D4SP.

F. Discussion We now discuss the research-based findings of the study. Despite the significant focus on spare parts inventory management, little attention has been paid to investigating a systems engineering-based approach for developing a real time, friendly, user, and easy-to-adapt digital platform that can ensure traceability and efficient management of spare parts inventory and warehousing operations, which led to decreased maintenance and production performances and increased critical spare parts inventory levels. Therefore, our research focuses on developing an adaptive framework for a spare parts management system, especially for mining companies. D4SP is a digital framework specifically designed for spare parts management. It involves reengineering existing business processes related to spare parts tracing, claims processing, and inventory monitoring. Each process is carefully considered in a user-friendly design, incorporating different KPIs for effective inventory management within an ore mine.

The implementation of D4SP is evaluated from various perspectives, including financial, industrial performance, and environmental metrics. The study compares the existing situation with the results after deploying the proposed tool, highlighting several advantages. For example, the system has reduced inventory inaccuracies by 12%, and inventory carrying costs by almost 5%. The framework has also helped companies improve their ability to forecast demand and manage inventory levels more efficiently. Moreover, the study found that D4SP reduced the time required for inventory auditing by 70% while improving inventory record accuracy significantly. The framework has also helped to optimize environmental efficiency by reducing traveling rates by 60% to geographically dispersed mine warehouses where spare parts are stored.

D4SP proposes a comprehensive vision of the spare parts inventory management process and allows managers to monitor the process. Therefore, mining companies can reduce the time of ensuring real-time control over the spare parts inventory activities.

V. Conclusion and Future Scope of the Study

While several studies have focused on spare parts management in manufacturing industries, there is a dearth of literature on developing an integrated and collaborative digital platform for managing spare parts warehousing and inventory operations in the mining industry. To fill this gap, the authors utilized a hybrid approach that combined business process reengineering, systems engineering, and software development to design and develop a general framework and a detailed analysis for researchers and industry professionals.
The proposed platform was implemented for a Moroccan mining company, and the authors evaluated its impact, which demonstrated significant improvements in performance. In addition to its practical contributions, the article also makes theoretical and conceptual contributions to the field.

KPI_ID	KPI_Description	KPI_Measurement
Distribution of items by number	Breakdown of inventory items by user, expressed in number of items	The sum of items in stock for the current year
Breakdown of items by amount	Breakdown of items in stock per user, expressed in amount (MDH)	The sum of the weighted average prices (WAP) of the items in stock for the current year
Breakdown of items by nature	Distribution of articles in percentage compared to the global stock	The sum of the WAP’s of the items in stock by nature of the current year, divided by the total sum of the WAP’s
Stock of Regular Consumption Items	Stock in MDH of regular consumption items compared to the minimum and the maximum stock	The sum of the WAP's of the items in stock of the current year of the items for regular consumption. And the sum of the min and max stock multiplied by the WAP of each item.
Distribution of regular consumption items	Distribution of regular consumption items in percentage by [stock below min, stock between min and max, stock above max]	This calculation involves dividing the sum of the WAPs for three different groups of articles, based on regular consumption levels, by the sum of the WAPs for all articles with regular consumption.
Stock critical consumption items	Stock in MDH of critical consumption items for the current year compared to min stock and max stock	The sum of the current year's in-stock item WAP's of critical consumable items. And the sum of the min and max stock multiplied by the WAP of each item
Breakdown of Critical Consumption Items	Distribution of critical consumption items in percentage by [stock below min, stock between min and max, stock above max]	This calculation involves dividing the sum of the WAPs for three different groups of articles, based on critical consumption levels, by the sum of the WAPs for all articles with critical consumption.
Breakdown of other items by user by number	Breakdown of consumable items (Active, Surplus, to be liquidated, Unusable) per user in number of items	The sum of items in stock for the current year for consumption (Active, Surplus, To be liquidated, Unusable) per user
Breakdown of other items by user by amount	Breakdown of consumable items (Active, Surplus, To be liquidated, Unusable) per user in amount	The sum of the WAP's of items in stock for the current year for consumption (Active, Surplus, To be liquidated, Unusable) per user in MDH.

Figure 7. D4SP KPIs description.

1) Managerial Contributions The main focus of this study is to enhance spare parts inventory and warehousing management, as well as to automate the current processes relevant to the mining industry. By working closely with our industrial partner, we have identified the need to streamline information flows by reengineering the existing processes. To achieve this, collaboration and effective communication among various stakeholders, such as industry experts, mining managers, and researchers, were essential. Re-engineering business processes is a crucial step toward a successful digital transformation journey. The proposed framework is developed in collaboration with the end user, aiming to develop multiple user stories using an agile approach. The proposed tool includes dashboards that serve as a cockpit for managers to manage critical spare parts efficiently.

Executive management must raise managers' levels of digital competence in order to implement D4SP, which can be done with the help of this case study. The proposed technology should demonstrate to the end user how it can reduce their workload and processing time. To save up to 1,332,450.13 DH annually (calculated based on historical data and two years of testing), planning managers can use this study as a guide. Practitioners can use this comprehensive strategy and thorough technique to solve inventory issues in mines and raise customer satisfaction.

2) Theoretical Contributions The study offered a number of theoretical applications. It first combined agile software development, spare parts management system modeling, and business process reengineering. Business process reengineering is frequently employed in the service and manufacturing sectors. However, the proposed approach has a better structure and is suitable for the mining industry. Also, the article articulates the balancing of accuracy in managing spare parts warehousing and inventory, optimization of inventory levels, and business process complexity for spare parts tracing in the case study. Therefore, this article provides directions for synergizing several steps toward better spare parts inventory and warehousing management, including analyzing, modeling, developing, and implementing.

This article also paves the way for future theoretical studies applying the D4SP framework to other mining contexts, such as coal and gold. Studying how the human element affects the execution of a digital transformation plan for a mining company would also be interesting. Additionally, companies may need to assess the success of implementing a digital project related to spare parts management beyond financial metrics.

3) Limitations of the Study The limitations of the study are well articulated. The first limitation is that the proposed approach did not integrate AI-based demand forecasting techniques commonly mentioned in the literature for spare parts inventory management. Integrating AI-based demand methods could potentially improve the accuracy of demand forecasting, resulting in better inventory control and cost savings. The authors could consider incorporating AI-based demand forecasting techniques in their future research. The second limitation is that the study only focused on major spare parts inventory and warehousing operations. At the same time, reverse logistics-related operations are also crucial for significant cost savings, which were not considered. Reverse logistics-related operations involve the collection and transportation of used and defecated parts and materials back to the manufacturer or supplier for reuse or recycling. The authors might consider incorporating reverse logistics-related operations in their future research to provide a comprehensive framework for spare parts warehousing inventory management.

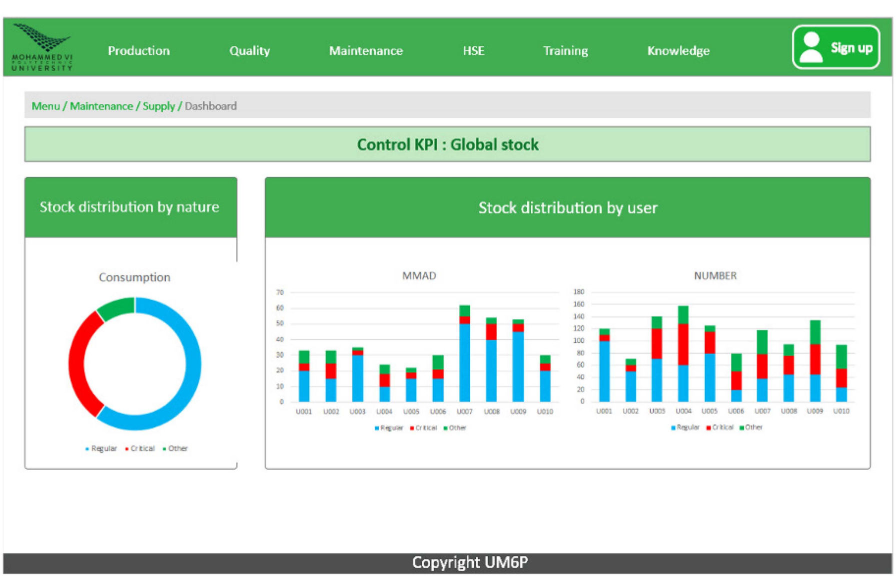

Figure 8. D4SP stock tracking dashboard.

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