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RESEARCH ARTICLE

Toward Construction 4.0: A Hybrid Centralized-Decentralized UML Model for Enhancing Procurement and Inventory in Construction Projects

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ABSTRACT In construction projects, delays and budget overruns often stem from inefficient procurement and inventory management practices. This study presents a novel UML model designed to streamline procurement and inventory management processes. The model aims to bridge the gap between conventional and digital construction practices. By integrating centralized control with decentralized decision-making, the model offers a dynamic solution for managing real-time tracking, procurement autonomy, and operational efficiency across multiple projects. Key features include the use of use-case, activity, class, and sequence diagrams to model the material flow, procurement lifecycle, and data-driven decision-making processes. This work is a significant step towards enabling the practical application of Construction 4.0 principles. In addition it sets a new standard in the field, providing a scalable and adaptable solution ready for empirical validation in future case studies.

INDEX TERMS Centralized inventory management, Construction 4.0, real-time inventory tracking, UML model, web-based inventory system application.

I. INTRODUCTION

The construction industry is known to be one of the least digitalized industries, lagging behind manufacturing and service industries in adopting modern technologies [1]. This slow adoption has resulted in numerous inefficiencies, such as delayed projects and low productivity rates [2]. However, the rise of the fourth industrial revolution (IR 4.0) has provided new opportunities for the construction industry to excel and improve its performance [3]. Industry 4.0 involves the integration of digital technologies into manufacturing and production processes. It includes technologies such as the Internet of Things (IoT), big data, artificial intelligence (AI), augmented and virtual reality (AR/VR), and automation. These technologies can revolutionize the construction industry, making it more efficient, productive, and sustainable [4]. This paper proposes a groundbreaking UML model designed to overcome these specific technological lags by enabling more integrated and responsive inventory management systems.

Construction 4.0, adapted specifically for the construction sector, extends the scope of Industry 4.0 [5]. While Construction 4.0 seeks to transform the sector, the proposed UML model specifically advances this transformation by providing a precise framework that operationalizes the theoretical benefits of Industry 4.0 in the field of inventory management. Construction 4.0 represents the fourth industrial revolution in the construction industry, aiming to make the sector more

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efficient, sustainable, and customer-centric. It embodies a transformative approach that leverages advanced technologies to revolutionize traditional construction processes [6].

Inventory and materials management can be crucial factors in determining the success of any business, and the construction industry is no exception [7]. Inventory management in construction can be highly complex and dynamic, as it involves numerous processes such as procurement, storage, and distribution of materials and equipment [8]. Efficient inventory management can help construction companies streamline operations, reduce costs, and meet project deadlines [9]. However, the construction industry poses unique complexities, including the need for specialized storage, diverse materials and equipment. Additionally, the unpredictable nature of construction projects can make effective inventory management challenging [10], [11]. In this paper, a state-of-the-art model is developed based on the Unified Modeling Language (UML) tailored specifically to address these challenges in inventory management in the construction industry. The UML model aims to provide a comprehensive solution that can adapt to changing requirements, improve efficiency, and reduce costs. The use of UML is becoming increasingly popular for modeling complex systems and processes across various industries [12], [13]. Distinct from existing applications, the proposed UML model incorporates advanced tracking and predictive analytics capabilities tailored for the dynamic and unpredictable environment of construction sites. This enhances both operational efficiency and strategic decision-making. This stems from its standardized approach to representing the structures and behaviors of a system and helps improve communication, track key performance indicators, and proactively identify potential problems [14]. The UML model developed in this article addresses these complexities through a novel integration of real-time data analytics and adaptive system design. This approach, not present in current applications, sets a new benchmark for inventory management in construction.

The UML model is an essential step in developing a web-based application that various stakeholders can access to manage or view different system activities. This model aims to provide a comprehensive solution that addresses some of the challenges of inventory management in the construction industry. It achieves this by offering the flexibility to adapt to changing requirements, improving efficiency, and reducing costs. Specifically, the UML model captures the key components and processes involved in inventory management, including procurement, storage, tracking, and distribution of materials and equipment. The model facilitates the collection and analysis of data on the inventory management process in a construction project. This helps identify potential areas for improvement and develop strategies for optimization.

Construction projects are known for their high costs and tight schedules; thus, effective inventory management is vital. Previous research shows that construction materials account for more than half of the total project expenditure, making inventory management a critical aspect of project success [9]. However, with increasing concerns surrounding the management of construction and demolition debris, it is clear that issues still need to be addressed [15]. Moreover, significant gaps exist between enterprise resource planning (ERP) procedures and construction procedures, highlighting the need for better alignment and integration [16]. Researchers are actively exploring ways to optimize material management in construction through cutting-edge methods such as the genetic algorithm multi-layer perceptron approach (GA-MLP) [17]. Additionally, researchers are paving the way toward more sustainable construction practices by identifying factors that significantly impact waste reduction and analyzing the results with a structural equation modeling approach [18]. Despite these advancements, utility maintenance works continue to pose significant issues for the industry. As a result, researchers have explored using as-built drawings to mitigate these issues [19]. Furthermore, a recent study proposed a model for three-echelon supply chain management in off-site construction with stochastic constraints. This model has the potential to revolutionize the industry's supply chain management practices [10]. The papers [20] and [21] incorporate the latest research and cutting-edge approaches, improving inventory management practices and ultimately achieving greater construction project success.

The implementation of Industry 4.0 technologies in the construction industry has been hindered by several challenges, as identified in a comprehensive review conducted by [4]. However, significant opportunities can be gained in the long run, making it an area of great interest for research. A case study of the Xiong'an Citizen Service Center explores the technological feasibility and preliminary implementation effects of a proposed framework, providing valuable insights for similar applications [22]. To understand the main areas of application and limitations of each technology when utilized in the construction industry, the authors in [18] provide a summary of findings. The study in [23] presents a methodological-technological framework adapted to the Architecture, Engineering, Construction, and Operations industry, while in [24], the authors examine a leading UK-based construction firm to ascertain the prognosis for Industry 4.0 rollout in terms of the impediments and opportunities. To improve construction processes and resource management through lean construction and Industry 4.0, [25] provides an enhanced approach. Meanwhile, the authors in [26] aim to develop a novel theoretical framework for adopting environmentally sustainable blockchain-based digital twins (BCDT) for Construction 4.0. In [27], the risk factors hindering the process of building information modeling (BIM) adoption are analyzed, emphasizing the factors specific to each industry. Finally, influential work by [28] and [29] also contributes to the ongoing research and development of Industry 4.0 technologies in the construction industry. These latter two studies collectively provide valuable information on the challenges, opportunities, and potential applications of Industry 4.0 technologies, which acquaint the development of strategies for their successful implementation, paving the way toward Construction 4.0.

Despite robust advancements in inventory management and procurement systems, a significant gap persists. Integrated, real-time, data-driven systems have not yet been fully implemented to optimize material requests and procurement processes across multiple construction sites. Existing systems fail to adequately leverage the benefits of a centralized approach, which is essential for managing the dynamic and complex nature of construction projects.

The primary objective of this research is to present a UML model of a system designed to enhance procurement and inventory management in conventional construction projects. This model will integrate real-time data, providing dashboards for data-driven decision-making. It also aims to streamline material requests and procurement processes, thereby reducing delays and cutting costs. The study advocates for a hybrid model that combines centralized and decentralized elements. This approach is expected to improve resource allocation and project efficiency. Additionally, the model promotes sustainable building practices by optimizing resource use and minimizing material waste.

This research provides a significant scholarly contribution to the construction industry by presenting a model that assists construction organizations in effectively managing their inventory and addressing distinct issues in their operations. The provided UML model has the potential to function as a comprehensive framework for further research and development endeavors in the inventory domain for construction projects. By bridging these innovative elements with the foundational principles of Construction 4.0, the UML model not only addresses current inefficiencies, but also paves the way for future advancements in construction technology integration.

The article is designed to provide a systematic and orderly approach, beginning with the methodology in Section II. The functional perspective of the system is delineated in Section III through the definition of functional requirements and use case diagrams. Section IV presents the dynamic view of the system through activity and sequence diagrams. Furthermore, the structural perspective of the system is detailed in Section V, which is illustrated through various packages of class diagrams. Moreover, the discussion in Section VI presents a comprehensive analysis of the possible advantages and drawbacks associated with the UML model. Finally, Section VII identifies potential topics for further research, setting the stage for additional studies focused on tackling the issues faced by the construction sector in inventory management.

II. METHODOLOGY

In the rapidly evolving construction industry, a decentralized approach has been adopted for decades for inventory and procurement. Site engineers independently order materials based on preliminary project estimates, leading to significant procurement inefficiencies. These range from premature material orders to delays caused by cash flow issues. The manual review process for ensuring budget compliance is time-consuming and prone to errors. Furthermore, the absence of a centralized system for material requests and inventory levels decreases transparency, causing project delays and extended capital freezing, which impacts liquidity.

To tackle these issues, a hybrid approach was developed that integrates centralized and decentralized elements to enhance operational efficiency, reduce costs, and improve transparency and accountability. The centerpiece of this approach is a Unified Modeling Language (UML) model, which supports a web-based application accessible to all stakeholders. This application streamlines material requests, allows for real-time dashboard monitoring, and enables data-driven decision-making by providing live updates.

The development of the UML model began with comprehensive interviews involving CEOs, procurement heads, and other key executives from Isam Khairi Kabbani Group (IKK), specifically from Kabbani Architectural Concepts (KAC). These interviews highlighted several operational challenges and provided critical insights that influenced the initial design of the UML model.

A. UML MODEL DEVELOPMENT STEPS

1) **Requirements Gathering:**
   - Conducted detailed interviews and workshops with stakeholders to understand their pain points, needs, and expectations.
   - Documented these requirements and translated them into use cases, user stories, and functional specifications.
2) **Functional Modeling:**
   - Used UML class diagrams to model the key entities and their relationships.
   - Highlighted key attributes and operations associated with these entities.
   - Created UML use case diagrams to illustrate how different users interact with the system.
3) **Dynamic Modeling:**
   - Developed UML sequence diagrams and activity diagrams to model the flow of events and interactions between different components of the system.
   - Visualized how the system will function in response to user actions.
4) **Structural Modeling:**
   - Designed package class diagrams to organize related classes into packages to improve system modularity and maintainability.
   - Created detailed classes to define the system's data structures, including classes for items, orders, inventory, and their attributes and methods.
5) **Refinement and Validation:**
   - Iteratively refined the UML model based on feedback from stakeholders and the development team.

- Used validation techniques (simulations) to ensure that the model accurately reflects the system's requirements.

This model was designed with innovative features tailored to the unique needs of the construction sector. It includes a workforce distribution dashboard, project progress tracking, and an advanced cost control mechanism. Each feature is crafted to work seamlessly within existing workflows, offering enhanced functionality and real-time analytical capabilities. These tools are designed to transform traditional management practices by integrating more sophisticated data analysis and user-friendly interfaces.

The theoretical UML model was then converted into a practical web-based application. This application features dynamic dashboards for managing workforce distribution, visualizing real-time project progress, and conducting comprehensive cost management. Additionally, it includes a smart shift detection system that optimizes salary calculations, further enhancing operational efficiency.

The methodology employed in this research has successfully addressed significant gaps in construction management technology and established a solid foundation for ongoing enhancements. Future initiatives will focus on scaling the model's capabilities, incorporating cutting-edge predictive analytics, and refining user interfaces to accommodate the complexities of larger, more diverse projects.

III. SYSTEM FUNCTIONAL VIEW

In the system functional view, the main actors, use cases, and functional requirements are identified [30]. An actor in the system is any person or system that interacts with the system under development to perform a specific action [31]. Furthermore, use cases refer to the actions that actors perform within a system to achieve a particular goal or objective [32]. Primary actors in this system include the Inventory Worker, Estimation Engineer, Senior Inventory Manager, Site Engineer, Senior Operations Manager, and Cost Control Engineer.

A critical aspect of the inventory management system is the adoption of a standardized coding system, such as MasterFormat, which is widely used in the construction industry to code different items. This ensures consistency and efficiency in managing inventory. However, the current coding system may not cover all items, as the range of items used in construction is continuously expanding. Therefore, there is a need to regularly update the item codes to include new materials and components as they become relevant in construction projects.

The functional requirements of an inventory management system in the construction industry are outlined in Table 1. These requirements cover the key features and capabilities that the system should have to manage inventory in multiple locations and support construction projects efficiently.

TABLE 1. Inventory management system functional requirements.

Requirement	Priority	Description
Item Manag.	High	Add, edit, delete, and view items in the inventory, including the item name, description, units, and current stock level.
Inventory Count	High	Perform physical inventory counts and update the system with current stock levels.
Order Management	High	Place and track orders for items that are needed for construction projects.
Receiving	High	Receive ordered items, update stock levels, and verify that the items received match the order.
Issuing	High	Issue items to construction sites, update stock levels, and track items that have been issued.
Reporting	High	Generate reports on inventory levels, usage, and movements, as well as reports on order status and delivery schedules.
Alerts and Notifications	Med.	Set alerts and notifications for low stock levels, stockouts, and other events.
Access Controls	High	Control access to the system, including setting up user accounts with different levels of privileges and permissions.
Integration with Other Systems	High	Integrate the inventory system with other systems used by the company, such as accounting, project management, and supply chain manag.
Audit Trail	Med.	Track and audit changes in inventory data, including additions, deletions, and updates to items and stock levels.
Vendor Manag.	Med.	Manage vendor information, including contact details, order history, and payment terms.
Cost Management	Med.	Manage the cost of items, including tracking the cost of items over time and calculating the value of inventory.
Multi-Location Support	High	Manage inventory in multiple locations, including construction sites, warehouses, and storage facilities.
Mobile Support	Low	Access and manage inventory information from mobile devices, such as smartphones.
Barcode Scanning	Low	Scan barcodes on items to quickly and accurately update inventory levels.
Stock Transfers	High	Transfer stock between locations, including from one construction site to another or from a warehouse to a construction site.
Invoice Matching	High	Match invoices to purchase orders and update inventory levels based on the delivered items.
Purchase Order Approvals	High	Route purchase orders for approval and track the approval status of purchase orders.
Vendor Lead Times	High	Track the lead time for items from each vendor, which will help plan future purchases.
Stock Adjustments	High	Adjust stock levels, including adding or subtracting items from inventory for damage, theft, or other reasons.
Return Merchandise Authorization	High	Manage the return of items to vendors, including creating RMA documents and tracking the status of RMAs.
Bill of Materials (BOM)	High	Manage the material bill for each construction project, including tracking the quantities of items required for each project and updating inventory levels based on the amounts used.
Activity Logs	High	Log user activity within the system, including who changed inventory data and when.

A. USE CASE DIAGRAMS

The Use Case Diagram is a powerful tool that helps visualize the functional requirements of a system [33]. Since the system is large and complex, multiple use case diagrams are developed, including a high-level general use case diagram. Then, several smaller use case diagrams are presented, each focusing on specific system components separately. This approach can help simplify the overall design and make it easier to understand, manage, and address design deficiencies.

The Inventory Management and Control Module is designed to manage and control the inventory of materials and equipment in the construction industry. The general use case diagram for the module is shown in Figure 1. The diagram represents the actors, the simple use cases, and the relationships between them. The actors in the system include the Inventory Worker, who is responsible for managing the inventory and making decisions related to inventory management.

Additionally, an Estimation Engineer adds new items to the system with unique identification codes. Moreover, the procurement system receives material requests and processes them after the cost control department confirms that they are within budget. The Senior Operations Manager is responsible for approving or disapproving the transfer of materials from one site to another based on need and availability. Finally, the Site Engineer, who initiates the material requests, starts the whole process. The use cases are the ellipses in the diagram.

The dashed arrows in the diagram represent the relationships between the actors and the use cases. Use cases that are part of other use cases are represented by the ≪Include≫ notation and use cases that extend other use cases are represented by the ≪Extend≫ notation. For example, the *Add Items* use case is extended for the *Search Items* use case, while the *Track Deliveries* use case is included in the *Receive Deliveries* use case.

Figure 2 shows the detailed module use case diagram of the site inventory, a component of the inventory management and control system. This sub-module provides detailed inventory management and control capabilities for site inventory workers. The module allows for the entry and modification of item descriptions, unit measures, and pictures, as well as linking items to bar-codes or QR codes. It also enables workers to scan items in and out, generate inventory reports, and receive deliveries. The use case diagram includes extension points for adding, viewing, and searching for items, and printing historical stock levels. Additionally, the diagram explains the integration of the Site Inventory Detailed Module with other systems such as the Estimation System, Procurement System, and Site Engineer Use Cases.

The Materials Supply Request Module in Figure 3 is a use case diagram that outlines the various functionalities of managing material requests from different stores. The users have different roles and responsibilities within the system, and the use case diagram shows how they interact with the system to accomplish their tasks. The system has been specifically created to facilitate the management of the material procurement process from various retailers. The accompanying figure provides a visual representation of the sequential phases included in this process. The system enables users to approve or disapprove new goods, obtain verified suppliers, access projected or real lead times, acquire purchase pricing, and include estimated prices. In addition to their primary functions, users have the ability to authorize release orders, add products to a request, generate reports on past orders, verify the status of Material Supply Requests (MSR), and conduct inquiries based on specific dates or store locations. Furthermore, the module offers extension points, enabling users to customize objects and generate and receive requests. The system is also engineered to accommodate diverse scenarios, such as when some or all items are unavailable at the present shop or when certain or all items are accessible at alternative stores. It enables users to reject release orders and accept MSRs. Additionally, it can distribute MSR materials to either the designated stores or the originating store, contingent upon the approval status of the release order.

The system is also designed to notify procurement and cost control engineers when an MSR is submitted and to check whether the request is within the project budget. Finally, the system notifies site engineers of any changes in the inventory system and provides an interface for managing the inventory at different stores.

IV. SYSTEM DYNAMIC VIEW

The dynamic view of the system focuses on how various components interact, particularly in response to specific events and actions. This perspective provides detailed insights into the behavior of the system under different scenarios, ensuring that all processes and interactions are well-coordinated and efficient. The dynamic view is represented through several activity and sequence diagrams, each illustrating a specific process within the inventory and procurement system.

An activity diagram represents the steps involved in a process or workflow. It is a powerful tool for modeling complex systems and business processes and can help clarify and communicate the flow of activities and decisions within a process [34]. These diagrams are often used by software developers, system analysts, and business stakeholders to better understand a system's behavior and identify areas for improvement. On the other hand, sequence diagrams are useful for understanding the dynamic aspects of a system, showing how processes operate and interact over time. These diagrams help visualize the order of operations and the timing of interactions between different components of the system, providing a clear depiction of the sequence of events and the flow of data throughout the system.

Together, activity and sequence diagrams enhance the understanding of the system's operational dynamics. They help identify potential bottlenecks and inefficiencies that can be optimized. By mapping out the specific interactions and temporal relationships between system components, these

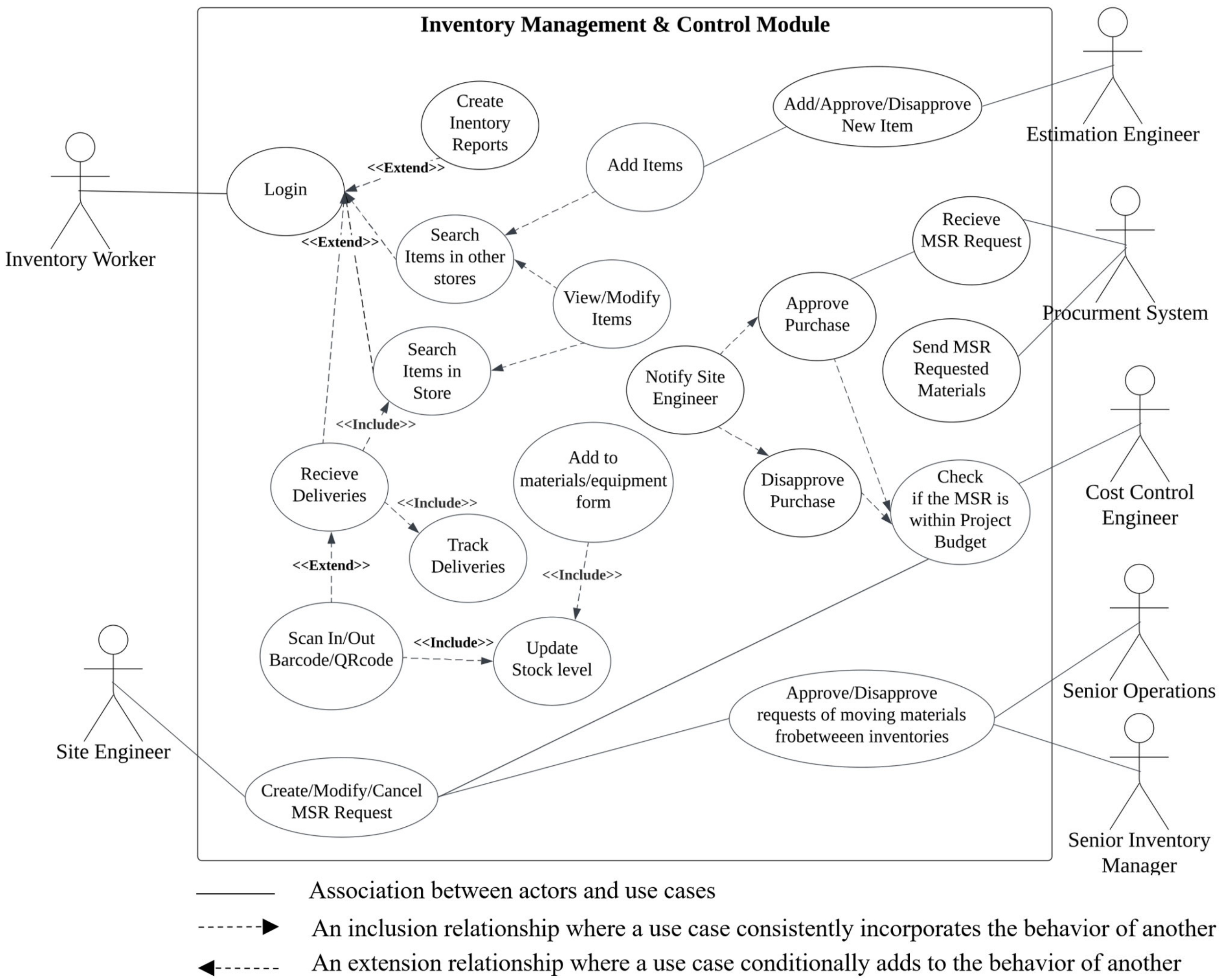

FIGURE 1. High-level general use-case diagram.

diagrams play a crucial role in system design and continuous improvement efforts. They serve not only as tools for initial system design but also to manage changes and ensure that modifications align with the system's intended dynamic behavior.

A. MATERIAL REQUEST AND NEW ITEM ADDITION PROCESSES

Figure 4 and Figure 5 collectively illustrate the detailed process of item ordering in construction projects. Figure 4, a sequence diagram that elaborates on the process of adding a new item. It details the interactions among the site engineer, estimation engineer, and the inventory system, concluding with stakeholder notifications upon the successful addition of an item. Together, these diagrams clarify the comprehensive material request process in construction project management.

Figure 5, an activity diagram, initiates with the site engineer logging into the system. This step allows them to either review previous requests or generate a new one. Upon creating a new request, the site engineer compiles a list of required items, referring to a database coded according to MasterFormat/CSI construction industry standards. If an item is absent from the database, the inquiry is forwarded to the estimation engineer, who either updates the database with the new item or provides the correct item code.

This process ensures that all materials used in construction projects are standardized according to industry norms, which enhances consistency and efficiency in procurement and inventory management. Figure 4 explains the specifics of adding new items to the system, showcasing the roles and responsibilities of the estimation engineer in maintaining an up-to-date and comprehensive inventory database. Meanwhile, the activity diagram illustrated in Figure 5 highlights the step-by-step flow from login to the final decision on item inclusion, providing a clear visual representation of the process.

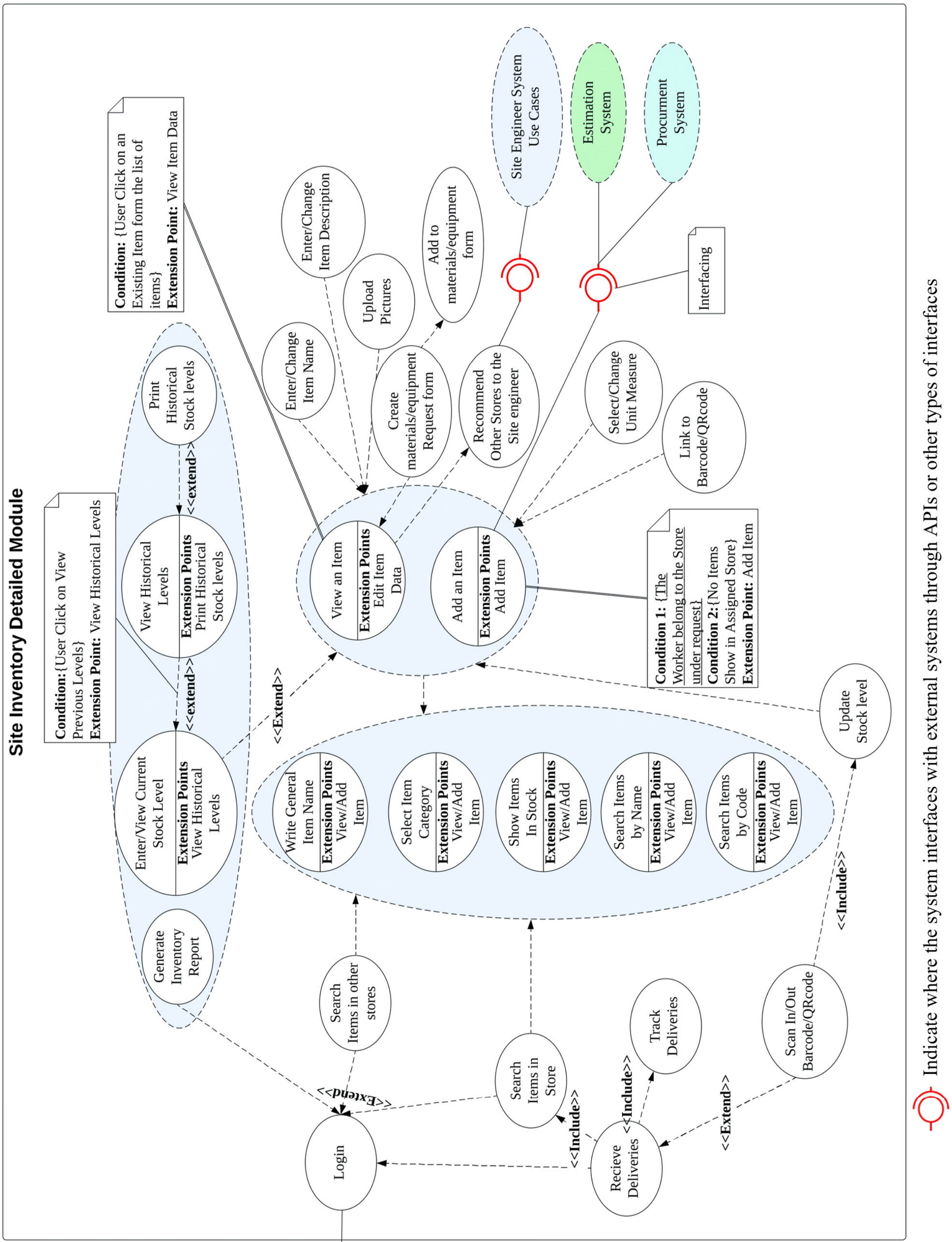

FIGURE 2. Site inventory detailed module use-case diagram.

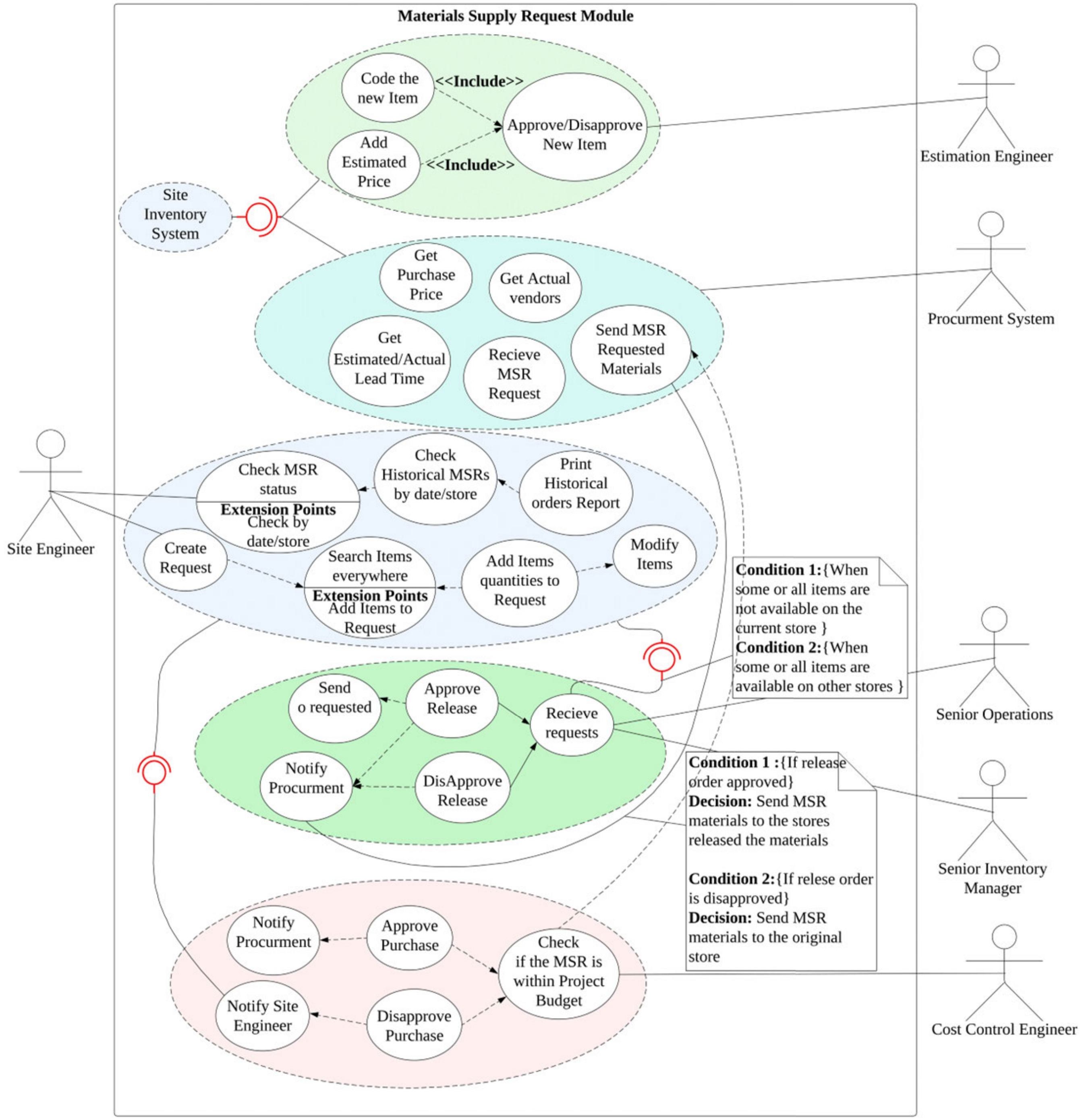

FIGURE 3. The materials supply request module use-case diagram.

B. ORDER FULFILLMENT AND INVENTORY REDISTRIBUTION STRATEGIES

1) SCENARIO I: LOCALIZED INVENTORY SYNCHRONIZATION PROTOCOL (LISP)

To optimize resource allocation, it is essential to regularly check inventories and initiate internal transfers or material requisitions as needed. This approach helps maintain efficiency and minimize delays in the supply chain, ensuring that resources are utilized effectively and cost-effectively. Continuous monitoring of inventory levels and streamlining procurement helps organizations avoid stockouts and overstock, improving resource management and operational efficiency.

LISP Protocol Description:

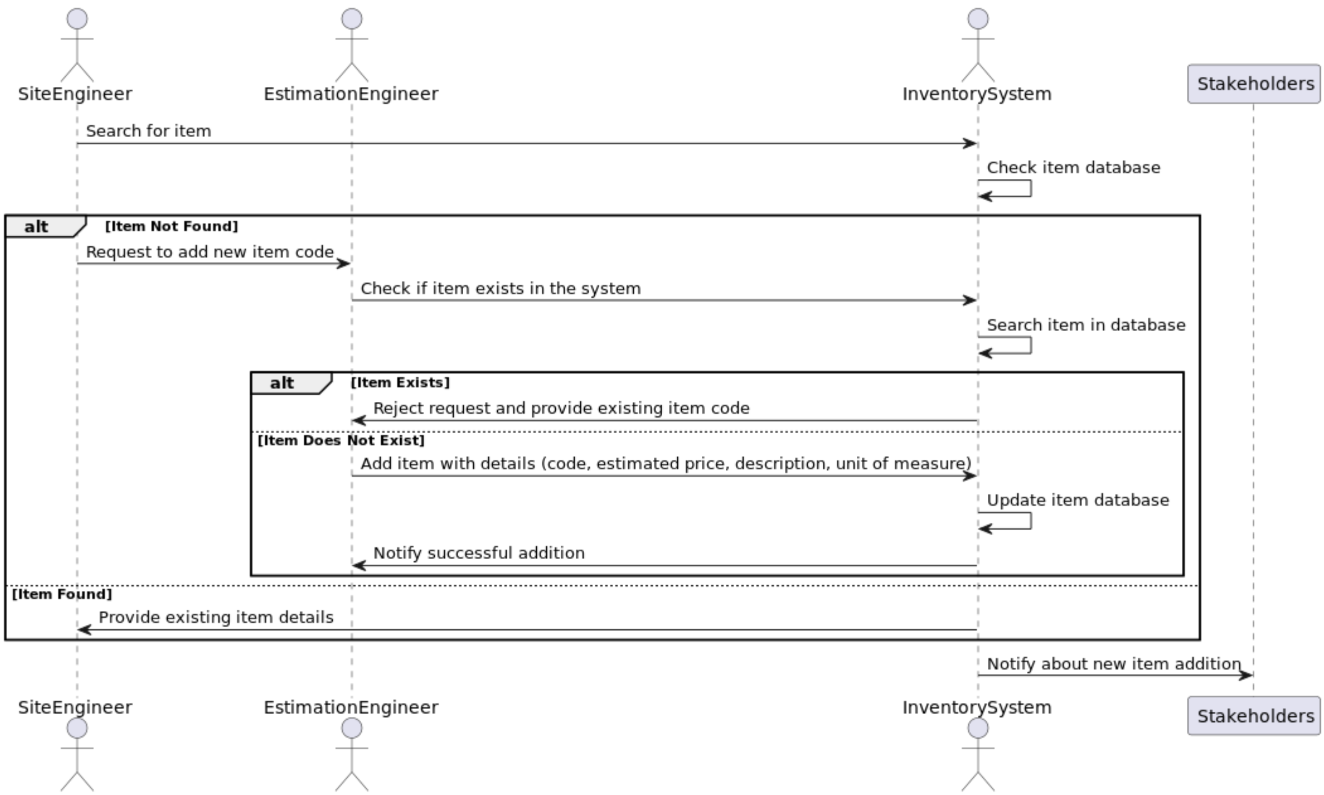

FIGURE 4. Adding new item sequence diagram.

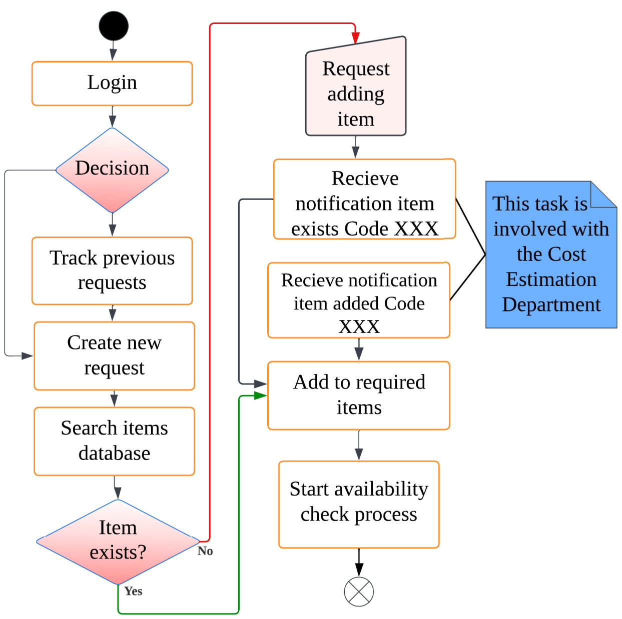

FIGURE 5. Construction site materials/equipment requests activity diagram.

1) **Inventory Availability Assessment:**
   - Upon receiving a material request from a site engineer, the system first checks the local site inventory for availability.
   - If the required items or a portion thereof are available, they are displayed for the site engineer's confirmation.
   - The site engineer can either approve the use of available items or request additional quantities.

2) **Inter-site Inventory Query:**
   - If the required materials are not fully available at the local site, the system queries other site inventories within the organization.
   - If the materials are available elsewhere, the system initiates a transfer approval process.
   - The transfer involves a systematic review and approval from designated authorities to ensure compliance with internal resource allocation policies.

3) **Material Supply Request (MSR) Initiation:**
   - If the materials are not available in any site inventory, the system generates an MSR.
   - The MSR is automatically forwarded to the cost control department, detailing the unavailable items and requesting external procurement.

4) **Documentation and Notification:**
   - Throughout the process, all actions are documented, and relevant parties are notified.
   - This includes notifications regarding the status of material requests, transfer approvals, and MSR submissions.

The diagram presented by Figure 6 illustrates the systematic process from initial request through various inventory checks, decision points, and final actions, ensuring a clear understanding of the material allocation workflow.

2) SCENARIO II: INTEGRATED RESOURCE ALLOCATION MODEL (IRAM)

To optimize resource allocation, it is crucial to dynamically choose between procurement and transfer based on real-time assessments of lead times, costs, and inventory levels. This strategy ensures that decisions are data-driven, allowing for the most cost-effective and timely allocation of resources, ultimately enhancing operational efficiency and reducing unnecessary expenditures.

IRAM Protocol Description:

1) **Initial Assessment:** Verify the immediate availability of required materials across all inventories. If unavailable, proceed to assess procurement options.
2) **Comparative Cost Analysis:** Conduct a dual threshold analysis:
   - **Temporal Alignment:** Compare procurement lead times against project deadlines.
   - **Cost Effectiveness:** Calculate and compare the immediate financial impacts of lateness versus transportation costs.
3) **Strategic Decision Making:** Implement decision rules based on cost-benefit analysis:
   - **Procurement Priority:** Initiate purchase if the procurement aligns with project timelines or if lateness costs exceed logistical costs.
   - **Transfer Mechanism:** Proceed with material transfer if it offers a cost advantage and meets temporal requirements.
4) **Operational Execution:** Execute the chosen strategy, update inventory records, and communicate actions to all stakeholders.
5) **Financial Reconciliation:** Adjust financial accounts to reflect the cost implications of the chosen strategy on the involved inventories.

3) SCENARIO III: STRATEGIC MATERIAL REDISTRIBUTION FRAMEWORK (SMRF)

A prioritization model based on penalization costs is used to address situations where multiple sites require the same materials but face different delay consequences. This approach ensures that resources are allocated efficiently, taking into account the varying impacts of delays at different sites. The model evaluates the penalty costs associated with delays and prioritizes material distribution to sites with more severe financial or operational consequences. This approach optimizes resource utilization and minimizes overall project disruptions.

SMRF Protocol Description:

1) **Simultaneous Demand Assessment:** Identify and quantify concurrent demands across multiple sites.

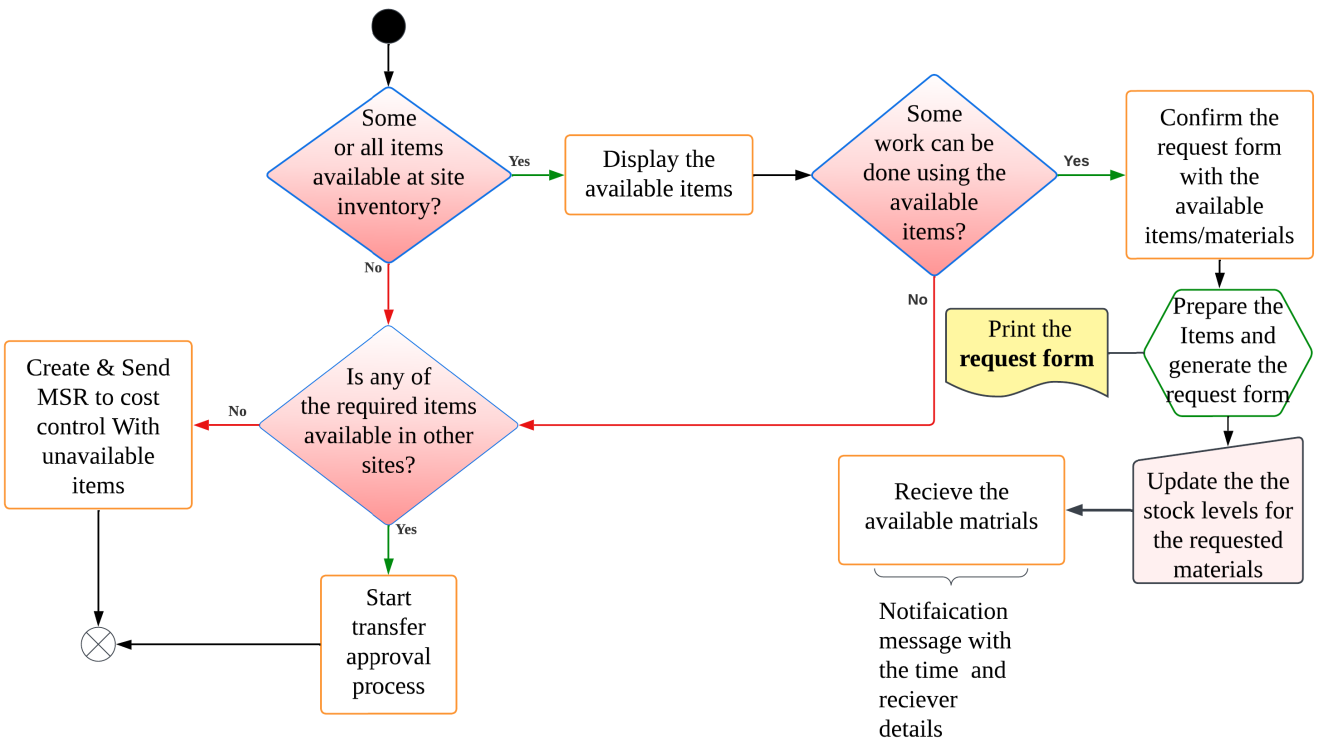

FIGURE 6. Material availability check across all inventory activity diagram.

2) **Penalty Cost Evaluation:** Calculate potential delay penalties for each site and determine the differential impact.
3) **Resource Prioritization:** Allocate resources preferentially to sites with higher delay penalties.
4) **Cost-Efficiency Execution:** Implement the most cost-effective strategy (transfer vs. direct purchase) based on a comprehensive cost analysis.
5) **Inventory and Financial Management:** Replenish transferred materials, update inventory levels, and manage financial implications between sites.

Figure 7 and Figure 8 collectively illustrate the decision-making process for handling material requests, emphasizing the scenarios where transfers and procurement are possible. Figure 7, an activity diagram, illustrates the IRAM and SMRF scenarios: inter-site inventory queries, and cost-effective decision-making based on lead times and penalties. It details the steps from initial request assessment, cost and lead time estimations, to final approval decisions. Figure 8, a sequence diagram, complements this by detailing the systematic process from the initial request through inventory checks, decision points, and final actions, ensuring a clear understanding of the material allocation workflow and resource optimization.

C. BUDGET COMPLIANCE AND COST CONTROL PROCESSES

The system ensures that all material requests are within budget as illustrated in Figure 9. When an MSR is received by Cost Control, the following steps are taken:

1) **Check for Transfer Request:**
   - If there is a transfer request, the system shows the materials transfer request status.
   - If approved, the procurement process for the transferring site begins, and the cost burden is placed on the requesting site.
2) **Budget Check:**
   - If there is no transfer request, the system checks if the MSR is within the project's budget.
   - If within budget, the procurement process for the requesting site begins.
   - If not within budget, the MSR is rejected, and the site engineer is notified to modify the request.

By providing a comprehensive view of the system's dynamics, these diagrams help identify potential bottlenecks, optimize processes, and ensure that all interactions are well-coordinated and efficient. This dynamic view complements the structural view, providing a holistic understanding of the inventory and procurement system within the construction industry.

V. SYSTEM STRUCTURAL VIEW

Structural models in object-oriented systems illustrate the static relationships between objects within the system [35]. Constructing a package class diagram is one way to represent these relationships and functions. Within the UML, a class is defined as a rectangle separated into three distinct sections: the class name in the top section, the attributes of the class in the middle section, and the methods or behaviors in the bottom section [36]. These behaviors define the responsibilities and constraints of each object. Class diagrams effectively provide a static perspective on the relationships and constraints between different classes [37].

The class diagram provides a detailed view of the system's data structures and relationships, which can be used as a database design module [38]. The class diagram was developed based on the functional requirements identified in the use case diagram and the workflow identified in the activity diagram. The class diagram consists of classes, attributes, and associations representing the data structures and relationships in the inventory management system [39].

The class diagram for the Inventory Management System (IMS) presented in this section identifies the different classes and their associated attributes and methods. The IMS comprises several packages related to other subsystems. This includes the Staff Package, Units of Measure Package, Reporting Package, and Materials Package, each containing classes that encapsulate the system's functionalities.

The use of different packages within software development fulfills many significant objectives. Firstly, the use of logical groups in code structure facilitates maintenance and enhances reusability. The practice of partitioning code into distinct packages offers many advantages to developers. Firstly, it enhances the ability to browse and comprehend the overall architecture of a project. This improved understanding of the code structure subsequently diminishes the probability of mistakes occurring during development. Additionally, segregating code into packages promotes seamless communication among team members, enabling their collective efforts in software development. Furthermore, using packages can help avoid naming conflicts between different parts of a project, which can otherwise lead to errors and confusion. By defining clear boundaries between various system modules, packages ensure that each component is uniquely identifiable and can be referred to without ambiguity. Besides, using packages facilitates the creation of libraries or frameworks that may be employed in many projects, hence enhancing the effectiveness and uniformity of software development. Packages have the potential to streamline software development and enhance code quality by offering a standardized collection of features that can be seamlessly included in other projects. This can effectively minimize the time and resources needed for creating new software. Moreover, the use of packages is widely recognized as a means of reducing the complexity of a software system. A package is a container that groups related classes, interfaces, and other packages together, providing a level of abstraction and encapsulation that can simplify the overall structure of the system.

By organizing classes into packages, developers can create a modular design that allows for better separation of concerns and promotes code reusability. This makes it easier to

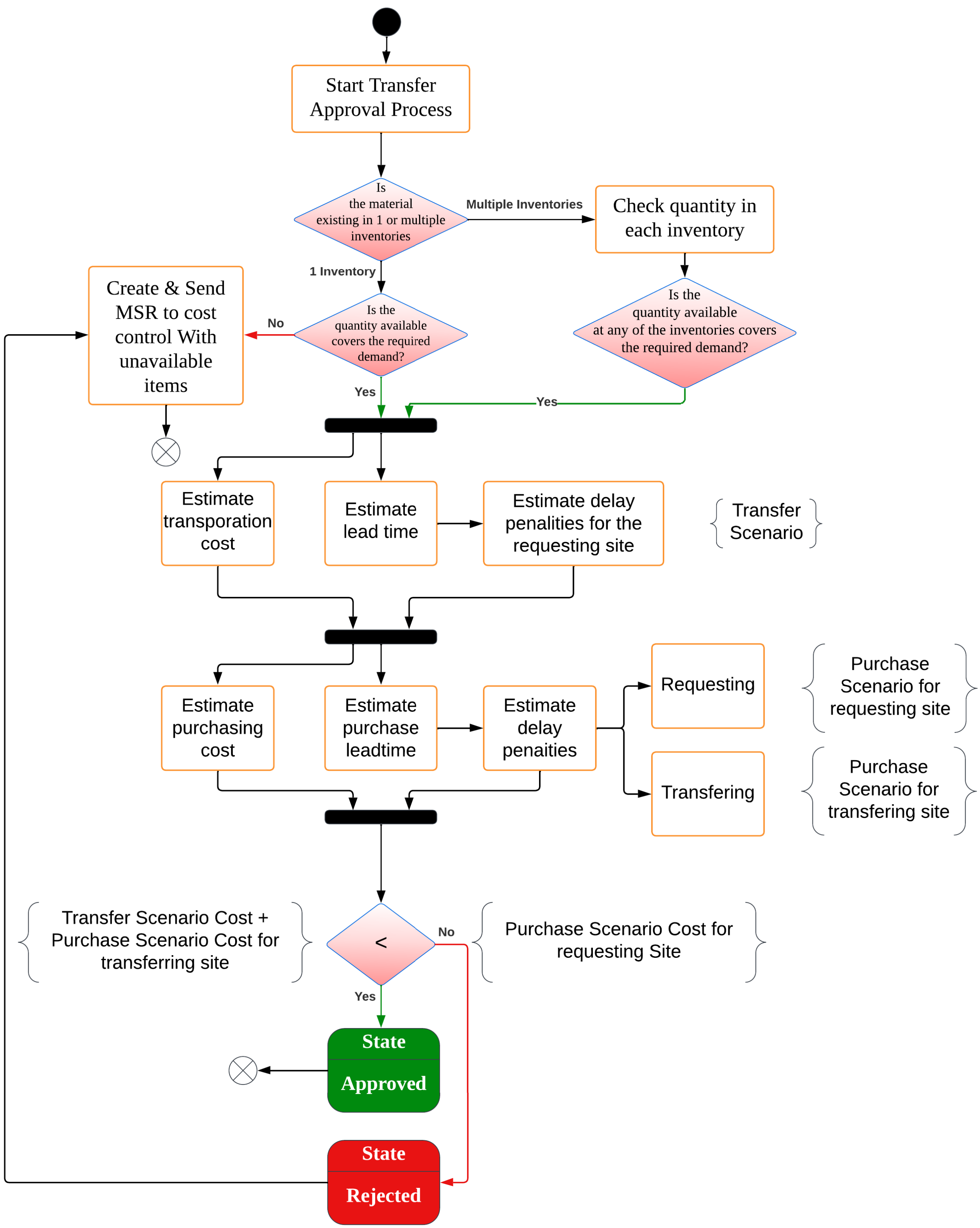

FIGURE 7. **Material transfer approval and purchasing optimization activity diagram.**

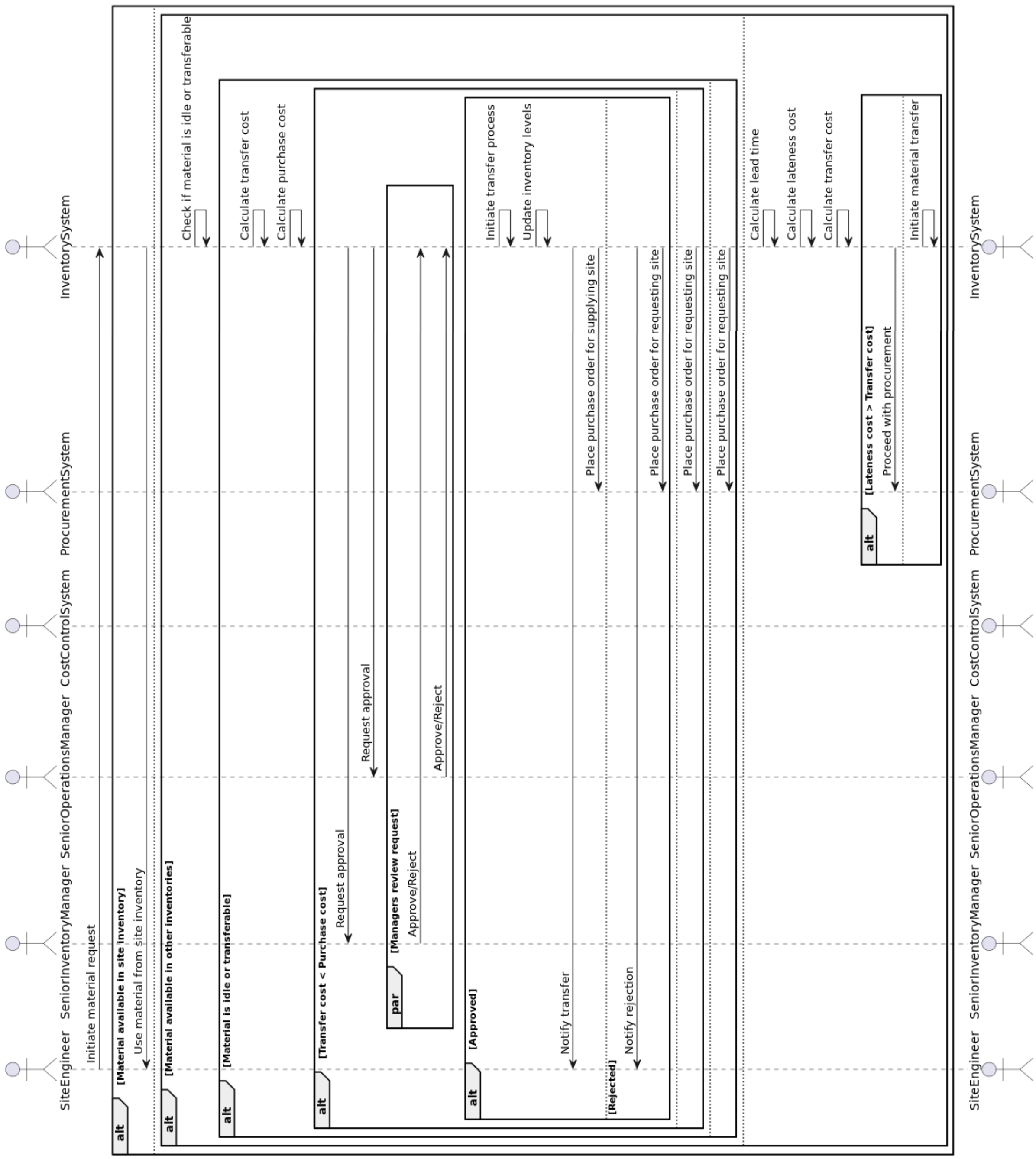

FIGURE 8. Sequential decision-making process for material request handling and resource optimization.

maintain and update the system over time, as changes can be made to individual packages without affecting the entire system. Additionally, using packages can improve the understanding of the system for developers and other stakeholders. When related components are grouped together, the system's overall structure becomes more coherent and easier to navigate. This can be particularly important in larger systems, where the system's complexity can be a major challenge for developers. The class diagram plays a crucial role in the development of a database, as it serves as a blueprint for the database design. It allows developers to visualize the structure of the database and the relationships between different entities in the system.

Using the class diagram, developers can easily identify the data that needs to be stored in the database, the attributes of each entity, and the relationships between entities. This helps ensure that the database is designed to accurately represent the data and relationships in the system. Additionally, the class diagram helps identify potential problems or challenges during the development process. This enables developers to proactively address these issues and make any necessary adjustments to the database design.

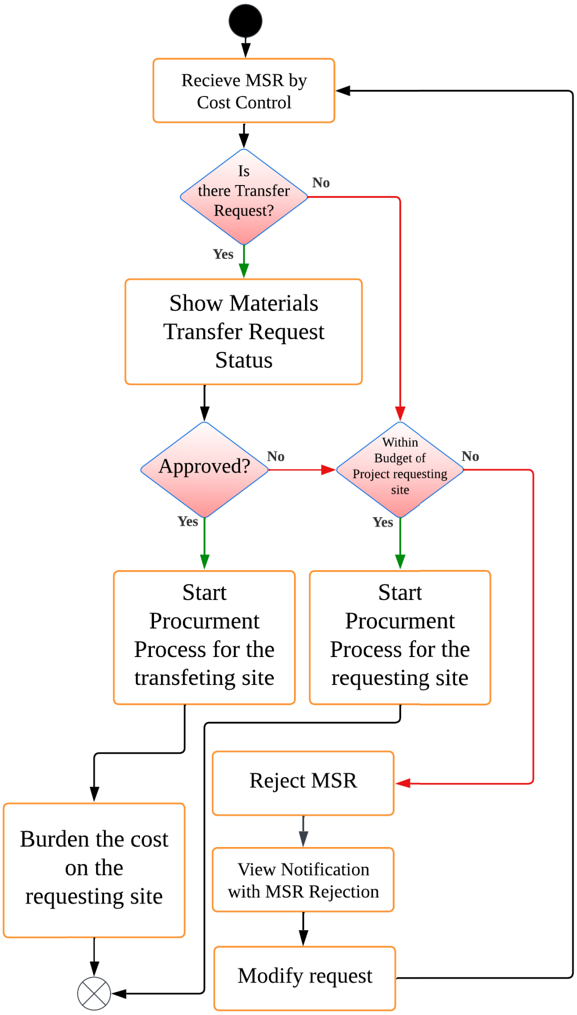

FIGURE 9. Cost control MSR activity diagram.

A. MASTER INVENTORY PACKAGE

The Master Inventory Class Diagram in Figure 10 provides a comprehensive overview of the inventory and materials management system in the construction industry. It is designed to provide a structural system view, showcasing the main classes and their relationships. The diagram consists of several key classes, including Items and Materials, Inventory, Stock Levels, Reorder Stock Level, Materials Transportation Cost, Projects, Locations, Staff Package, Reporting Package, Procurement Package, Estimation Package, and Units Package.

The diagram also highlights the relationships between the classes, including one-to-one and one-to-many relationships. For instance, the Inventory class has a one-to-many relationship with the Items/Materials class, meaning an inventory can have multiple items, but an item can only belong to one inventory. Similarly, the Projects class has a one-to-many relationship with the Requests/Orders class, meaning a project can have multiple requests/orders, but a request/order can only belong to one project.

The detailed packages, such as the Procurement Package, the Estimate Package, and the Measurement Units Package, provide additional information and functionality to the inventory and materials management system. For example, the Procurement Package contains classes and methods for creating and managing purchase orders and supplier information. In contrast, the Estimate Package provides tools for estimating the cost and quantity of materials needed for a project. The Measurement Units Package includes classes and methods for managing different units of measurement used in the inventory system.

B. PROCUREMENT PACKAGE

The procurement package is a critical component of the procurement process in construction companies [40]. The Procurement Package class diagram in Figure 11 consists of several related classes, including Actual Lead Time, Actual Prices, Expected Lead Time, Vendors/Suppliers, and Items/Materials. These classes are associated with each other in various ways to achieve the objectives of the procurement package.

The Actual Lead Time class contains item ID, actual lead time, and actual lead time measurement unit. It also includes methods for updating and retrieving the actual lead time of an item. The Expected Lead Time class contains the item ID, expected lead time, and expected lead time unit, along with methods to update and retrieve the expected lead time.

The Actual Prices class contains the item ID, measurement unit ID, unit price, and discount amount. This class allows the procurement team to track the actual price paid for each item, including any discounts received. The Vendors/Suppliers class contains the supplier ID, supplier name, supplier contact information, and methods for adding, removing, and updating suppliers.

The Items/Materials class is the central class of the procurement package, containing information on each item, including the item ID, supplier ID, measurement unit ID, item category, item name, item description, item status, supplier name, and actual delivery date.

The use of different classes and associations in the procurement package allows for the reduction of complexity in the procurement process, making it easier to understand and manage. The Actual Lead Time, Expected Lead Time, and Actual Prices classes help to track and manage the procurement process. In contrast, the Vendors/Suppliers and Items/Materials classes provide a comprehensive view of the procurement process, including supplier details and item details.

C. ESTIMATION PACKAGE

The Estimation Package is an important component of the construction project management system. It provides a way to estimate the cost of different items and materials required for a construction project. This package class diagram is shown in Figure 12 and contains several classes, including

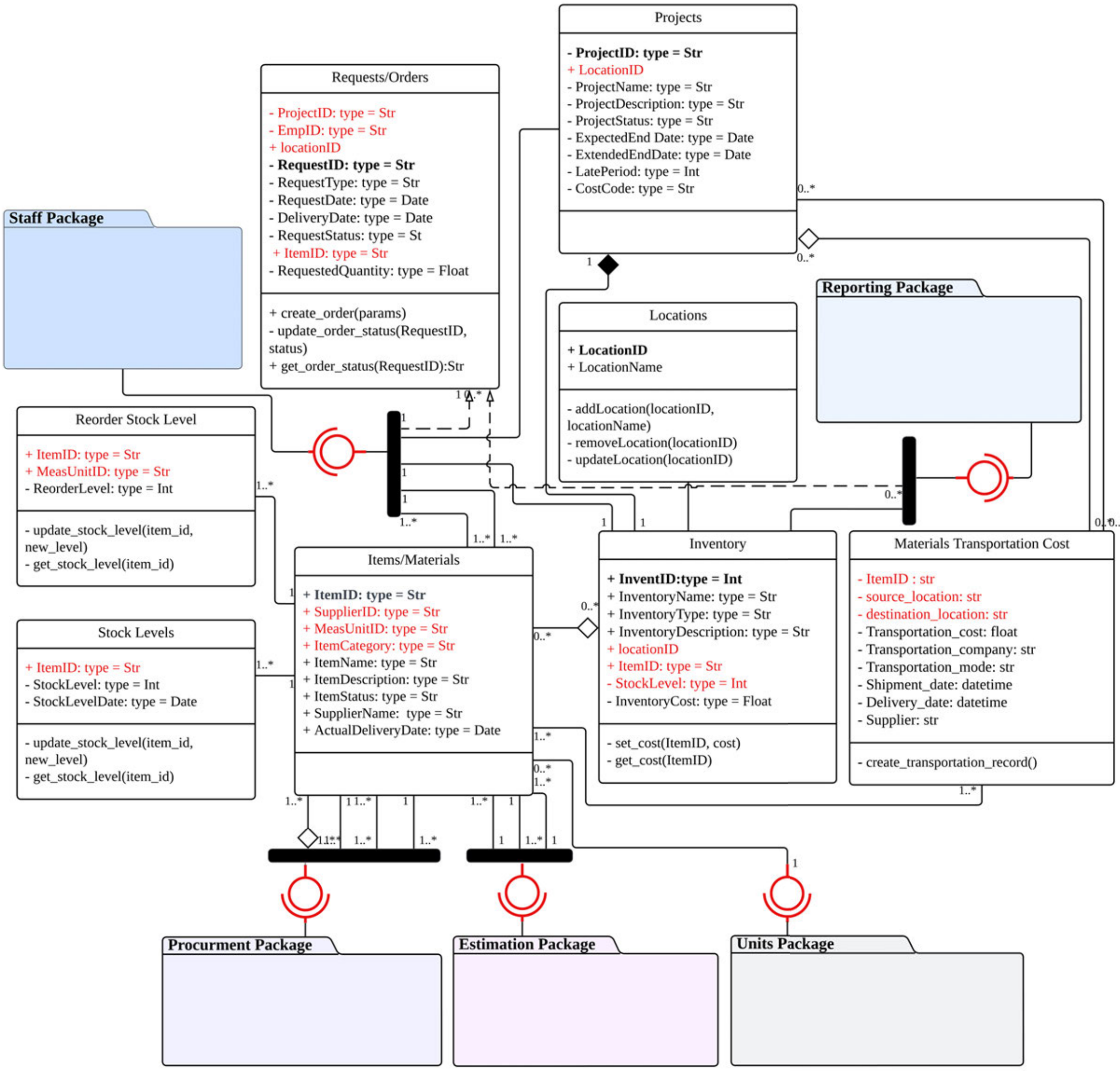

FIGURE 10. Master inventory class diagram.

Items/Materials Categories, Items/Materials Subcategories, Estimated Prices, and Items/Materials.

The Items/Materials Categories class helps categorize the items and materials required for a construction project. This class includes the Category ID, Category Name, and Category Description. It also provides a method to add a new category to the system.

The Items/Materials Subcategories class provides further subcategorization of items and materials. This class includes the subcategory ID, subcategory name, and subcategory description. It also provides a method for adding a new subcategory to the system.

The Estimated Prices class helps estimate the cost of different items and materials. This class includes item ID, estimated price, and date of sale. It provides methods to update the estimated price of an item, get the estimated price of an item, and set the estimated price of an item.

The Items/Materials class includes the Item ID, Supplier ID, MeasUnitID, Item Category, Item Name, Item Description, Item Status, Supplier Name, and Actual Delivery Date. This class helps you keep track of the different items and materials required for a construction project.

D. REPORTING PACKAGE

The Reporting Package class diagram in Figure 13 allows the construction company to generate various reports, including the inventory report, delivery note, damaged items report, and equipment custody report. This information is essential to ensure that different departments are up to date on relevant information. Multiple relations are developed between the package and other classes and packages. For instance, an example is the relation between the MSR (BackOrder) class, generating the MSR reports, and the Orders class. Other relations with projects and inventory classes are essential

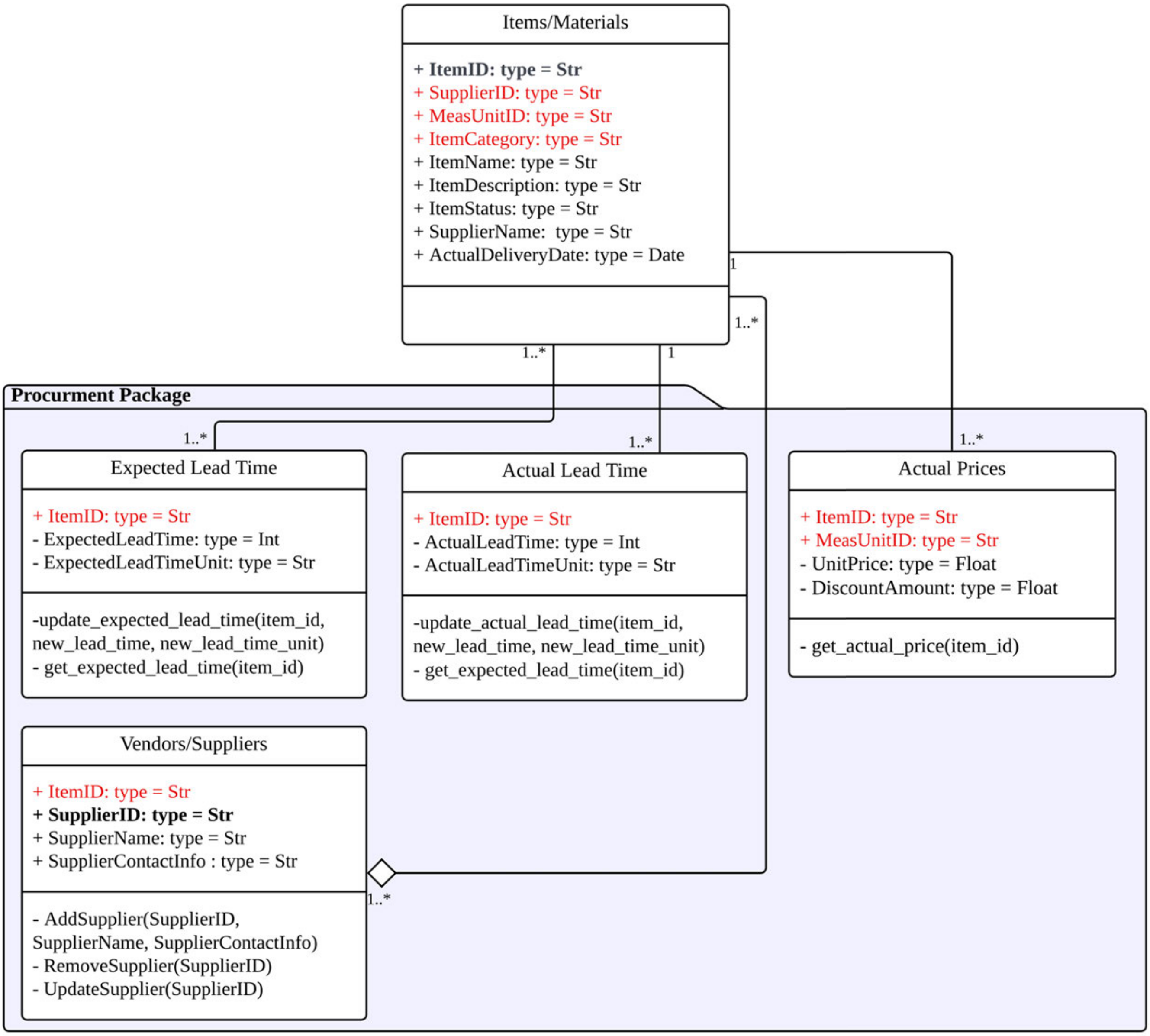

FIGURE 11. Procurement package class diagram.

to collect the proper information to include in different reports. Each type of report is meant to be generated and viewed by a specific staff member. Thus, the Reporting Package interfaces with the Staff Package. When a report is generated, notifications are sent to the interested parties, so a Notifications Class is also associated with the Reporting Package.

Reports are essential for any type of business, including construction contractors. For example, the Release Report is important to keep track of inventory levels and ensure that all items are accounted for and that quantities are accurate. This report can help ensure that projects are not delayed due to shortages of essential materials. Furthermore, the Delivery Note is important to ensure that materials are delivered to the correct location and arrive on time. Again, the Equipment Custody Report is important to track the use of equipment and ensure that it is properly maintained. This report can help ensure that the equipment is available when needed and in good condition. Furthermore, having these reports on file, the company can refer to them to resolve any issues or disputes that may arise in the future.

VI. DISCUSSION

A hybrid model that combines elements of centralization and decentralization has several benefits. First and foremost, this approach facilitates a more effective and efficient decision-making process, enabling choices to be taken by individuals with the right amount of authority. This implies that choices of lesser significance may be delegated to the decentralized level, whilst those of greater significance can be retained

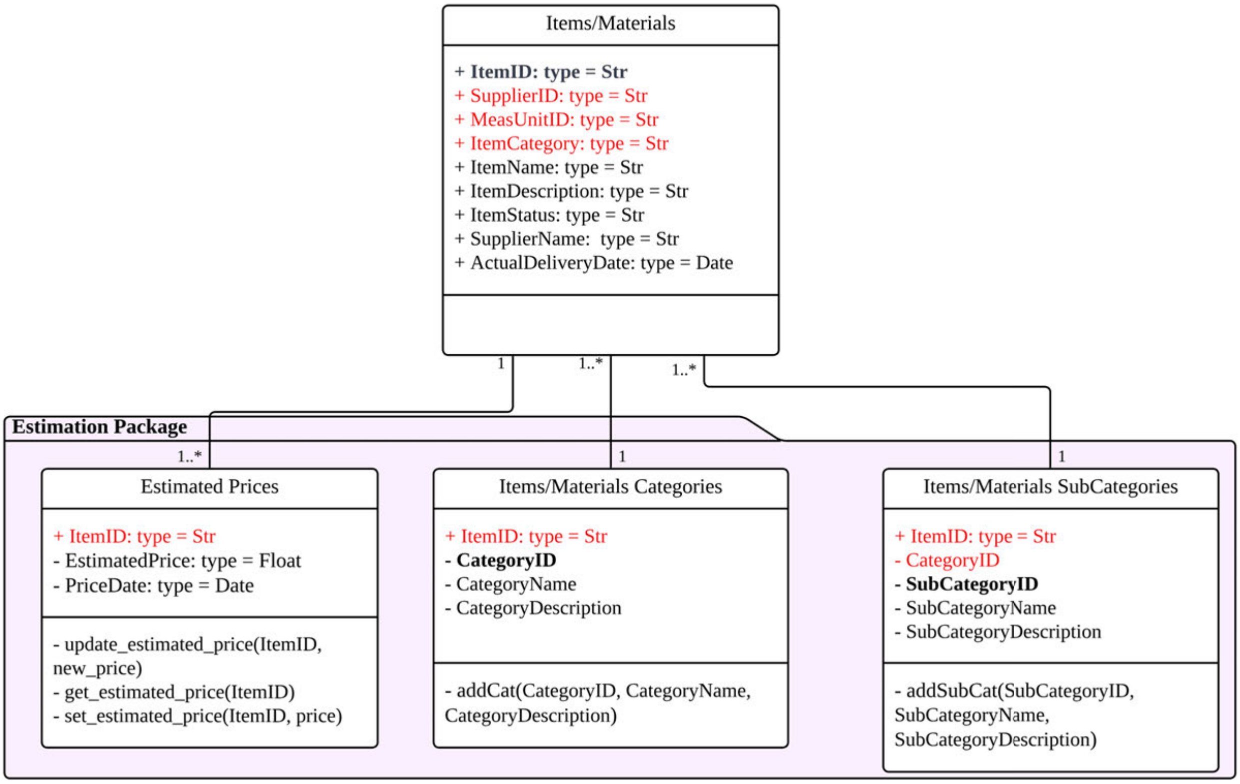

FIGURE 12. Estimation package class diagram.

at the centralized level. For instance, minor decisions can be made at the decentralized level, while major decisions can be made at the centralized level. This can lead to faster decision-making, as minor decisions need not be referred to higher authorities. Second, it allows for better coordination between different departments and units, as a central authority oversees the various decentralized units. This trend has the potential to enhance communication and foster cooperation across multiple divisions within the business. A hybrid system combining centralization and decentralization elements may provide enhanced flexibility by effectively responding to changing conditions and varying demands. Decentralized entities can promptly address local demands, while the central authority offers comprehensive advice and direction on a broader scale. In general, a hybrid model combining centralization and decentralization elements may provide a harmonious equilibrium between operational effectiveness, collaborative synchronization, and adaptability.

The current construction site system involves a site engineer ordering only items they know are unavailable in the site inventory. Then, the cost control department checks if the request is within the project budget. If it is, they send the request to procurement to purchase the materials and send them to the site. If the request is not within budget, it is rejected and revised by the site engineer for resubmission. Many phone calls and paperwork are involved in this process, resulting in a lengthy and inefficient procedure. Sometimes, site engineers order materials too early to ensure availability, leading to additional costs and budgetary misallocation. Moreover, some projects receive the materials early, while others may struggle due to the unavailability of funds.

In contrast, the suggested system enhances the efficiency of the material request process by providing site engineers with a user-friendly digital platform to place orders for supplies conveniently. Subsequently, the system conducts an inventory assessment of the designated location and other plausible sources to ascertain the availability of the required items. If the items are available, the system initiates the procurement process and updates the inventory levels accordingly. The system alerts the relevant personnel to begin the procurement process if items are unavailable. The system also calculates the expected purchase lead time and transportation cost to ensure efficient and cost-effective procurement.

Upon comparing the two systems, the proposed system offers several advantages over the current system. First, the proposed system eliminates the need for manual paperwork and phone calls, reducing the risk of human errors and speeding up the request process. Second, the system offers real-time inventory tracking, allowing site engineers to make informed decisions when requesting materials. Third, the system provides cost estimates for procurement, ensuring that the project stays within budget. Finally, the system enables efficient allocation of funds, ensuring that materials are available when needed, thus saving costs on early orders

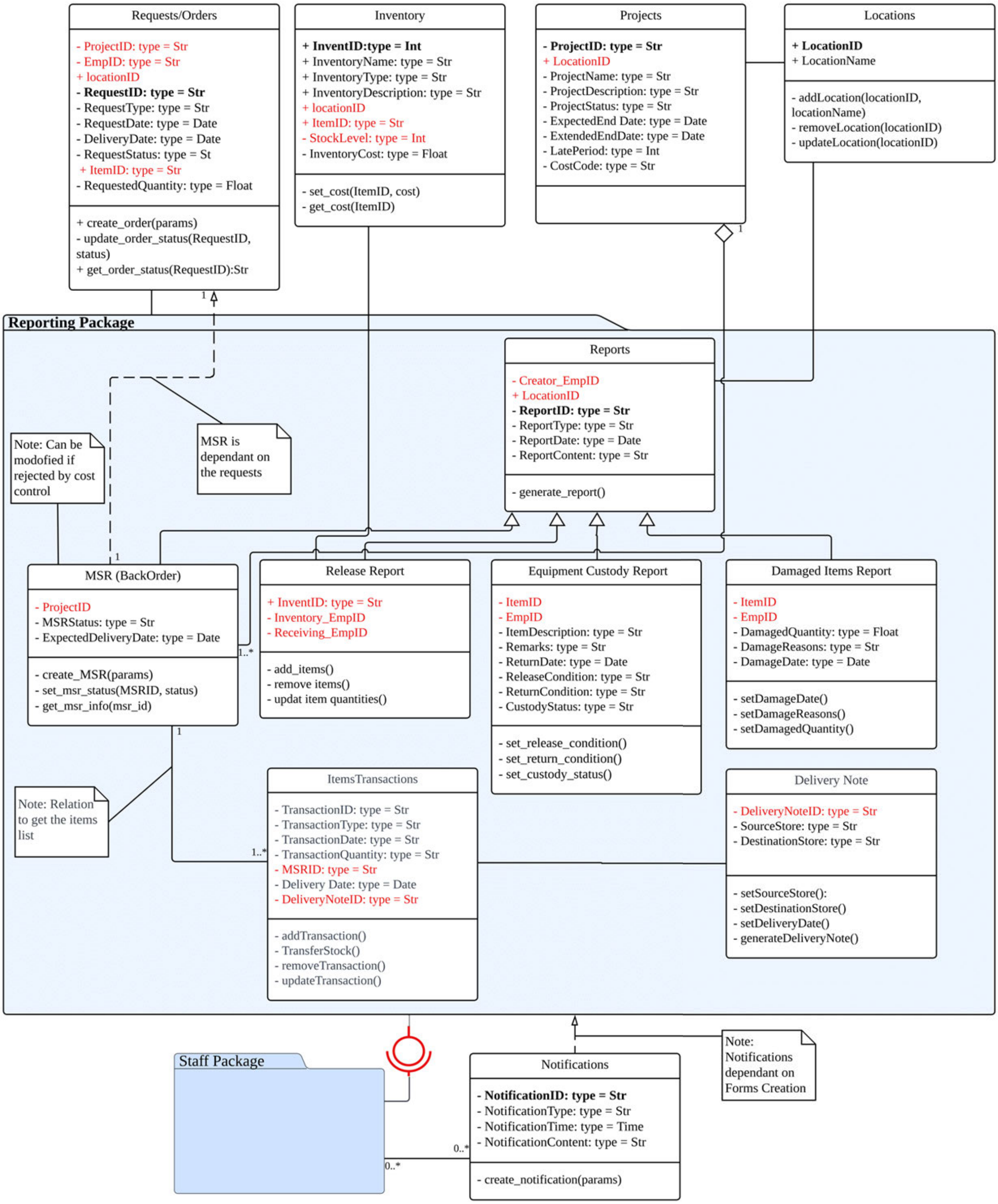

FIGURE 13. Reporting package class diagram.

and unnecessary storage fees. The proposed system offers significant benefits over the current system, making it a worthwhile investment for the construction company.

Incorporating sustainability practices is crucial in advancing towards Construction 4.0. The proposed UML model integrates several sustainability-focused features, such as optimizing inventory management to reduce material waste, improving energy efficiency through real-time tracking and predictive analytics, and promoting sustainable procurement by selecting and managing suppliers based on sustainability

TABLE 2. Future functional requirements incorporating industry 4.0 principles.

Requirement	Priority	Description
Predictive modeling for inventory management	High	Use data analytics and machine learning algorithms to predict demand and optimize inventory levels.
Predictive maintenance	Med.	Predict when equipment or machinery will fail and schedule preventive maintenance.
Demand forecasting	High	Forecast the demand for materials, equipment, and supplies based on historical data, current trends, and future projects.
Optimization of logistics	High	Optimize supply chain and logistics operations using data analytics and optimization algorithms.
Equipment utilization prediction	Med.	Predict equipment utilization and schedule maintenance to minimize downtime.
Supply chain risk management	High	Use AI algorithms to identify and mitigate risks in the supply chain, such as supplier disruptions, delays, and price fluctuations.

criteria. These features ensure that the construction processes align with sustainable development goals, minimizing environmental impact while enhancing operational efficiency.

In this context, developing a UML model for a centralized materials procurement system represents a step toward implementing Industry 4.0 in the construction industry. The model addresses inefficiencies and lack of transparency in the procurement process by providing a centralized system that can track material requests and inventory levels in real-time. This will help optimize cash flow and improve project timelines. The developed UML model aligns with Industry 4.0 principles in several ways. First, Industry 4.0 aims to create interconnected systems for more efficient and flexible production processes. The proposed UML model can enable this by providing a centralized material procurement system that connects various stakeholders and streamlines the procurement process. Secondly, Industry 4.0 emphasizes the importance of data analytics and real-time decision-making. The model can facilitate this by providing live data and dashboards that allow management to make informed decisions about material procurement and inventory management in real-time. Finally, Industry 4.0 emphasizes employing advanced technologies such as Internet of Things (IoT) sensors, automation, and artificial intelligence to improve efficiency and productivity. Although the UML model may not directly incorporate these technologies, it is a foundation for their implementation in the future. Some additional future functional requirements can be found in the Table 2.

The work presented in this article finds synergies with existing research in this academic landscape. Recent studies have outlined the adoption of Industry 4.0 technologies in construction, emphasizing the importance of data analytics and AI [41]. Additionally, the role of Construction 4.0 in sustainability has been explored, focusing on its impacts on environmental, economic, and social sustainability [28]. The proposed model aligns with these focuses by aiming to improve operational efficiency, thereby contributing to financial sustainability while setting the foundation for future implementations that could further enhance environmental and social sustainability.

Furthermore, the complexities of managing inter-organizational relationships, particularly in public construction projects, have been highlighted [42]. The presented UML model addresses this by streamlining interactions among key supply chain partners. Significantly, another article discusses the need for adaptable process models in complex environments [43]. This insight complements the UML model presented, which can be viewed as a specialized process model designed to address the complexities of construction projects, particularly in the domain of material procurement.

Moreover, emerging technologies like Blockchain are being considered for creating a circular economy in construction, focusing on material tracking and reuse [44]. While the UML model may not directly incorporate Blockchain technology, it sets the stage for its future integration by providing a real-time tracking system that could be synergistically combined with Blockchain systems for enhanced traceability and accountability.

By improving the procurement process, construction companies can take a step towards increasing their overall productivity rates. Implementing such a system can help bridge the gap between the construction industry and other more digitalized industries, ultimately leading to a more sustainable and productive industry.

Following its development, the model was showcased to the initial interviewees and additional stakeholders. The feedback received was overwhelmingly positive, praising the system's innovation and its potential to revolutionize current practices in the industry. This strong endorsement not only confirmed the effectiveness of the model but also highlighted its innovative approach to addressing long-standing industry challenges.

The basic web-based application, developed from the UML model, was deployed as a prototype, accessible at https://www.kac-ikk.com/. This platform served not only as a demonstration site but also as a live testing environment to evaluate the application's real-world functionality and user interface. Stakeholders could interact with the system's features, such as the workforce distribution dashboard, real-time project tracking, and cost management tools directly through the website. This integration provided an essential touchpoint for gathering robust user feedback and enabled the continuous refinement of the application based on real user experiences. The positive feedback received from this live deployment highlighted the system's potential to significantly enhance operational efficiency and transparency in the construction industry. The prototype's success on this website validated the effectiveness of the hybrid UML model and underscored the practical benefits of the developed application.

TABLE 3. Comparison between decentralized and hybrid systems for managing construction site materials/equipment requests.

Feature	Decentralized System	Hybrid System
Inventory Visibility	Limited to individual site engineers, leading to isolated decision-making.	Centralized view of all inventories, ensuring informed decisions based on global availability.
Efficiency	Inefficiencies due to redundant orders and lack of coordination.	Streamlined processes, reducing redundancy and ensuring efficient use of resources.
Procurement Process	Site engineers place orders directly with suppliers, often leading to higher costs and delays.	Coordinated procurement process, optimizing cost and lead time through internal transfers and centralized purchasing.
Cost Management	Higher costs due to lack of bulk purchasing and potential for over-ordering.	Reduced costs through bulk purchasing, optimized transfers, and better cost control mechanisms.
Lead Time	Longer lead times due to independent supplier orders and lack of internal transfers.	Shorter lead times by leveraging internal transfers and optimizing procurement based on comprehensive data.
Coordination	Poor coordination between sites, leading to misallocation of resources and delays.	Improved coordination across sites, ensuring optimal resource allocation and timely project completion.
Budget Control	Difficult to manage and track budgets across multiple sites independently.	Centralized budget control, ensuring all requests are within budget and financial resources are optimally utilized.
Approval Process	Time-consuming manual approvals, often with delays and miscommunication.	Streamlined digital approval process, reducing delays and ensuring timely decisions.
Handling Backorders	Challenging to manage, leading to potential project delays and increased costs.	Efficient handling of backorders through coordinated inventory checks, transfers, and cost calculations.
Lateness Costs	High lateness costs due to delayed procurement and lack of alternative solutions.	Minimized lateness costs through quick processing, internal transfers, and proactive management.
System Flexibility	Less flexibility in adapting to changing project needs and priorities.	Greater flexibility with real-time data, allowing for dynamic adjustments to procurement and inventory strategies.
Reporting and Analytics	Limited reporting capabilities, often manual and time-consuming.	Advanced reporting and analytics, providing real-time insights and data-driven decision-making.
Sustainability Practices	Less focus on sustainability due to decentralized decision-making.	Enhanced sustainability through optimized resource utilization and reduced material waste.
Scalability	Difficult to scale effectively across multiple sites.	Easily scalable system, adaptable to projects of varying sizes and complexities.

The comparison between the current decentralized system and the proposed hybrid system highlights significant enhancements in inventory management and procurement processes. As detailed in Table 3, the hybrid system offers a centralized view of inventories, leading to more informed and efficient decision-making. It addresses inefficiencies such as redundant orders, uncoordinated procurement, and poor cost management that are prevalent in the decentralized system. Key improvements include streamlined processes, optimized procurement, reduced costs, and better coordination across sites. The table effectively summarizes the contrasts in system features such as inventory visibility, efficiency, procurement process, and sustainability practices, underscoring the benefits of adopting a hybrid model for construction project management.

VII. CONCLUSION

The UML model developed in this paper addresses the complexities faced by the construction industry with respect to inefficient materials procurement and lack of transparency. By adopting a centralized approach, the proposed model aims to optimize the procurement process, reduce delays, and improve cost control. The model also offers real-time tracking of material requests and inventory levels, providing stakeholders with better visibility into project progress.

Moreover, the construction industry has been slow to adopt Industry 4.0 technologies, leading to lower productivity and higher costs. However, the proposed UML model can serve as a step towards Construction 4.0. By adopting a more digitalized and data-driven approach to materials procurement, companies can improve their overall productivity and competitiveness in the market.

Promising future research might include the incorporation of manpower optimization models into the proposed Unified Modeling Language (UML) paradigm. Through the process of workforce optimization, construction businesses may attain increased productivity and decreased labor expenses, hence facilitating the achievement of more efficient project delivery. Incorporating Industry 4.0 technologies, such as AI and IoT, can further enhance the effectiveness of the proposed UML model.

In conclusion, the UML model proposed in this study has the potential to enhance the procurement process of materials within the construction sector via the facilitation of improved efficiency, transparency, and cost management. This model may be seen as a crucial advancement in the incorporation of Industry 4.0 technologies inside the construction sector, eventually resulting in enhanced productivity and competitiveness.

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interpretations, and conclusions presented in this work are entirely they and do not reflect the outputs of the tool used.

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