

**Integrated Workforce Scheduling and Routing
Problem Optimization in the Construction Industry:
An Integer Linear Programming Approach**

BY

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**INTEGRATED WORKFORCE SCHEDULING AND ROUTING
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AN INTEGER LINEAR PROGRAMMING APPROACH**

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INDUSTRIAL & SYSTEMS ENGINEERING

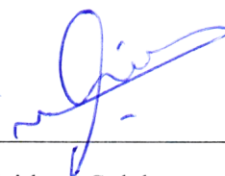
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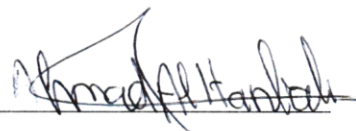
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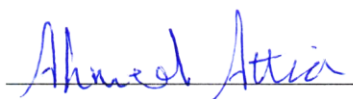
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Dedication

To my beloved mother, the woman who has loved me unconditionally from the moment I came into this world. Her endless sacrifices, support, encouragement, and compassion have shaped me into the person I am today. She is my guardian angel, my inspiration, my world. Words cannot express my gratitude and love for all she has given and continues to give so selflessly each day.

In loving memory of my father, who always believed in me and the bright future he knew I could achieve. Though he is no longer here to share this milestone with me, his endless love, support and encouragement made this journey possible. I wish more than anything he could be here today, but I carry his spirit in my heart and in each step I take towards fulfilling the dreams he had for me.

This thesis is dedicated to you, Mum, you loved me enough for two parents and filled my world with light after loss. This thesis is also dedicated to you, Dad. Though gone from this world, you are forever my inspiration. I love you and miss you each and every day.

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LIST OF ABBREVIATIONS

UML	:	Unified Modeling Language
MILP	:	Mixed-Integer Linear Programming
ILP	:	Integer Linear Programming
IoT	:	Internet of Things
ERP	:	Enterprise resource planning
GA-MLP	:	Genetic algorithm-multi-layer perceptron
BCDT	:	Blockchain-based digital twins.
BIM	:	Building Information Modeling
WSRP	:	Workforce Scheduling and Routing Problem
RMA	:	Return Merchandise Authorization
BOM	:	Bill of Materials
IMS	:	Inventory Management System
SAR	:	Saudi Riyal
MSR	:	Materials Supply Request

ABSTRACT

Full Name : [Ayman Roshdy Mohammed Rashad Mohammed]
Thesis Title : [Integrated Workforce Scheduling and Routing Problem Optimization in the Construction Industry: An Integer Linear Programming Approach]
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This thesis presents two studies aimed at improving efficiency and productivity in the construction industry through innovative materials procurement and workforce management models. The first study introduces a Unified Modeling Language (UML) model for materials procurement and inventory management in construction projects, based on insights from a construction company group working on 27 ongoing projects of varying sizes. The proposed UML model combines centralized and decentralized approaches, enhancing procurement process efficiency by enabling real-time tracking and data-driven decisions. The study also explores Industry 4.0 alignment and future work possibilities, such as implementation evaluation and integrating manpower optimization models.

The second study develops a comprehensive integer linear programming (ILP) model for workforce scheduling and resource allocation in the construction industry, considering both economic and social constraints for four selected professions. The proposed optimization approach demonstrates robust performance and potential cost savings of up to 15% in a 2022 real case study without significantly impacting social constraints. By identifying limitations and areas for improvement, this study aims to contribute to more efficient workforce management, increased productivity, and profitability within the construction sector and stimulate further research in this field.

ملخص الرسالة

الاسم الكامل: أيمن رشدي محمد رشاد محمد

عنوان الرسالة: تحسين اشكالية الجدولة والتوجيه المتكاملة للقوى العاملة في صناعة البناء والتشييد: نهج البرمجة الخطية الصحيحة

التخصص: الهندسة الصناعية والنظم

تاريخ الدرجة العلمية: مايو 2023

هذه الأطروحة تقدم دراستين تهدفان إلى تحسين الكفاءة والإنتاجية في صناعة البناء من خلال نماذج مبتكرة لشراء المواد وإدارة القوى العاملة. تقدم الدراسة الأولى نموذجًا بلغة النمذجة الموحدة لشراء المواد وإدارة المخزون في مشاريع البناء ، استنادًا إلى رؤية من مجموعة شركات إنشاء تعمل على 27 مشروعًا جاريًا تختلف في الحجم. يجمع النموذج المقترح بلغة النمذجة الموحدة بين النهج المركزية وغير المركزية ، مما يعزز كفاءة عملية الشراء من خلال تمكين التتبع في الوقت الفعلي والقرارات القائمة على البيانات. تستكشف الدراسة أيضًا محاذاة الثورة الصناعية الرابعة وإمكانات العمل المستقبلية ، مثل تقييم التنفيذ ودمج نماذج تحسين القوى العاملة.

تطور الدراسة الثانية نموذج برمجة خطية عددية (ILP) شامل لجدولة العمالة وتخصيص الموارد في صناعة البناء ، مع مراعاة كل من القيود الاقتصادية والاجتماعية لأربع مهن مختارة. يظهر النهج المقترح للتحسين أداء قويًا وتوفرًا محتملة في التكاليف تصل إلى 15٪ في دراسة حالة حقيقية لعام 2022 دون التأثير بشكل كبير على القيود الاجتماعية. من خلال تحديد القيود ومجالات التحسين ، تهدف هذه الورقة إلى المساهمة في إدارة القوى العاملة وزيادة الإنتاجية والربحية داخل قطاع البناء وتحفيز المزيد من البحوث في هذا المجال.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Construction projects often face challenges, including delays, budget overruns, and inefficiencies in materials procurement and workforce management. As the industry evolves, there is a growing need for innovative models and approaches to increase productivity and reduce costs. The objective of this thesis is to address two key aspects of construction project efficiency: materials procurement and inventory management, as well as workforce scheduling and resource allocation.

The thesis is divided into two studies, each focusing on one of these aspects. In the first study, a Unified Modeling Language (UML) model is introduced for materials procurement and inventory management. This model, developed based on insights from a construction company group working on 27 ongoing projects, streamlines the procurement process via a combination of centralized and decentralized approaches, enabling real-time tracking and data-driven decision-making.

In the second study, a comprehensive integer linear programming (ILP) model for workforce scheduling and resource allocation in the construction industry. This novel model considers both economic and social constraints and is demonstrated to reduce total

costs by up to 15% with minimal impact on social considerations in a real-world 2022 case study.

1.2 UML Model for Materials Procurement and Inventory Management in Construction Industry: Study Objectives

1. Develop a UML model that captures the key components and processes involved in materials procurement and inventory management for construction projects.
2. Identify areas of inefficiency and challenges in current practices of materials procurement and inventory management based on the developed UML model.
3. Propose strategies and solutions for improving materials procurement and inventory management in construction projects based on the UML model.
4. Evaluate the potential benefits and limitations of the proposed UML model in enhancing materials procurement and inventory management.
5. Explore opportunities for further research and development in achieving optimized, digitized materials procurement and inventory management for construction projects.
6. Contribute to ongoing efforts for the successful implementation of Industry 4.0 technologies in the construction industry.
7. Provide recommendations for the application of the proposed UML model in industry to achieve more efficient, cost-effective and sustainable construction projects.

8. Highlight the significance of effective materials procurement and inventory management in reducing costs, improving productivity and ensuring the success of construction projects.

1.3 Workforce Scheduling and Routing Problem Optimization in the Construction Industry: Study Objectives

1. Develop a comprehensive framework for optimizing workforce scheduling, staffing and routing in construction projects.
2. Identify the key factors and interdependencies involved in construction workforce scheduling, staffing and routing problems.
3. Explore metaheuristic and optimization techniques for solving the construction workforce scheduling, staffing and routing problem.
4. Evaluate the pros and cons of different solution approaches for the construction workforce scheduling, staffing and routing problem.
5. Assess the potential benefits of optimized workforce scheduling, staffing and routing to the construction industry.
6. Analyze current practices in construction workforce scheduling, staffing and routing and determine areas for improvement.
7. Provide recommendations to construction companies for achieving more efficient and effective workforce utilization.
8. Highlight the need for digitization and technological innovation in construction workforce management.

9. Contribute to bridging the gaps in the literature on construction workforce scheduling, staffing and routing optimization.
10. Pave the way for further research on construction workforce optimization through the proposed comprehensive framework.

1.4 Thesis Structure

The thesis is organized into five chapters:

1. Introduction: This introductory chapter provides an overview of the research problem, the significance of the study, the background information, and a brief explanation of the two studies conducted.
2. Literature review: A review of the current knowledge and understanding of construction project efficiency, materials procurement, inventory management, workforce scheduling, and resource allocation is presented.
3. Study 1: Materials Procurement and Inventory Management: In this chapter, the problem, scope, methodology, results, and implications of the first study are discussed. In addition, a conclusion and suggest future research directions are provided for materials procurement and inventory management.
4. Study 2: Workforce Scheduling and Resource Allocation: This chapter presents the second study, including its objective, scope, methodology, results, and implications. A conclusion and future research directions for workforce scheduling and resource allocation are also provided.
5. Conclusion and Recommendations: The final chapter summarizes the main findings from the two studies, restates the overarching research problem, and

outlines the thesis's overall contribution to the field. Based on the findings, the author offers recommendations for construction industry practice and future research.

CHAPTER 2

Literature Review

2.1 UML Model for Materials Procurement and Inventory Management in Construction Industry: Literature Review

The construction industry is known to be one of the least digitized industries, lagging behind other industries in adopting modern technologies [1]. This slow adoption has resulted in various inefficiencies, such as delayed projects and low productivity rates[2]. However, the rise of Industry 4.0 has provided new opportunities for the construction industry to catch up and improve its performance [3]. Industry 4.0 represents the fourth industrial revolution that 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, and robotics. These technologies have the potential to revolutionize the construction industry, making it more efficient, productive, and sustainable [4] .

Inventory and materials management can be a crucial factor in determining the success of any business, and the construction industry is no exception [5]. Inventory management in construction can be highly complex and dynamic as it is involved with many processes such as procurement, storage, and distribution of materials and equipment [6]. Efficient inventory management can help construction companies streamline operations, reduce

costs, and meet projects deadlines [7]. However, the unique challenges posed by the construction industry, including the need for specialized storage, diverse materials and equipment, and the unpredictable nature of construction projects, can make effective inventory management challenging [8], [9].

To address these challenges, this study proposes the development of a Unified Modeling Language (UML) model for 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 in modeling complex systems and processes across various industries [10], [11]. This is due to its standardized approach in representing structures and behaviors of a system [12]. This can help in improving communication, facilitating analysis, and identifying potential problems.

The UML model is the first stage in developing a web-based application that can be accessed by the stakeholders 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. This is by offering the flexibility to adapt to changing requirements, improving efficiency, and reducing costs. Specifically, the UML model will capture the key components and processes involved in inventory management, including procurement, storage, tracking, and distribution of materials, and equipment. The model enables data collection and analysis of the inventory management process in a construction project. It also helps in the identification of potential areas of improvement, and development of strategies for optimization.

As construction projects are known for their high costs and tight schedules, effective management of inventory is vital. In fact, research shows that construction materials account for over half of the total project expenditure, making inventory management a critical aspect of project success [13]. However, with the rising concerns surrounding the management of construction and demolition debris, it is clear that there are still challenges to be addressed in the industry [14]. To further complicate matters, there are also significant gaps between enterprise resource planning (ERP) procedures and construction procedures, highlighting the need for better alignment and integration [15].

Thankfully, researchers are actively exploring ways to optimize material management in construction through cutting-edge methods such as the genetic algorithm-multi-layer perceptron (GA-MLP) approach [16]. Additionally, by identifying the factors that significantly impact waste reduction in construction and analyzing the results with a structural equation modeling approach, researchers are paving the way towards more sustainable construction practices [17].

Despite these advancements, utility maintenance works continue to pose significant challenges for the industry. As a result, researchers in New Zealand are exploring the use of as-built drawings to mitigate these issues [18]. Furthermore, a recent study proposes a model for three-echelon supply chain supply management in off-site construction with stochastic constraints, which could revolutionize the industry's supply chain management practices [9].

The works of [19], [20] also deserve mention as influential works in this field. By incorporating the latest research and cutting-edge approaches, the construction industry can

continue to improve its inventory management practices and ultimately achieve greater success in its projects.

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, there are significant opportunities to be gained in the long run, making it an area of great interest for research. To explore the technological feasibility and preliminary implementation effect of the proposed framework, a case study of the Xiong'an citizen service center is introduced by [21].

In order to understand the main areas of application and limitations of each technology when utilized in the construction industry, [17] provide a summary of their findings. [22] present a methodological-technological framework adapted to the Architecture, Engineering, Construction, and Operations industry, while [23] examine a leading UK-based construction firm to ascertain the prognosis for Industry 4.0 roll-out in terms of the impediments and opportunities.

To improve construction processes and resource management through application of lean construction and Industry 4.0, [24] provide an attempt at evolving an enhanced approach. Meanwhile, [25] aim to develop a novel theoretical framework for the adoption of environmentally sustainable blockchain-based digital twins (BCDT) for Construction Industry (CI) 4.0. The authors of [26] introduce the risk factors that might hinder the process towards Building Information Modeling (BIM) adoption, with an emphasis on the risk factors of each industry.

Finally, influential work by [27] also contributes to the ongoing research and development of Industry 4.0 technologies in the construction industry. These studies collectively provide valuable insights into the challenges, opportunities, and potential applications of Industry 4.0 technologies, which can inform the development of strategies and frameworks for their successful implementation.

This study seeks to provide a valuable contribution to the construction industry by proposing a UML model that can help construction companies address the unique challenges posed by inventory management. The proposed model can serve as a framework for future research and development in this field, ultimately improving the efficiency and success of construction projects.

2.2 Workforce Scheduling and Routing Problem Optimization in the Construction Industry: Literature Review

The Workforce Scheduling and Routing Problem (WSRP) is a challenge that has arisen from the needs of specific industries and services where employees are required to perform their duties at various locations and for differing durations of time. These industries include repair technicians who must visit customer sites [28] and security guards who must carry out their responsibilities at multiple locations [29]. In such business domains, it is crucial for both employers and workers that scheduling and mobility policies are flexible.

The WSRP presents various challenges, including ensuring worker well-being and satisfaction. Assigning workers extended months at a single location or requiring long-distance travel can result in decreased job satisfaction and increased stress levels [30]. This can negatively impact work quality and lead to a higher turnover rate. To address these

concerns, it's crucial to consider workers' preferences and quality of life when developing scheduling and routing policies [31]. This helps to find a balance between efficiency and worker well-being.

The WSRP has been extensively studied, given the varying circumstances and constraints. The authors of this work are particularly interested in workforce scheduling within medium and mega construction projects, where worker mobility is a key factor. Workers in such projects may be required to transfer between projects to perform specific tasks, and then relocate once again.

Construction companies often face difficulties determining the exact number of personnel needed, as the number of ongoing projects changes frequently. Predicting the number of projects and their sizes in the near future is a challenge. As a result, these companies may need to outsource workers when facing a shortage [32]. Additionally, the number of activities across ongoing projects can exceed the number of available employees, leading to workers needing to travel between projects to perform their work [33]. Therefore, the problem at hand can be viewed as a combination of both workforce scheduling and vehicle routing problems [34]. It is a complex issue faced by construction companies, but finding solutions can greatly benefit both employers and workers.

These studies offer valuable insights, methodologies, and limitations that are relevant to the current study. Table 1 provides an overview of each paper, summarizing their main focus, key aspects, and potential limitations.

Table 1 Summary of Reviewed Research Papers

Paper	Summary	Main Aspects	Limitation
Scheduling technicians and tasks in a telecommunications company [28]	The article proposes a construction heuristic and an adaptive large neighborhood search heuristic for the technician and task scheduling problem.	- Repair technician scheduling - Customer visits - Single location scheduling	Doesn't consider transferring between projects, workers outsourcing or any social aspects.
Security personnel routing and rostering: a hyper-heuristic approach [29]	Analyzes scheduling and routing for security guards working at multiple locations	- Security guard scheduling - Multiple locations - Worker flexibility	The nature of the problem is different from construction industry
A multimonth workforce scheduling and routing problem with dependent tasks [30]	This article presents a new Workforce Scheduling and Routing Problem, called Multiperiod Workforce Scheduling and Routing Problem with Dependent Tasks	The problem involves scheduling and routing teams to complete services with dependencies among tasks, multiple visits to customers, and work regulations	The study does not consider some important constraints in workforce scheduling and routing problems, such capacity constraints.
Influencing factors of outsourcing in construction projects: a holistic perspective [32]	This research paper focuses on identifying the influencing factors of outsourcing decisions in construction projects and unraveling their interactions from a holistic perspective.	The study develops a holistic perspective of the influencing factors of outsourcing in construction projects by analyzing the causal relationship between them	The study employs the decision-making and trial evaluation laboratory (DEMATEL) method, which may have limitations in capturing the complexity of real-world outsourcing decisions.
Optimizing travel distance of construction workers considering their behavioral uncertainty using fuzzy graph theory [33]	a new approach to construction site layout planning that considers worker behavioral uncertainty (WBU) in travel distance optimization.	The article highlights the importance of considering WBU in travel distance optimization for CSLP.	The article focuses solely on travel distance optimization and does not consider other factors such as resource allocation and scheduling

The general scheduling problem aims to optimize the assignment of different workers to different projects or tasks at specific times [35]. On the other hand, the vehicle routing problem aims to minimize the total distance traveled by a fleet of [36]. The association between the vehicle routing problem and the WSRP is minimizing the transferring cost when a worker is transferred from one project to another [37]. It is inferred that WSRP is a multi-objective problem by nature. Its objectives can include minimizing outsourcing, ensuring a specific employees utilization level, minimizing travel costs etc [38], [39].

Both the scheduling problem and the vehicle routing problem are complex, combinatorial NP-hard problems, and often require the use of metaheuristic techniques to solve them [40], [41]. A popular approach to modeling WSRP variants is through Mixed-Integer Linear Programming (MILP) [42], which can be solved using exact or metaheuristic techniques [43]. For example, [44] utilized a hybrid particle swarm and whale optimization algorithm for the dynamic WSRP. Similarly, the authors of [45] solved a home health care problem, which is a WSRP, by using constraint programming as the first phase and metaheuristic techniques in the second phase to improve the solution quality. Although metaheuristics are advantageous for searching a large feasible region, they may get stuck in a local minimum [40]. However, some techniques result in optimal or near optimal solutions without the use of metaheuristics, such as the use of branch and price for the master problem with a partitioning formulation. The model includes binary variables to indicate if a particular task is performed by a specific worker and real variables for scheduling tasks [46].

It can be observed that there are several methods for solving WSRP and each one has its own pros and cons. In order to come up with an optimal solution, one needs to consider

different aspects like the size of the problem, computational power, and the desired accuracy [47]. In cases where a high level of accuracy is needed and the size of the problem is manageable, mathematical optimization methods like MILP can be used [48]. On the other hand, if the size of the problem is large and the computational power is limited, metaheuristic techniques are more suitable [49], [50]. The challenge in solving WSRP is to determine the best approach depending on the requirements of each case.

WSRP characteristics can vary from one industry to another, but there are some general characteristics that should be considered when handling such a problem. Among the WSRP characteristics is the ‘Time windows’ which is the start and end time of performing a task. A time window can be flexible in some situations, but generally, it is assumed that a worker would start performing his work once arrives at the working location [51]. Furthermore, ‘Transportation Modality’ is another characteristic for the WSRP as it is associated with the travel time and cost of a worker transferring between projects [52]. Moreover, in some industries workers gather at some location at the beginning of the working month then they move to their assigned locations. Such characteristic is referred to as ‘Start and End Locations’ [53]. Again, ‘Skills and Qualifications’ is another factor that should be considered as some problems assume all workers have the same skills and qualifications levels while others assume different skills [28]. In this case, matching the right employees to the right tasks becomes an objective for the problem. Another characteristic is the estimated time to perform a task, ‘Service Time’, which depends on the worker, type of task and the environment [54].

In addition to the aforementioned characteristics, WSRP problems also take into account ‘Worker Availability’ which refers to the schedule of each worker and the amount of time

they are willing to work [42]. This is a crucial factor as it affects the overall efficiency of the workforce and their ability to complete tasks within a given time frame. The availability of workers can vary depending on their personal schedules and other commitments, which can make scheduling a challenging task for managers.

‘Task Dependencies’ is another important characteristic that involves identifying the relationship between tasks and determining the order in which they need to be completed [55]. Some tasks may require certain prerequisites to be completed before they can be started, while others may need to be completed in a specific order to avoid conflicts or delays. In some cases, multiple workers may be needed to complete a task, which adds another layer of complexity to the problem.

Moreover, ‘Equipment and Resource Constraints’ is another key characteristic of WSRP as it refers to the availability of necessary equipment and resources to complete a task. This could include tools, machinery, raw materials, or even space in some cases [56]. Without the required equipment or resources, the workers may not be able to complete their tasks, which can lead to delays and potential losses for the company.

The construction industry is a crucial sector that plays a vital role in the global economy. According to recent statistics, construction accounts for 13% of the world's GDP, including infrastructure, industrial structures, and real estate [1]. Despite its significant contribution to the global economy, the industry faces several challenges that hinder its growth and productivity [57]. One of the significant challenges is the lack of proper resources and underutilization of technological advancements. As a result, the construction industry

experiences low productivity levels, which adversely affect its overall performance and competitiveness [58].

Furthermore, the culture of resistance to change among most industry stakeholders poses a considerable challenge to the construction industry's growth and development [22]. The lack of willingness to embrace change, particularly in adopting modern technologies and digitization, makes it challenging to manage construction projects efficiently. As a result, most construction projects suffer from delays, cost inefficiencies, and poor-quality performance [59]. The manual nature of the industry's operations also contributes to these challenges, making it even more complex to manage construction projects.

Moreover, the lack of digital expertise in the construction industry poses a significant challenge to its growth and development [60]. Poor decision-making due to the lack of digital expertise could lead to safety issues and low-quality performance, which could lead to project failures and reputational damage [61]. It is evident that the construction industry needs to embrace digitization and modern technologies to improve its operations, enhance efficiency and productivity, and reduce delays and costs [62]. The industry needs to embrace change and invest in digital expertise to help in decision-making and improve safety performance.

Despite being one of the largest industries in the global economy [1], construction workforce scheduling, staffing, and routing optimization problems have received relatively little attention in the literature. This is reflected in the limited number of journal articles that have been published on this subject. According to the SCOPUS library, there are only 12 journal articles that contain the keywords "construction, manpower, scheduling, and

optimization." This number is even lower when the keyword "manpower" is replaced with "workforce" with only 9 articles. Again, when the keyword "manpower" is replaced with workers the number of articles becomes only 17.

The limited number of articles on this subject is a cause for concern given the importance of construction workforce scheduling, staffing, and routing optimization to the industry. These problems are complex and require sophisticated solutions to achieve efficient and effective construction project management. While the existing literature provides some valuable insights, it is clear that much more research is needed in this area to fully address the challenges faced by the construction industry.

It is worth noting that the current study is unique in that it takes a different perspective on construction workforce scheduling, staffing, and routing optimization than previous studies. The previous studies were limited in their scope and did not consider all the relevant factors that contribute to the problem. This study, on the other hand, takes a comprehensive approach that considers most of the relevant factors and provides a framework for addressing these factors.

2.3 Workforce Scheduling & Routing Problem in Industry Vs Construction

Workforce scheduling and routing are essential processes in various industries, including construction companies. Comparing their characteristics across different industries highlights the unique aspects present in each area.

General industries:

Nature of tasks: In various industries, tasks may range from simple and routine activities to complex and multi-step projects, which may or may not require interdependencies between tasks.

Diversity of skillsets: Industries usually employ a range of workers with varying skill levels and expertise to cater to diverse project requirements. Workforce scheduling and routing need to account for this diversity to ensure that the appropriate employees are assigned to suitable tasks.

Temporal factors: Demand for services and workload in different industries may fluctuate over time. Consequently, scheduling and routing must take into account factors such as seasonal demand, holidays, and peak operating hours.

Geographical factors: Work locations may vary from a single site (e.g., a factory) to multiple sites (e.g., retail stores or warehouses). Routing and scheduling workers must consider travel times, distances, and associated costs.

Regulatory requirements: Industries must adhere to labor laws, work regulations, and safety standards. Workforce scheduling and routing need to ensure compliance with these regulations, including working hours, breaks, and overtime limitations.

Construction companies:

Project-based nature: Construction projects typically involve multiple phases, tasks, and dependencies between tasks. Workforce scheduling and routing must be responsive to these dynamic project requirements, adapting and optimizing as necessary.

Skill specialization: Construction companies often require highly specialized skillsets, including architects, engineers, and contractors. Matching the right workers with appropriate tasks while optimizing resource utilization is a priority in workforce scheduling and routing.

Dynamic site conditions: Construction site conditions can change frequently due to weather, delays, or unforeseen events. Scheduling and routing must be flexible enough to handle these changes and reallocate resources if needed.

Coordination of resources: Construction projects not only rely on human resources but also on equipment, materials, and subcontractors. Workforce scheduling and routing must be integrated with resource management, considering their availability and optimal timing.

Health and safety considerations: Construction sites often involve higher risks and potential for accidents. Therefore, workforce scheduling and routing should consider worker experience, certifications, and safety precautions to minimize the potential for incidents.

The above comparison showcases that workforce scheduling and routing in construction companies often involve more complex, dynamic, and specialized requirements compared to other industries. As a result, tailored approaches and methodologies are required to address the unique characteristics of construction projects.

CHAPTER 3

UML Model for Materials Procurement System

3.1 Introduction

Construction projects often face inefficiencies in inventory and procurement processes, leading to delays and budget overruns. In this study, the Unified Modeling Language (UML) model for materials procurement and inventory management in construction projects is presented. The model is based on insights gathered from experts in a construction company group working on ongoing 27 projects, some of which are medium, and some are mega projects. The model aims to address the inefficiencies resulting from the current decentralized approach, where site engineers are responsible for ordering materials they need for their projects. The proposed model combines centralized and decentralized approaches, enabling real-time tracking of material requests and inventory levels while maintaining project-specific procurement autonomy. The study provides a detailed description of the UML model, including the use case, activity, and class diagrams. The study suggests that the proposed UML model aligns with Industry 4.0 principles. It can improve the procurement process efficiency in construction companies by providing real time data and dashboards that can help in taking data-driven decisions. Future work could involve implementing the model and evaluating its effectiveness through a case study or controlled experiment. An integration of manpower optimization models with the proposed UML model is another possibility. By optimizing the workforce, construction

companies can achieve higher productivity and reduce labor costs, leading to more efficient projects' delivery.

3.1.1 Problem Statement

A construction company group with ongoing 27 projects, ranging from medium to mega projects, is currently using a decentralized approach to manage inventory and procurement. Site engineers are responsible for ordering materials for their projects based on a bill of quantity that is decided at the beginning after accepting a project. This approach has led to inefficiencies in the procurement process, as some engineers may order materials too early, while others may struggle to get the materials they need due to cash flow constraints. Additionally, cost control must manually review each request to ensure that it falls within the project budget, which can be time-consuming and prone to error. Furthermore, the decentralized approach can result in a lack of transparency and accountability, as there is no centralized system to track material requests and inventory levels. As a result, some projects have been delayed, and cash has been frozen in inventory for longer than necessary, reducing liquidity.

To address these challenges, the authors and company experts have identified the need for a hybrid approach that combines elements of both centralized and decentralized inventory management. It is believed that this approach can improve efficiency, reduce costs, and increase transparency and accountability. To develop this hybrid approach, a Unified Modeling Language (UML) model for inventory management and control is developed.

The UML model is meant to be used to develop a web-based application that all stakeholders can use to make activities related to materials requests or to view the

dashboards and keep track of the real situation. The application aims to provide live data that can be used by management to make data-driven decisions.

3.2 System Functional View

In the system functional view, the main actors, use cases and the functional requirements are identified [63]. An actor in the system is any person or system that interacts with the system under development to perform a specific action [64]. Furthermore, use cases refer to a set of actions that actors perform in a system to achieve a specific goal or objective [65]. The primary actors in this system include the Inventory Worker, Estimation Engineer, Senior Inventory Manager, Site Engineer, Senior Operations Manager, and Cost Control Engineer.

Table. 1 outlines the functional requirements for an inventory management system in the construction industry. These requirements cover the key features and capabilities that the system should possess to effectively manage inventory across multiple locations and support construction projects. The table includes the functional requirement, priority level, requirement description. This information serves as a guide for system designers and developers to ensure that the system meets the needs of the construction industry.

Table 2 Inventory Management System Functional Requirements

N	Requirement	Priority	Description
1	Item Management	High	Add, edit, delete, and view items in the inventory, including item name, description, category, unit of measure, and current stock level.
2	Inventory Count	High	Perform physical counts of inventory and update the system with the current stock levels.

3	Order Management	High	Place and track orders for items that are needed for construction projects.
4	Receiving	High	Receive deliveries of items, update the stock levels, and verify that the items received match the order.
5	Issuing	High	Issue items to construction sites, update the stock levels, and track the items that have been issued.
6	Reporting	High	Generate reports on inventory levels, usage, and movements, as well as reports on order status and delivery schedules.
7	Alerts and Notifications	Medium	Set up alerts and notifications for low stock levels, stock-outs, and other events.
8	Access Controls	High	Control access to the system, including setting up user accounts with different levels of privileges and permissions.
9	Integration with Other Systems	High	Integrate the inventory system with other systems used by the company, such as accounting, project management, and supply chain management.
10	Audit Trail	Medium	Track and audit changes to inventory data, including additions, deletions, and updates to items and stock levels.
11	Vendor Management	Medium	Manage vendor information, including contact details, order history, and payment terms.
12	Cost Management	Medium	Manage the cost of items, including tracking the cost of items over time and calculating the value of inventory.
13	Multi-Location Support	High	Manage inventory across multiple locations, including construction sites, warehouses, and storage facilities.

14	Mobile Support	Low	Access and manage inventory information from mobile devices, such as smartphones and tablets.
15	Barcode Scanning	Low	Scan barcodes on items to quickly and accurately update inventory levels.
16	Stock Transfers	High	Transfer stock between locations, including from one construction site to another, or from a warehouse to a construction site.
17	Invoice Matching	High	Match invoices to purchase orders and update inventory levels based on the delivered items.
18	Purchase Order Approvals	High	Route purchase orders for approval and to track the approval status of purchase orders.
19	Vendor Lead Times	High	Track the lead time for items from each vendor, which will help with the planning of future purchases.
20	Stock Adjustments	High	Make adjustments to stock levels, including adding or subtracting items from inventory due to damage, theft, or other reasons.
21	Return Merchandise Authorization (RMA)	High	Manage the return of items to vendors, including creating RMA documents and tracking the status of RMAs.
22	Bill of Materials (BOM)	High	Manage the bill of materials for each construction project, including tracking the quantities of items required for each project and updating inventory levels based on the quantities used.
23	User Activity Logs	High	Log user activity within the system, including who made changes to inventory data and when.

2.2.1 Use-Case Diagrams

The Use Case Diagram is a powerful tool that helps to visualize the functional requirements of a system [66]. Since the system is too 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 focusing on specific system components separately. This approach can help to simplify the overall design and make it easier to understand and manage. This is to make it easier to identify and address any deficiencies in the design.

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, simple use cases, and relationships between them. The actors in the system are the Inventory Worker who is responsible for managing the inventory and making decisions related to inventory management. Furthermore, Estimation Engineer, who is responsible for adding new items to the system with unique codes. Moreover, the procurement system receives the materials requests and processes them after they are confirmed to be within budget by the cost control department. Again, Senior Operations Manager is responsible for approving or disapproving transferring materials from one site to another based on need and availability. Finally, the Site Engineer who makes the materials requests initiates the whole process. The use cases are represented by the ellipses in the diagram.

The relationships between the actors and the use cases are represented by the dashed arrows in the diagram. The use cases that are included in other use cases are represented by the <<Include>> notation, and the 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.

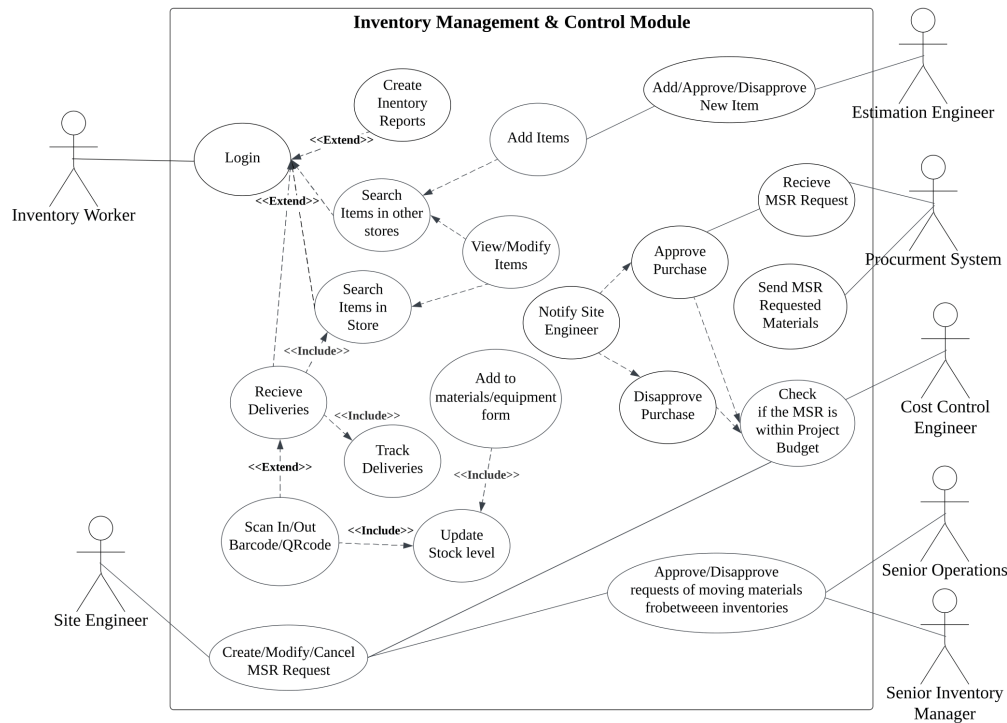


Figure 1 High-Level General Use-Case Diagram

Figure. 2 shows the Site Inventory Detailed Module Use-Case Diagram which is a component of the Inventory Management and Control system. This sub-module is designed to provide 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 barcodes or QR codes. The module 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, as well as printing historical stock levels. Additionally, the diagram depicts the integration of the Site Inventory Detailed Module with other systems such as the Estimation System, Procurement System, and Site Engineer Use Cases.

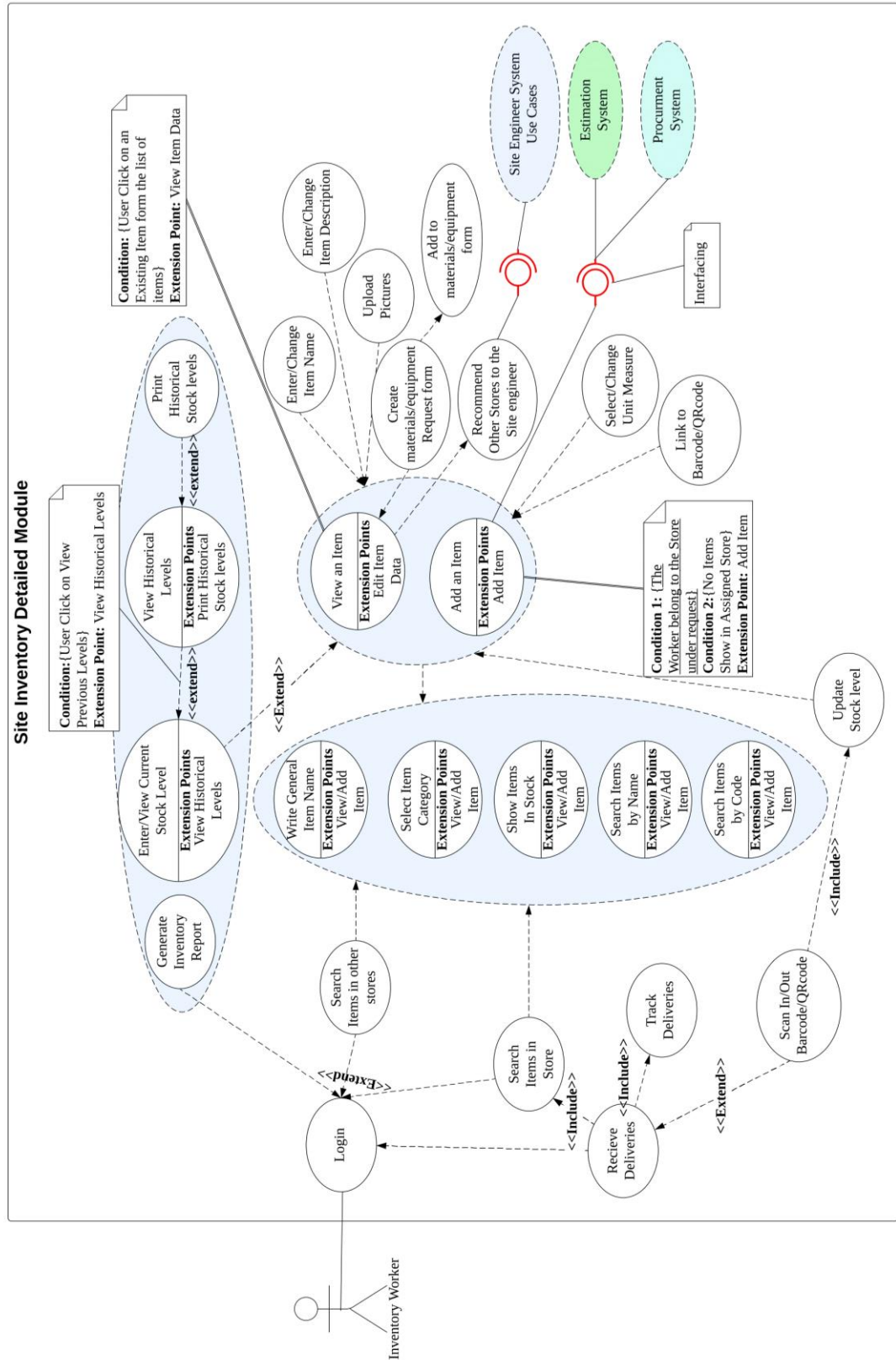


Figure 2 Site Inventory Detailed Module Use-Case Diagram

The Materials Supply Request Module in Figure. 3 is a use case diagram that outlines the various functionalities of managing materials requests from different stores. The users have different roles and responsibilities within the system, and the use case diagram outlines how they interact with the system to accomplish their tasks.

The system is designed to manage the process of requesting materials from different stores, and the diagram outlines the steps involved in this process. The system allows users to approve or disapprove new items, get actual vendors, get estimated/actual lead time, get purchase prices, and add estimated prices. Users can also approve release orders and add items to a request, print historical order reports, check Materials Supply Request (MSR) status, and check by date/store.

In addition, the module provides extension points that allow users to modify items, create requests, and receive requests. The system is also designed to handle various conditions, such as when some or all items are not available on the current store or when some or all items are available on other stores. The system allows users to disapprove release orders and receive MSR requests, and it can send MSR materials to stores or the original store depending on the release order's approval status.

The system is also designed to notify procurement and cost control engineers when an MSR is submitted and to check if 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.

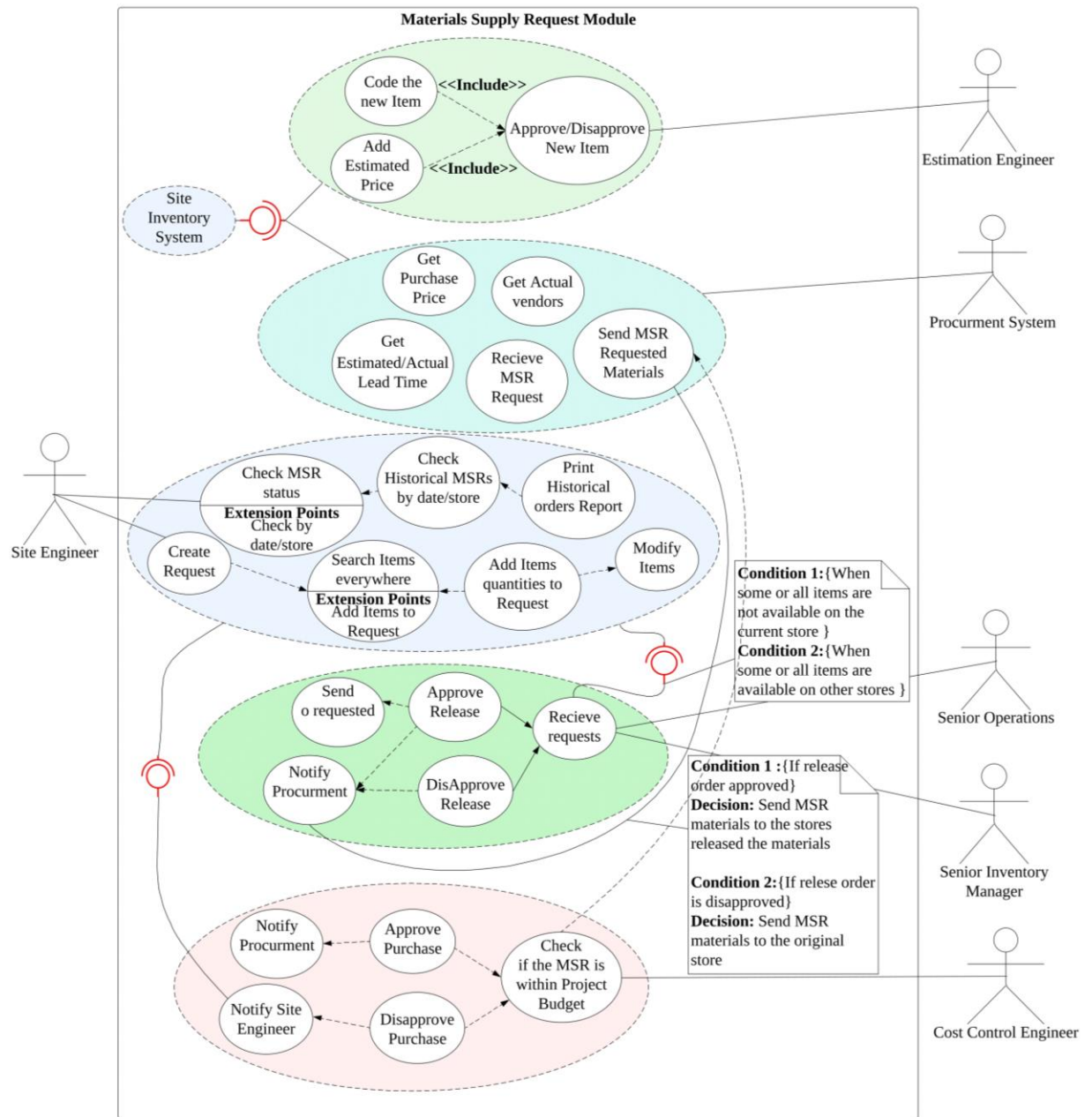


Figure 3 The Materials Supply Request Module Use-Case Diagram

2.2.2 Activity Diagrams

An activity diagram is a type of UML diagram that provides a visual representation of the steps involved in a process or workflow. It is a powerful tool for modeling complex systems and business processes and can help to clarify and communicate the flow of activities and decisions within a process [67]. Activity diagrams can be used to analyze, design, and document various aspects of a system, including business processes, software workflows, and organizational structures. They are often used by software developers, system analysts, and business stakeholders to gain a better understanding of the behavior of a system and to identify areas for improvement. This section focuses on the Construction Site Materials/Equipment Requests activity diagram and its importance in the context of construction site management.

The Construction Site Materials/Equipment Requests activity diagrams in Figure. 4 to 7 illustrate the streamlined process for managing requests for materials and equipment on construction sites. The efficient management of construction site materials and equipment is critical to ensuring smooth and timely project completion. This is because the delays in acquiring required materials can cause significant setbacks in the construction process. The activity diagram provides a visual representation of the steps involved in requesting and acquiring materials, from creating a new request to tracking previous requests. Additionally, the diagram showcases two backorder scenarios that can occur and provides detailed steps on how to handle these scenarios. The activity diagram serves as a guide to help construction site engineers' requests effectively, reducing delays and improving project efficiency.

One interesting feature of this diagram is the consideration of multiple sites and inventories, which could be helpful in ensuring that materials are readily available where needed. The diagram also highlights the importance of efficient procurement processes and budget considerations, which are crucial in project management.

When a request is ordered by a site engineer, the first scenario involves checking if any of the required materials are available in other inventories. If the material is found in another inventory, the system will check if it is idle, i.e., it is not being used for any other project. Furthermore, it will notify the senior inventory management and senior operations team, to review the request and decide whether to approve or reject it.

If the request is approved, the system will initiate a transfer process to move the material to the site in need and update the stock levels for the requested materials and print the request form. The materials will be prepared and delivered to the site in need, and a notification message will be sent to the receiver with the delivery details.

If the material is not available in any other inventory or if it is not idle, the system will calculate the expected purchase lead time for the material. If the lead time is less than the expected need time, the system will proceed with the purchase process.

If the lead time is greater than the expected need time, the system will calculate the lateness cost and the transportation cost from the site with the material to the site in need. If the lateness cost is greater than the transportation cost, the system will proceed with the purchase process. Otherwise, the system will initiate a transfer process to move the material to the site in need. If the request is rejected, the request will be checked by Cost Control Engineers for further processing.

If the material is not available in any other inventory or if it is not idle, the system will proceed to check if the lead time for the material purchase is less than the expected need time. If the lead time is less, the system will proceed with the purchase process. The system will update the stock levels for the requested materials, prepare and deliver the materials to the site in need, and send a notification message to the receiver with the delivery details.

If the lead time is greater than the expected need time, the system will calculate the lateness cost and the transportation cost from the site with the material to the site in need. If the lateness cost is greater than the transportation cost, the system will proceed with the purchase process. Otherwise, the system will initiate a transfer process to move the material to the site in need.

Furthermore, the system allows for the addition of new items to the inventory. If the required item does not exist, meaning it is not coded, the Estimation Engineer would receive the request and will check if the material exist. If they find it doesn't exist, they can add it by providing details such as the code and estimated price. The system will notify the user of the item's addition and provide the code for future reference. If the item is found, the request will be rejected with a message to the requester stating the reason for rejection and the code for the existing material.

The system also ensures that all requests are within budget. If materials are transferred from project B to project A, the MSR request is now for project B, the materials are automatically within budget. If the materials are not transferred from any other inventory, the Cost Control Engineers check if the request is within budget and proceeds accordingly. If the MSR is within the project budget, the request would be sent to the procurement

department for further processing. However, in case of being out of budget the request would be declined and sent back to the involved site engineer for modifications.

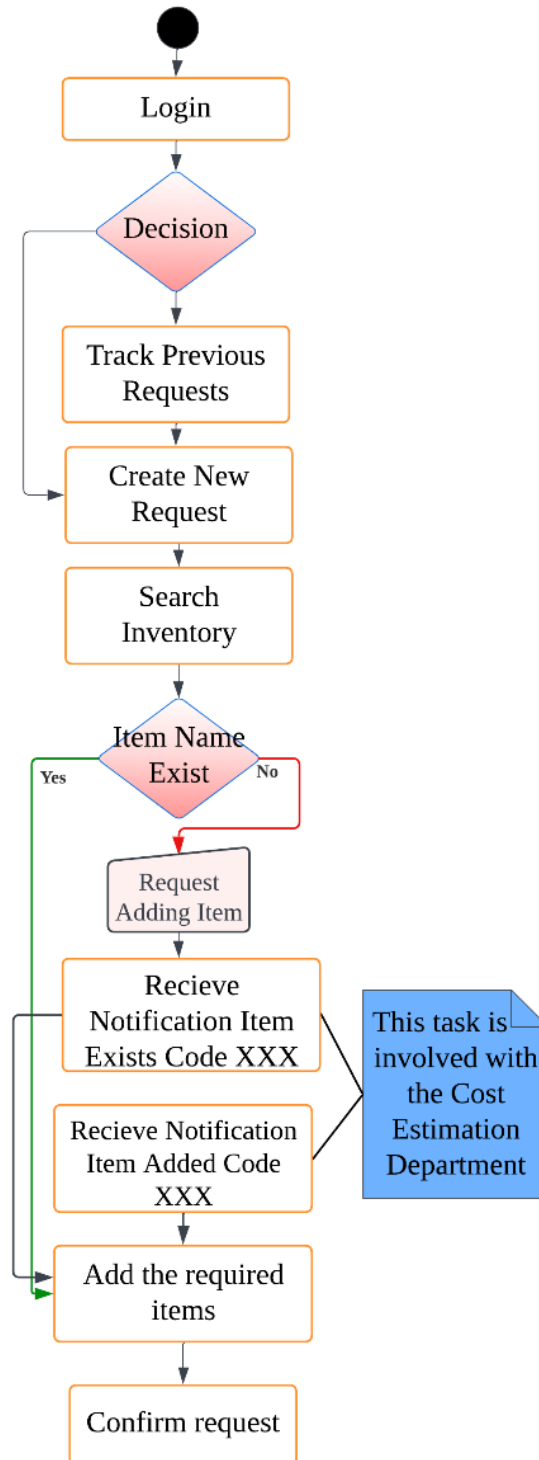


Figure 4 Construction Site Materials/Equipment Requests Activity Diagram

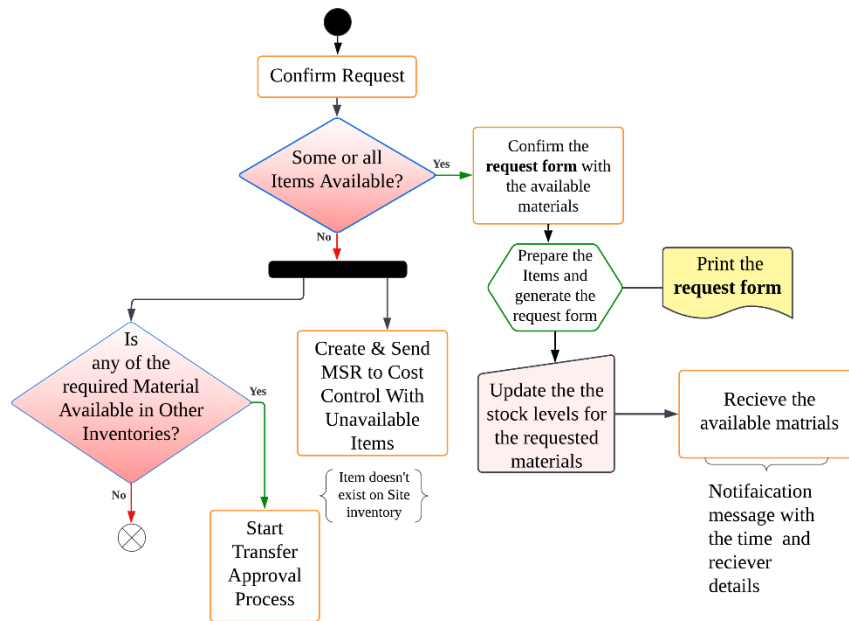


Figure 5 Material Availability Check Across All Inventories Activity Diagram

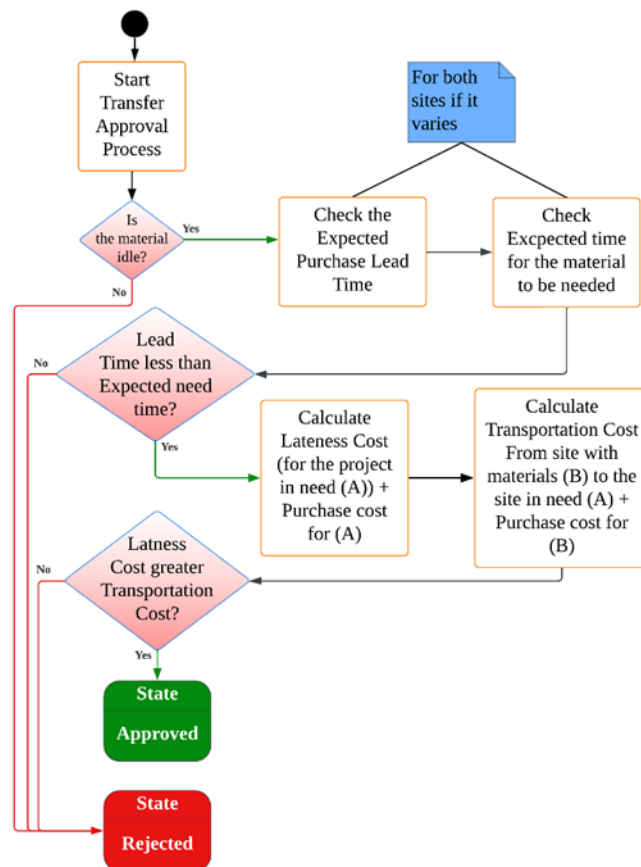


Figure 6 Materials Transfer Approval Activity Diagram

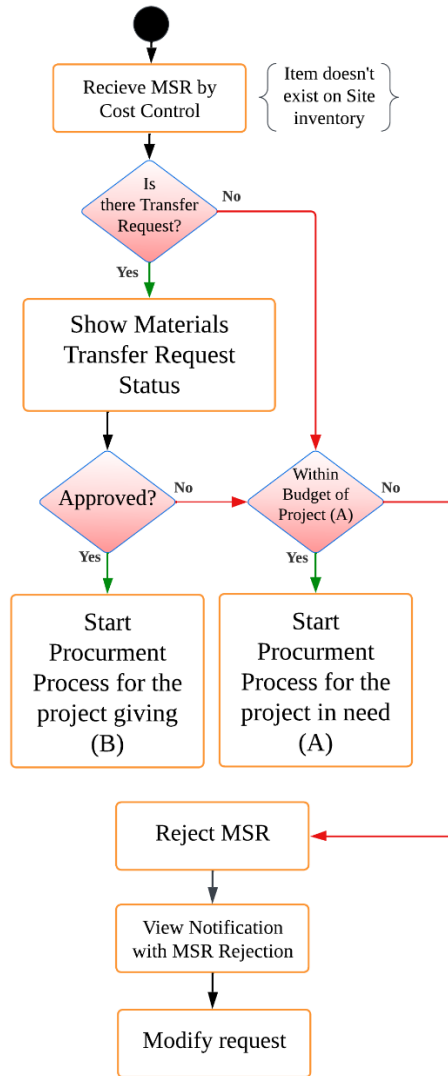


Figure 7 Cost Control MSR Activity Diagram

2.3 System Structural View

In object-oriented systems, structural models are instrumental in illustrating the static relationships between objects within the system [68]. One way of representing these relationships and function limitations is by constructing a package class diagram. Within the Unified Modeling Language (UML), a class is depicted 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 [69]. These behaviors define the responsibilities and constraints of each object. Class diagrams are a highly

effective technique for providing a static perspective on the relationships and constraints between different classes [70].

The class diagram provided a detailed view of the system's data structures and relationships which can be used as a database design module [71]. 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 consisted of a set of classes, attributes, and associations that represented the data structures and relationships in the inventory management system [72].

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 associated with different subsystems. This includes the Staff Package, Units of Measure Package, Reporting Package, and Materials Package, each of which contains classes that encapsulate the system's functionalities.

The use of different packages in software development serves a number of important purposes. Firstly, it allows for the organization of code into logical groupings, which can aid in its maintenance and improve its reusability. By separating code into different packages, developers can more easily navigate and understand the structure of a project, reducing the likelihood of errors and facilitating collaboration among team members.

In addition, the use of packages can help to avoid naming conflicts between different parts of a project, which can otherwise lead to errors and confusion. By defining clear boundaries between different modules of a system, packages can ensure that each component is uniquely identifiable and can be referred to without ambiguity.

Furthermore, the use of packages can enable the development of libraries or frameworks that can be reused across multiple projects, improving the efficiency and consistency of software development. By providing a standardized set of functionalities that can be easily integrated into different projects, packages can reduce the time and effort required to develop new software and improve the overall quality of the codebase.

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 maintain and update the system over time, as changes can be made to individual packages without affecting the entire system.

Finally, the use of packages can improve the understandability of the system for developers and other stakeholders. By grouping related components together, the overall structure of the system becomes more coherent and easier to navigate. This can be particularly important in larger systems, where the complexity of the system 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.

By 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 the entities. This helps to ensure that the database is designed to accurately represent the data and relationships that exist in the system.

Additionally, the class diagram helps to identify any potential issues or challenges that may arise during the development process. This enables developers to proactively address these issues and make any necessary adjustments to the database design.

2.3.1 Master Inventory Package

The Master Inventory Class Diagram in Figure. 8 provides a comprehensive overview of the inventory and materials management system in the construction industry. It is designed to provide a structural view of the system, showcasing the main classes and their relationships. The diagram consists of several key classes, including Items/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 the one-to-one and one-to-many relationships. For instance, the Inventory class has a one-to-many relationship with the Items/Materials class, which means that 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, which means that 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, Estimation Package, and Measure Units Package, provide additional information and functionality to the inventory and materials management system. For instance, the Procurement Package contains classes and methods for creating and managing purchase orders and supplier information, while the Estimation Package provides tools for estimating the cost and quantity of materials needed for a project. The Measure Units Package includes classes and methods for managing different units of measurement used in the inventory system.

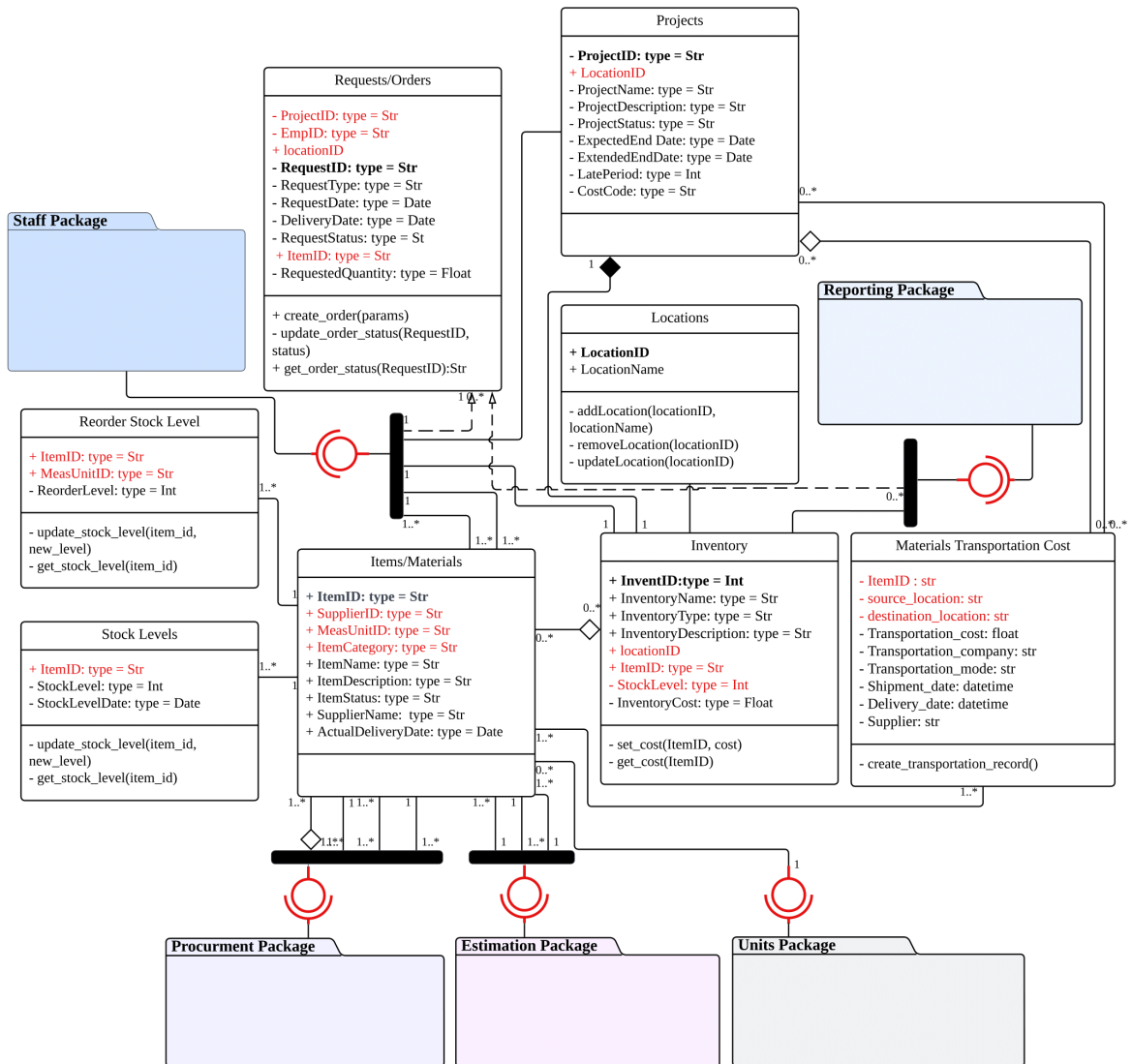


Figure 8 Master Inventory Class Diagram

2.3.2 Procurement Package

The Procurement Package is a critical component of the procurement process in construction companies [73]. Procurement Package class diagram in Figure. 9 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 the item ID, actual lead time, and actual lead time unit. It also includes methods to update and retrieve the actual lead time for 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 for an item.

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 to add, remove, and update 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 in tracking and managing the procurement process, while the Vendors/Suppliers and

Items/Materials classes provide a comprehensive view of the procurement process, including the supplier details and item details.

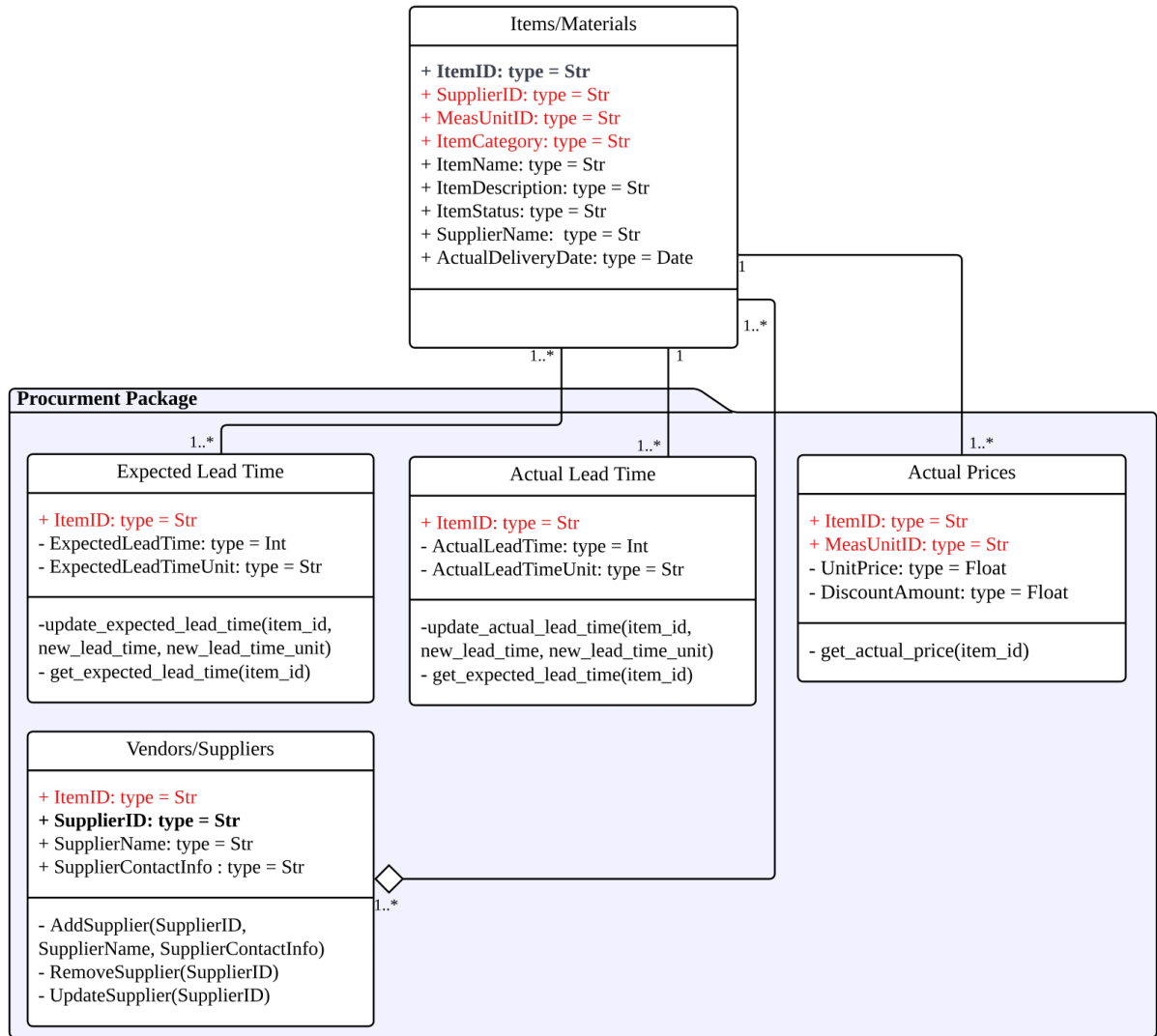


Figure 9 Procurement Package Class Diagram

2.3.3 Cost 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 in Figure. 10 contains

several classes, including Items/Materials Categories, Items/Materials Subcategories, Estimated Prices, and Items/Materials.

The Items/Materials Categories class helps in categorizing the different 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 sub-categorization of items and materials. This class includes the Subcategory ID, Subcategory Name, and Subcategory Description. It also provides a method to add a new subcategory to the system.

The Estimated Prices class helps in estimating the cost of different items and materials. This class includes the Item ID, Estimated Price, and Price Date. It provides methods to update the estimated price for 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 in keeping track of the different items and materials required for a construction project.

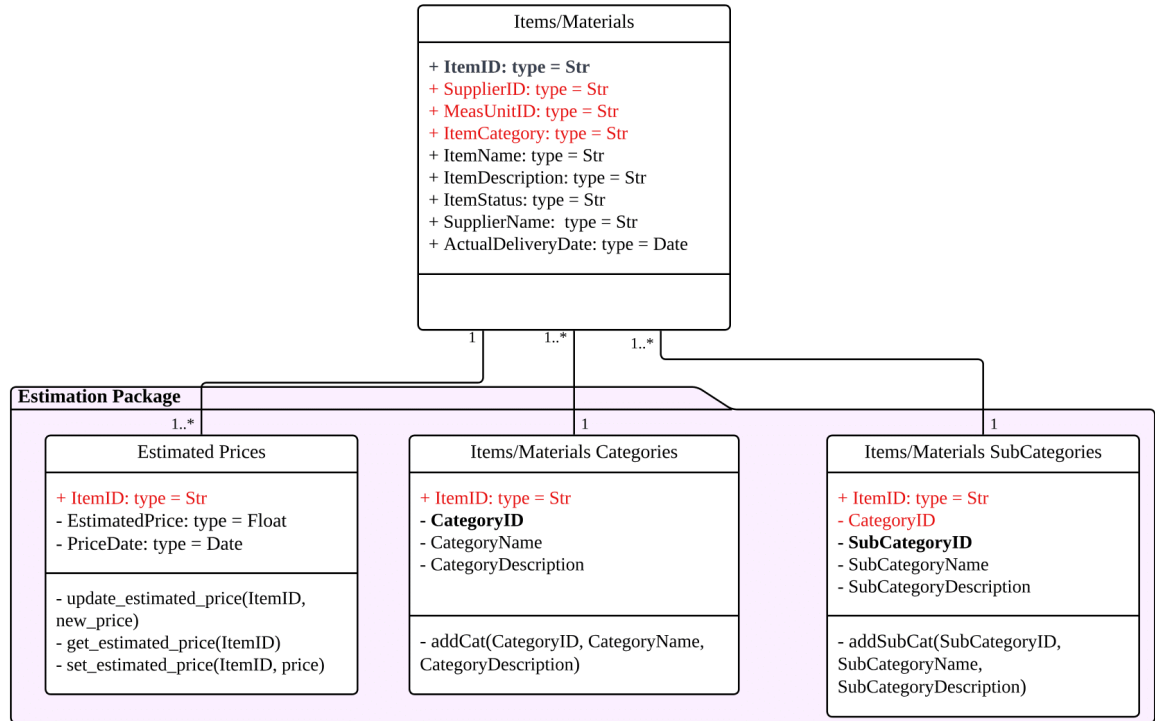


Figure 10 Estimation Package class diagram

2.3.4 Reporting Package

The Reporting Package class diagram in Figure. 11 provides a means for the construction company to generate various reports, including the inventory report, delivery note, damaged items report, and equipment custody report. This information is essential in ensuring that different departments are kept up to date on relevant information. For these multiple relations are developed between the package and other classes and packages. For instance, the relation between the MSR (BackOrder) class which generates the MSR reports and the Orders Class. Other relations with Projects and Inventory Classes are essential 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 is interfacing 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 instance, the Release Report is important for keeping track of inventory levels, ensuring 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 for ensuring that materials are delivered to the correct location and that they arrive on time. Again, the Equipment Custody Report is important for tracking the use of equipment and ensuring that it is properly maintained. This report can help ensure that equipment is available when needed and that it is in good condition. In addition, having these reports on record, the company can refer to them to resolve any issues or disputes that may arise in the future.

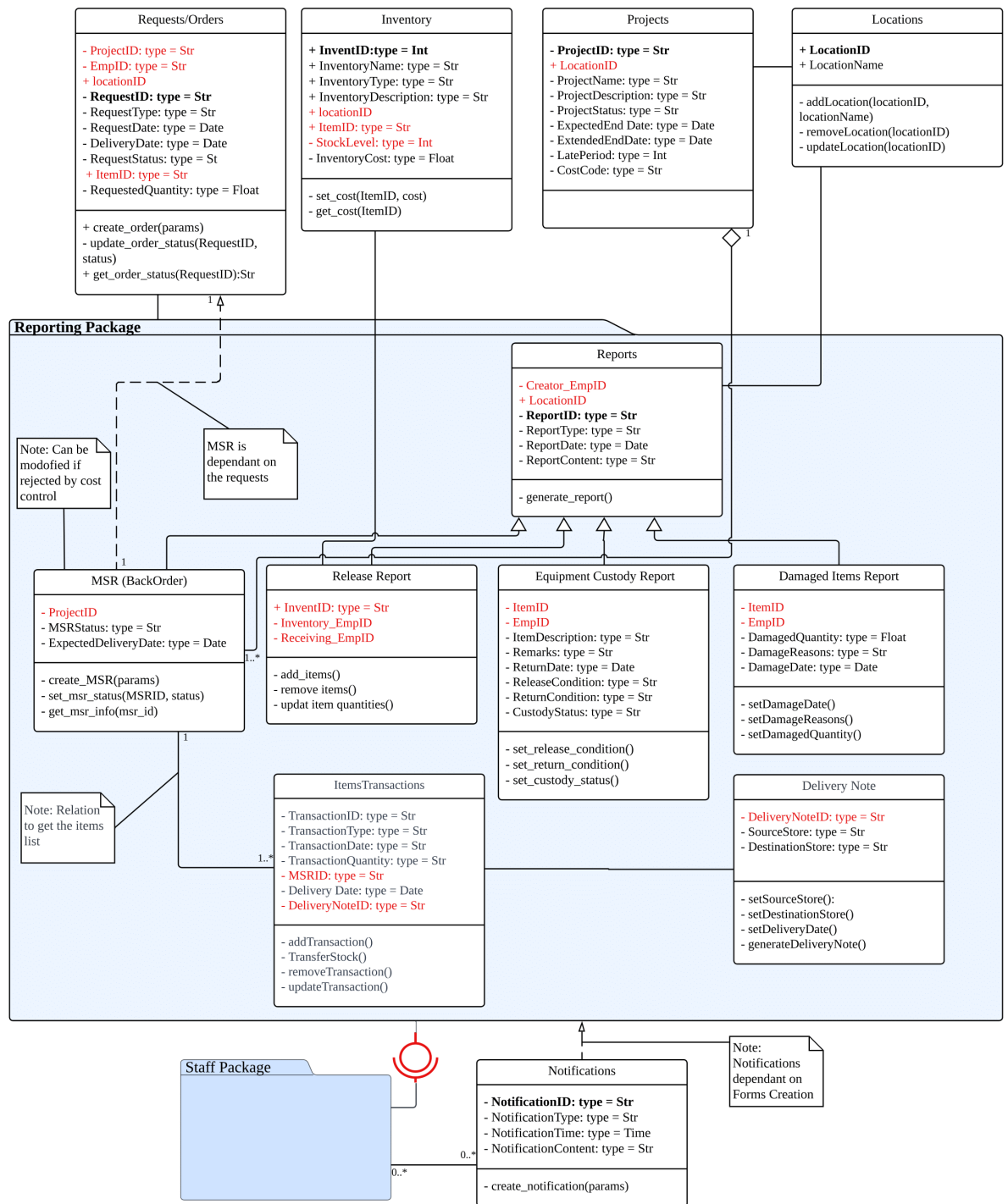


Figure 11 Reporting Package Class Diagram

2.4 Chapter Discussion

A mixed centralized and decentralized system offers several advantages. Firstly, it allows for a more efficient and streamlined decision-making process, where decisions can be made at the appropriate level of authority. This means that minor decisions can be made at the decentralized level, while major decisions can be made at the centralized level. This can lead to quicker decision-making, as minor decisions do not need to be referred to higher authorities. Secondly, it allows for better coordination between different departments and units, as there is a central authority overseeing the various decentralized units. This can lead to better communication and collaboration between different parts of the organization. Finally, a mixed centralized and decentralized system can provide greater flexibility, as it can adapt to changing circumstances and requirements. Decentralized units can respond quickly to local needs, while the central authority can provide overall guidance and direction. Overall, a mixed centralized and decentralized system can provide a balance between efficiency, coordination, and flexibility.

The current system at the construction site involves a site engineer ordering only the items that they know are not available on the site inventory. Then, the cost control department checks if the request is within the project's 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 gets rejected and revised by the site engineer for resubmission. During this process, many phone calls and paperwork take place, resulting in a lengthy and inefficient process. In some cases, site engineers order materials too early to ensure availability, resulting in additional costs and budgetary misallocation. Moreover, some projects receive the materials early, while others may struggle due to the unavailability of funds.

On the other hand, the proposed system streamlines the material request process by allowing site engineers to order materials easily using a digital platform. The system then checks the inventory of the site and other potential sources to determine if the requested materials are available. If the items are available, the system initiates the procurement process and updates the inventory levels accordingly. If the items are not available, the system alerts the relevant personnel to begin the procurement process. The system also calculates the expected purchase lead time and transportation cost to ensure efficient and cost-effective procurement.

Comparing the two systems, the proposed system offers several advantages over the current system. Firstly, the proposed system eliminates the need for manual paperwork and phone calls, reducing the risk of human error and speeding up the request process. Secondly, the system offers real-time inventory tracking, allowing site engineers to make informed decisions when requesting materials. Thirdly, the system provides cost estimates for procurement, ensuring that the project stays within budget. Finally, the system enables efficient allocation of funds, ensuring that the materials are available when needed, thus saving costs on early orders and unnecessary storage fees. Overall, the proposed system offers significant benefits over the current system, making it a worthwhile investment for the construction company.

In this context, the development of a UML model for a centralized materials procurement system represents a step towards implementing Industry 4.0 in the construction industry. The model aims to address the 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 to optimize cash flow and improve project timelines.

The developed UML model aligns with Industry 4.0 principles in several ways. Firstly, Industry 4.0 aims to create interconnected systems that allow for more efficient and flexible production processes. The proposed UML model can enable this by providing a centralized system for materials procurement 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 materials procurement and inventory management in real-time. Finally, Industry 4.0 emphasizes the use of 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.

Table 3 Future Functional Requirements Incorporating Industry 4.0 Principles

N	Requirement	Priority	Description
1	Predictive modeling for inventory management	High	Use data analytics and machine learning algorithms to predict demand and optimize inventory levels.
2	Predictive maintenance	Medium	Predict when equipment or machinery will fail and schedule preventive maintenance.
3	Demand forecasting	High	Forecast demand for materials, equipment, and supplies based on historical data, current trends, and future projects.
4	Optimization of logistics	High	Optimize the supply chain and logistics operations using data analytics and optimization algorithms.
5	Equipment utilization prediction	Medium	Predict equipment utilization and schedule maintenance to minimize downtime.

6	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.
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By improving the procurement process, construction companies can take a step towards increasing their overall productivity rates. The implementation of such a system can help to bridge the gap between the construction industry and other more digitized industries and can ultimately lead to a more sustainable and productive industry.

2.5 Chapter Conclusion

The UML model developed in this study addresses the challenges faced by the construction industry regarding inefficient materials procurement and lack of transparency. By adopting a centralized approach, the proposed model aims to optimize the procurement process, reduce delays, and enhance 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 integrating Industry 4.0 in the construction industry. By adopting a more digitalized and data-driven approach to materials procurement, companies can enhance their overall productivity and competitiveness in the market.

Future work can include the integration of manpower optimization models with the proposed UML model. By optimizing the workforce, construction companies can achieve higher productivity and reduce labor costs, leading to more efficient project delivery.

Furthermore, the integration of other Industry 4.0 technologies, such as artificial intelligence, and Internet of Things (IoT), can further enhance the effectiveness of the proposed UML model.

In summary, the UML model presented in this chapter can significantly improve the materials procurement process in the construction industry by increasing efficiency, transparency, and cost control. This model can be considered a vital step towards integrating Industry 4.0 technologies in the construction industry, ultimately leading to increased productivity and competitiveness.

CHAPTER 4

Workforce Scheduling and Routing Problem

3.1 Introduction

This chapter presents a novel comprehensive integer linear programming (ILP) model for workforce scheduling and resource allocation within the construction industry. It takes into account both economic and social constraints for four selected professions. The proposed optimization approach leads to significant cost savings and outsourcing reductions while maintaining near-optimal solutions and exhibiting robust performance under different scenarios. A comprehensive analysis consisting of graphical representations and numerical evaluations for a real case study in 2022 demonstrates the high potential of the approach to reduce total costs by up to 15%, with minimal impact from the incorporation of social constraints. The study aims to contribute to more efficient workforce management, resulting in increased productivity and profitability within the construction sector. By acknowledging the limitations of the current model and identifying areas for improvement, the study provides valuable insights that can stimulate further research.

3.2 Problem Statement

Despite being the largest industry in the global economy, the construction industry lacks the effective use of modern technology and operations research in its project management. Workforce scheduling, staffing, and routing optimization problems have received little attention in the literature, with only a limited number of journal articles focused on the intersection of construction, manpower, scheduling, and optimization. As a result, the

industry continues to face challenges such as low productivity levels, poor quality performance, cost inefficiencies, and delays.

In this context, this study primarily develops a general model for construction companies, with a specific focus on its practicality and effectiveness. To demonstrate the applicability of the model, a case study has been conducted on a local construction company in Saudi Arabia, further supporting the model's potential for widespread implementation. The company has 27 medium and mega construction projects scattered across the Kingdom and more than 3000 workers. The company faces several challenges in managing its workforce effectively, such as transferring workers between projects according to demand, managing worker vacations, and outsourcing workers to satisfy demand in case of shortages. These challenges require careful consideration of social constraints, costs, and disruptions to ongoing projects.

Most of the workers employed by the company are non-Saudi citizens who travel to their countries for a vacation each year to visit their families. Upon their return to Saudi Arabia, the company assigns them to the same project, if it is still ongoing, to ensure that they can easily continue their work. This social constraint is important for maintaining a stable workforce and reducing disruptions to ongoing projects. However, the workers may transfer between projects according to demand, with each transfer incurring a cost. It is important for the company to manage these transfers carefully to minimize costs and disruptions to ongoing projects.

Another social constraint that the company must consider is that the workers are not allowed to transfer between projects more than three times per year. This constraint ensures

that workers are not constantly moving between projects typically at different locations far away from each other and that they have sufficient time to settle into their work and contribute to ongoing projects. By managing worker transfers effectively, the company can maintain a stable and productive workforce while minimizing costs and disruptions to ongoing projects.

In cases where the company experiences a shortage of workers, it may outsource workers to satisfy its demand and complete projects on schedule. However, outsourcing workers can be expensive, and it is important for the company to balance the cost of outsourcing with the cost of managing its existing workforce effectively.

To address these challenges, this research aims to develop a workforce scheduling, staffing, and routing optimization model tailored to the local construction company's unique constraints and requirements. The model should minimize worker transfers between projects, reduce the cost of outsourcing workers, and ensure that workers are assigned to the same project upon their return from vacation. By achieving these goals, the company can maintain a stable and productive workforce, complete projects on schedule and within budget, and improve its competitiveness in the construction industry.

3.3 Mathematical Model

In this subsection, the mathematical model describing the workforce scheduling problem with vacations plans, transfers, and outsourcing is presented. The model defines sets and indices for workers, working months, and projects. In addition, it defines parameters such as the number of required workers for each project, the monthly salary of each worker, and the hiring and transportation costs. The decision variables are binary and integer variables

representing the worker's activity, transfers between projects, the number of new outsourcings, and the possible vacation scenario for each worker. The objective function is to minimize the total cost, including the worker's salaries, hiring costs, and transportation costs. The model has several constraints to ensure that the number of workers assigned to each project meets the required demand, the worker's vacation scenarios do not exceed their vacation balance, and a worker can only work in one project at a time. In addition, social constraints include limitations on workers' ability to transfer between projects, with a maximum of three transfers per year. Furthermore, a constraint is needed to ensure that non-Saudi workers are able to travel to visit their families without disrupting ongoing projects. These social constraints are important for maintaining a stable and productive workforce while minimizing disruptions and costs. To address the aforementioned social and operational constraints, a mathematical model is developed as follows:

Model Assumptions

- All the projects are running through out the year
- Transfer of workers is allowed between all projects.
- All workers are working through out the year (new hires and fire are not considered)
- Demand and prices are assumed to be deterministic and known.
- Hiring cost is the same for each profession at each project throughout the year.
- Workers must take their vacation balance on a continuous basis.
- Workers must remain at the new project after a transfer for a stability month.
- Workers must return to the same project after vacation month.

Parameters

V_i	Vacation balance for worker i in months
D_{nj}	Number of required workers in month j for project n
R_i	Monthly salary of each worker i
H_n	Hiring cost in each project n per each new worker
Q_{mn}	Transportation cost from project m to project n
E_i	Starting project of worker i
A	The maximum allowed transfers for all workers
B	Minimum stay in a project after a transfer

Sets/Indices

W	Total number of workers
i	The i^{th} worker ($i = 1, 2, 3 \dots, W$)
T	Total number of working months
j	The j^{th} Months ($j = 1, 2, 3 \dots T$)
N	Total number of projects
n, m	The n^{th}, m^{th} project ($n, m = 1, 2, 3, \dots N$), $n \neq m$
u_i	Maximum number possible continuous vacations scenarios for worker i

$$(u_i = T - V_i + 1 = \text{number of working months} + 1)$$

k_{gi} 1st possible vacation month in g^{th} continuous vacation scenario for worker i scenario ($k_{gi} = 1, 2, \dots, u_i$)

$k_{gi}-1$ The month before the 1st vacation month for vacation scenario g for worker i

$k_{gi} + V_i$ The month following the vacation for vacation scenario g for worker i

Decision Variables

$x_{ijn} = \begin{cases} 1, & \text{when worker } i \text{ is active in month } j \text{ in project } n \\ 0, & \text{Otherwise} \end{cases}$

$z_{ijmn} = \begin{cases} 1, & \text{when worker } i \text{ transfer from project } m \text{ to project } n \text{ in month } j \\ 0, & \text{Otherwise} \end{cases}$

y_{jn} = Integer, number of outsourcing in month j for a project n

$s_{ig} = \begin{cases} 1, & \text{for all possible continuous vacation scenarios except for one scenario for worker (i)} \\ 0, & \text{for only one possible continuous vacation scenario (g) for worker (i)} \end{cases}$

Notes:

- 1- Starting project at $j = 1$ for each worker is given as an input.
- 2- When j is replaced with $(k_{gi}-1)$ this is the month before the 1st vacation month
- 3- when j is replaced with $K_{gi} + v_i$ this is the 1st working month after vacation for worker i

Objective Function

Minimize

$$\sum_{n=1}^N \sum_{i=1}^W \sum_{j=1}^T (x_{ijn} * R_i) + \sum_{n=1}^N \sum_{j=1}^J (y_{jn} * H_n) + \sum_{m=1}^N \sum_{n=1}^N \sum_{i=1}^W \sum_{j=1}^T (Z_{ijmn} * TQ_{mn}) \quad (1)$$

Constraints

$$y_{nj} + \sum_{i=1}^W x_{ijn} \geq D_{nj} \quad \forall n, j \quad (2)$$

$$\sum_{n=1}^N \sum_{j=1}^T x_{ijn} \geq T - V_i \quad \forall i \quad (3)$$

$$\sum_{n=1}^N \sum_{k=K_{gi}}^{K_{gi}+V_i-1} x_{ink} \leq (N * V_i) * s_{ig} \quad \forall i \quad (4)$$

$$\sum_{j=1}^T s_{ig} = u_i - 1 \quad \forall i \quad (5)$$

$$\sum_{n=1}^N x_{ijn} \leq 1 \quad \forall i, j \quad (6)$$

$$x_{ijm} + x_{i(j+1)n} - 1 \leq z_{mnij} \quad \forall i, j, n, m, \quad j \neq T, n \neq m \quad (7)$$

$$x_{i(k_{gi}-1)n} - x_{i(K_{gi}+v_i)n} \leq s_{ig} \quad \forall i, n \quad (8)$$

$$\sum_{m=1}^N \sum_{n=1}^N \sum_{j=1}^T z_{mnij} \leq A \quad \forall i, n, m, \quad n \neq m \quad (9)$$

$$\sum_{l=j+1}^{j+B} x_{iln} \geq z_{mnij} * B \quad \forall i, n, m, \quad n \neq m \quad (10)$$

Table. 3 provides descriptions for the set of constraints applied to the model. These constraints ensure that the model is consistent with the company requirements contributing to an efficient and effective workforce allocation. By following these constraints, the model will generate optimized work schedules that meet the needs of both the projects and the workers, leading to better workforce utilization and potentially reduced costs.

Table 4 Descriptions of the Problem Constraints

Constraint	Description	Type
(2)	The total number of inhouse workers i in project n in month j in addition to the total outsourced workers in project n in month j must be greater than the demand for project n in month j .	Economic
(3)	Each worker i must be active in one project n in all the non-vacation months.	Economic
(4)	Set of constraints for each possible vacation scenario checking if the worker i is active or not across all projects (N), $s_{ij} = 0$ only if the worker is on vacation for such a scenario.	Economic
(5)	Assures that $s_{ij} = 0$ for only one vacation scenario	Economic
(6)	Assures that each worker i will be assigned to a maximum one project n at any given month j	Economic
(7)	Forces $z_{mni} = 1$ to only in the case of transfer of worker i from project m to project n in the next month $j+1$	Economic
(8)	Each worker must return to the same project after vacation for at least 1 month	Social
(9)	Number of allowed transfers along all the months must not exceed the allowed number or transfers A for each worker i	Social
(10)	Assures that when a worker is transported from project m to project n , the sum of working months in project n after transportation must be at least equal to the stability month B .	Social

3.4 Data Collection, Cleaning & Descriptive Analysis

Data collection, cleaning, and analysis are critical components of any research project. This section discusses the process of data collection and cleaning undertaken in this case study, with a focus on how data was organized, cleaned, and analyzed to provide useful insights.

Initially data is collected from the cost control and administration departments. The cost control department provided spreadsheets with attributes such as Worker ID, Project, Date, Hiring Date, Salary, and other relevant attributes for each worker. However, the data suffered from duplications and missing IDs. To address this, a worker master sheet is obtained from the administration department and compared it with the data retrieved from the cost control department. This helped in identifying and eliminating duplications and missing IDs.

Termination dates of workers who had left the company were identified using the worker master sheet, which allowed for the determination of whether a worker had left a project or the company. Worker transfers between projects were identified by comparing worker IDs in each project. Since the company has 27 ongoing projects and 1200 in-house workers, this facilitated the accurate tracking of worker transfers across different projects.

Once the data is cleaned and organized, a new attribute is created called "worker type" to classify each worker as existing, new, or left. Then the active and vacation months are identified. Furthermore, more than 300 receipts from outsourcing contractors were analyzed to determine the exact number of outsourcings for different professions.

In order to reduce the size of the problem, four professions (plumbers-skilled, electricians-skilled, electricians-helpers, and plumbers-helpers) were selected for analysis because they

were the highest among others in outsourcing. This decision was based on the need to focus on the areas that were likely to have the most significant impact on overall costs and to ensure that the analysis was comprehensive. Finally, the data is sent to the cost control head for approval before proceeding with the analysis.

Table. 4 provides data on the cost associated with different categories of workers, including in-house workers, outsourcing, and transfers. The total cost for all categories is SAR 33,095,192. The largest cost is associated with in-house workers, which amounts to SAR 18,860,671, followed by outsourcing at SAR 13,973,271. The cost of transfers is relatively small, amounting to only SAR 261,250.

Table 5 Cost Breakdown for Workforce in 2022 Case Study

Category	Number	Cost
Inhouse Workers	1268	18,860,671
Outsourcing	4504	13,973,271
Transfers	1045	261,250
Total Cost	-	33,095,192

The cleaned and organized data was analyzed to provide useful insights. The 2022 case was summarized in the table. 5 that showed the number of workers and costs associated with different professions, including plumbers (skilled), electricians (skilled), electricians (helpers), plumbers (helpers), and total costs.

Outsourcing costs were identified for each category, along with transfer costs and salaries. The total cost was calculated for each category, with Electricians (Skilled) having the highest cost, followed by Plumbers (Skilled), Plumbers (Helpers), and Electricians

(Helpers). This table would serve as a baseline for comparison with the optimized scenarios.

Table 6 Cost Breakdown by for 4 Professions in 2022 Case Study

	Electricians (Skilled)	Plumbers (Skilled)	Plumbers (Helpers)	Electricians (Helpers)	Total
Sum Outsource Workers	676	733	939	621	2969
Sum Active Workers	1313	743	157	275	2488
Sum Transfers	44	23	12	11	90
Outsourcing	3,866,720	3,621,020	3,556,280	2,260,440	13,304,460
Transfer Cost	10,002	5,132	901	2,856	18,891
Salaries	3,386,640	1,854,396	214,788	443,124	5,898,948
Total Cost	7,263,362	5,480,548	3,771,969	2,706,420	19,222,299

As shown in the previous 2 tables 55% of the 2022 manpower cost was associated with these 4 professions with outsourcing as the main contributor of the total cost which makes it one of the main components to be considered.

In order to further optimize the problem, a final step was taken to reduce its complexity. This was achieved by clustering the 27 ongoing projects that were previously dispersed across Saudi Arabia into 9 distinct projects, based on their geographical proximity as shown in Figure. 12. This step was taken under the assumption that transportation costs among the projects within each cluster were negligible. By implementing this clustering approach, the problem was significantly reduced in size and complexity, allowing for a more efficient optimization process.

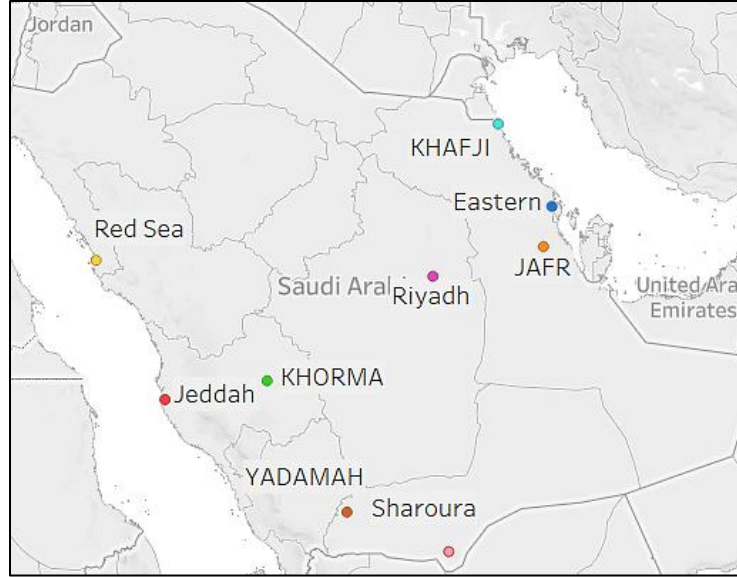


Figure 12 Scattered Projects in Saudi Arabia

An additional crucial input to the optimization model is the outsourcing cost per worker per month. In order to simplify the model, the outsourcing cost has been standardized for each profession across all projects. The corresponding outsourcing costs are delineated in Table 6. By incorporating these outsourcing costs for each profession as an input, the optimization model accounts for the financial consequences of outsourcing decisions.

Table 7 Outsourcing Cost Inputs by Profession

	Outsourcing Cost/Worker/Month (SAR)
Skilled Plumbers	4,940
Skilled Electricians	5,720
Electricians Helpers	3640
Plumbers Helpers	3640

3.5 Optimization Approach & Problem Parameters

One approach that was employed to evaluate the effectiveness of the proposed optimization model was to compare the results obtained from the model with and without incorporating

the social constraints. Initially, the model was solved without considering the social constraints, and the resulting solution was compared with the actual data to establish a baseline for performance evaluation. Subsequently, the model was solved again while incorporating the social constraints, and the resulting solution was compared with the baseline to evaluate the effectiveness of the social constraints on the optimization results. This approach allowed for a comprehensive evaluation of the optimization model under both ideal and realistic scenarios and provided insights into the impact of the social constraints on the overall performance of the system.

The optimization problem was solved using a PC equipped with an Intel(R) Core (TM) i5-2450M CPU @ 2.50GHz processor and 12 GB RAM. Parallel processing with 4 threads was employed to accelerate the solution process. The optimization method used to solve the mathematical model is using Pyomo with CPLEX, a widely used optimization software.

Pyomo is an open-source optimization modeling language that provides a flexible and efficient way to formulate and solve optimization problems. CPLEX, on the other hand, is a powerful commercial optimization solver that provides efficient algorithms to solve linear and integer programming problems.

Together, Pyomo and CPLEX allowed for the creation of an efficient and robust optimization model that was used to optimize the problem statement presented earlier. In the following sections, the optimization process is described in detail and the results of the optimization are presented.

Table. 7 presents the number of variables and linear constraints for each profession in both the optimized (without social constraints) and optimized (with social constraints)

scenarios. The optimized scenario with social constraints had a slightly higher number of variables and linear constraints for all four professions. The increase in the number of variables and linear constraints in the optimized scenario with social constraints suggests that incorporating social constraints resulted in more complex models. However, the benefits of improved accuracy and performance that resulted from incorporating the social constraints likely outweighed the increased complexity.

Table 8 Mathematical Model Variables & Constraints Numbers by Profession

Profession	Number of variables & Constraints	Optimized	Optimized (Social Constraints)
Skilled Plumbers	Number of Variables	80,848	81,112
	Number Linear constraints	67,700	75,098
Skilled Electricians	Number of Variables	142,390	142,918
	Number Linear constraints	119,237	132,512
Electricians Helpers	Number of Variables	28,731	28,887
	Number Linear constraints	24,051	26,796
Plumbers Helpers	Number of Variables	13,885	13,969
	Number Linear constraints	11,620	12,934

3.6 Results & Analysis

In this section the results of the mentioned optimization approach are presented involving the four selected professions. The original scenario, the optimized scenario, and the optimized scenario with social constraints incorporated are compared based on various metrics.

The bar chart in Figure 13 compares the total costs for each worker type under the original case, optimized model and optimized model with social constraints. For Skilled

Electricians, the total cost reduces from SAR 7.26 million in the original case to SAR 6.16 million in the optimized models, a savings of 15%. The savings are nearly the same regardless of whether social constraints are included or not. The potential savings in the optimized models are SAR 1,106,296 (with 1% gap from optimal) and SAR 1,101,205 (with 0.59% gap when including social constraints). The computational costs for solving are 35 minutes and 12 seconds for the optimized model without social constraints and 91 minutes and 23 seconds for the optimized model with social constraints.

For Skilled Plumbers, the total cost decreases 13% from SAR 5.48 million to around SAR 4.77 million in the optimized models. Again, the cost savings are comparable with and without social constraints. The potential savings in the optimized models are SAR 709,051 (with 1% gap from optimal) and SAR 710,704 (with 1% gap when including social constraints). The computational costs for solving are 5 minutes and 33 seconds for the optimized model and 89 minutes and 36 seconds for the optimized model with social constraints.

The total cost for Electrician Helpers sees a 11% reduction from SAR 2.71 million in the original case to SAR 2.41 million in the optimized models. The cost savings are slightly lower when including social constraints but still achieve most of the potential reduction. The potential savings in the optimized models are SAR 297,935 (with a 0.06% gap from optimal) and SAR 297,812 (with a 0.07% gap when including social constraints). The computational costs for solving are 10 minutes for the optimized model and 52 seconds for the optimized model with social constraints.

Finally, for Plumber Helpers the total cost savings are 4%, decreasing from SAR 3.77 million to between SAR 3.63 and SAR 3.64 million in the optimized models depending on social constraints. The cost savings here are the lowest of the worker types studied. The potential savings in the optimized models are SAR 140,806 (with a 0.05% gap from optimal) and SAR 141,463 (with a 0.03% gap when including social constraints). The computational costs for solving are 2.5 seconds for the optimized model and 7.3 seconds for the optimized model with social constraints.

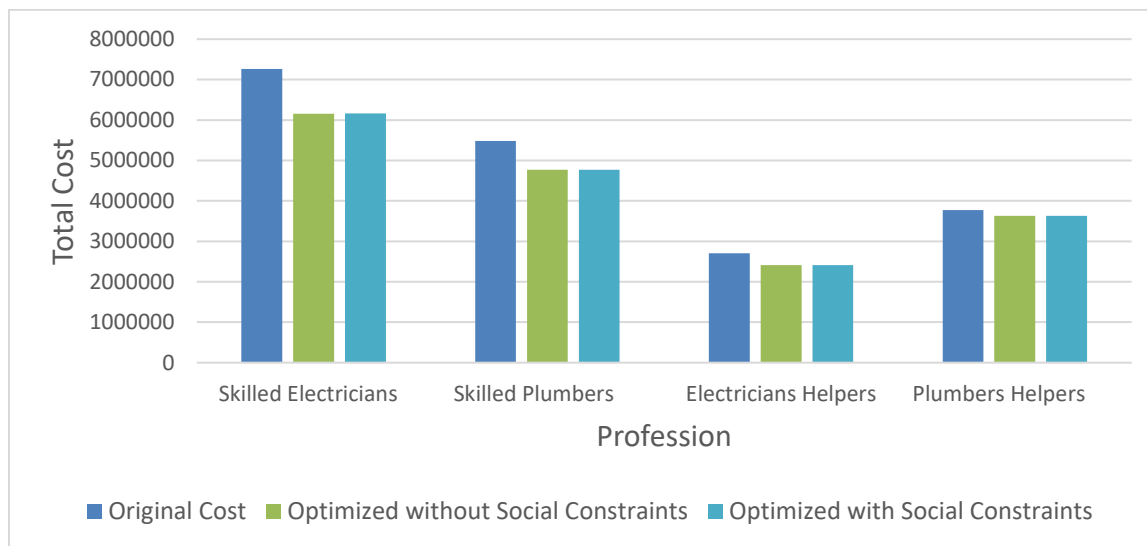


Figure 13 Total Costs Comparison Between the 3 Cases

The bar chart shows that optimized work distribution models can lower total costs by up to 15% depending on the worker type, with and without incorporation of social constraints. The largest cost savings accrued for Skilled Electricians and Skilled Plumbers. Social constraints appear to produce comparable or slightly lower total cost savings, suggesting they do not majorly impact the potential cost reductions achieved through optimized work scheduling and resource allocation alone.

The tables. 8 to 11 present a numerical analysis of the costs, outsourcing, transfers, and computational metrics associated with the original scheduling model and the two optimized models - with and without social constraints. For Skilled Electricians, the optimized models reduced total costs by approximately 15%, primarily through a roughly 29% decrease in outsourcing costs. This was achieved by reducing the number of outsourced workers by about 22% and increasing the total number of transfers. Consequently, the net cost reductions amount to SAR 1.1 million, despite the higher transfer costs.

Table 9 Workforce Planning Cost Optimization Results for Skilled Electricians

Skilled Electricians			
	Original	Optimized	Optimized (Social Constraints)
Outsourcing	3,866,720	2,745,600	2,745,600
Transfer Cost	10,002	24,826	29,917
Salaries	3,386,640	3,386,640	3,386,640
Total Cost	7,263,362	6,157,066	6,162,157
Potential Savings		1,106,296	1,101,205
Gap from Optimal	-	1%	0.59%
Computational Cost	-	35:12 Min	91:23 Min
Number of outsource	617	480	480
Sum Transfers	44	141	167

For Skilled Plumbers, the optimized models led to a reduction in total costs of approximately 13%, primarily due to a roughly 20% decrease in outsourcing costs. This reduction was facilitated by decreasing the number of outsourced workers by around 20%

and significantly increasing the total number of transfers. As a result, the net cost reductions amount to SAR 709,051 – SAR 710,704 despite increased transfer costs.

Table 10 Workforce Planning Cost Optimization Results for Skilled Plumbers

Skilled Plumbers			
	Original	Optimized	Optimized (Social Constraints)
Outsourcing	3,621,020	2,889,900	2,894,840
Transfer Cost	5,132	27,201	20,608
Salaries & Vacation Costs	1,854,396	1,854,396	1,854,396
Total Cost	5,480,548	4,771,497	4,769,844
Potential Savings	-	709,051	710,704
Gap from Optimal	-	1%	1%
Computational Cost	-	05:33 Min	89:36 Min
Sum Outsource Workers	733	585	586
Sum Transfers	22	187	112

For Electrician Helpers, optimized work distribution generated 11% cost savings predominantly from a 13.3% decline in outsourcing costs. These savings were enabled through 13.3% fewer outsourced workers and more transfers. Nearly the entire cost savings of SAR 0.3 million derived from outsourcing reductions, while transfer costs remained relatively unchanged.

Table 11 Workforce Planning Cost Optimization Results for Electricians Helpers

Electricians Helpers			
	Original	Optimized	Optimized (Social Constraints)
Outsourcing	2,260,440	1,961,960	1,961,960
Transfer Cost	2,856	3,401	3,524
Salaries	443,124	443,124	443,124
Total Cost	2,706,420	2,408,485	2,408,608
Potential Savings	-	297,935	297,812
Gap from Optimal	-	0.06 %	0.07%
Computational Cost	-	10 min	52 sec
Sum Outsource Workers	621	539	539
Sum Transfers	11	30	30

Optimized Plumber Helpers scheduling achieved the least cost savings at 3.7%, with only a 4% decrease in outsourcing costs resulting from 4% fewer average outsourced workers which is insignificant. This resulted in cost reductions of SAR 0.14 million.

Table 12 Workforce Planning Cost Optimization Results for Plumbers Helpers

Plumbers Helpers			
	Original	Optimized	Optimized (Social Constraints)
Outsourcing	3,556,280	3,414,320	3,414,320
Transfer Cost	901	2,055	1,398
Salaries	214,788	214,788	214,788
Total Cost	3,771,969	3,631,163	3,630,506

Potential Savings	-	140,806	141,463
Gap from Optimal	-	0.05%	0.03%
Computational Cost	-	2.5 sec	7.3 sec
Sum Outsource Workers	977	938	938
Sum Transfers	3	12	10

Generally, the computational experiments determined optimized models required substantially more solution time given increased complexity, especially when including social constraints. Yet, optimized models yielded near-optimal solutions, within 1% optimality gaps. This signifies the optimization methodology effectively identified high-quality solutions despite the more challenging problem formulations.

Numerical data corroborated the visualized conclusions that optimized workforce scheduling reduced costs, particularly through sizable decreases in outsourcing, with nearly same cost impacts whether including social constraints or not. The most substantial cost savings and outsourcing reductions accrued for models with inherently higher complexity and outsourcing levels originally. The optimization approach was shown capable of producing excellent solutions based on optimality gaps.

3.7 Chapter Discussion

The overall goal of this study is to create a robust and efficient solution that can be applied to real-world scenarios. By achieving a high-quality solution, the company can ensure a stable workforce while minimizing disruptions to ongoing projects, ultimately leading to increased productivity and profitability.

Most of the models in the literature do not satisfy the requirements for construction industry for example. Comparing the proposed model with the model of [44], it is clear that it cannot work for the construction industry due to several reasons. Firstly, it assumes a fixed demand for workers, which is often not the case in the construction industry where demand fluctuates based on the stage of the project. This inflexibility leads to inefficiencies and increased costs. Secondly, it does not consider the specific skills and qualifications required for different tasks in the construction industry. Finally, the first model does not account for the workers vacations or social constraints.

On the other hand, On the other hand, the proposed model is more suitable and comprehensive for the construction industry due to its ability to address these issues. Some key differences between the two models include:

- **Dynamic labor demand:** The second model accommodates fluctuating labor demands by incorporating the number of required workers and time needed for each task into its parameters. This approach enables the model to optimize workforce scheduling better, leading to increased efficiency and cost-effective workforce management.
- **Skillset and qualification consideration:** The second model takes into account the specific skills and qualifications of workers, allowing for more accurate worker assignments based on project requirements. This specificity helps better align the workforce with the tasks at hand, maximizing productivity.
- **Worker scheduling considerations:** Unlike the first model, the second model includes provisions for managing workers' vacation schedules, transfers between projects, and

outsourcing. This attention to detail helps maintain adequate staffing levels and productivity throughout the project duration.

Although the presented model has yielded promising results, it is important to acknowledge its limitations and consider potential avenues for improvement. In particular, the current model assumes that all in-house workers are available year-round, which may not reflect the reality of the workforce. A more realistic model would need to account for the hiring and firing of employees, to ensure that the model's optimization recommendations can be applied effectively.

To optimize the model's performance, it is necessary to run the model and consider previous solutions. In addition, the running time of the model can be lengthy, making it inefficient for real-world applications. Thus, it may be worthwhile to explore metaheuristic techniques as a means of improving the model's efficiency and computational cost.

It is important to note that the current model only considers four professions. To ensure a fair and accurate comparison of solutions, all professions should be included. As observed in the analysis, the cost savings can vary significantly for different professions, and the total cost savings are influenced by the number of professions included in the model.

While the current model has yielded promising results, there is a room for improvement. By taking into account the hiring and firing of employees, exploring heuristic techniques, and including all professions, a more accurate and effective model can be created.

3.8 Chapter Conclusion

In conclusion, this study developed a mathematical model to optimize workforce in a construction company. The model was able to identify the optimal number of workers to

outsource, and the optimal transfers of workers between projects resulting in significant cost savings for the company. However, it is important to note that the model assumes inhouse workers are hired before the beginning of the year and will not leave the company until the end of the year. This assumption is not realistic. Thus, future research should take into account the dynamic nature of workforce management in the construction industry.

Nonetheless, this study represents an important step towards creating a robust and efficient solution for workforce management in the construction industry. By achieving a high-quality solution, the company can ensure a stable workforce while minimizing disruptions to ongoing projects, ultimately leading to increased productivity and profitability.

The model robustness is evaluated by systematically varying input parameters, simulating different scenarios, and comparing the model's outcomes with alternative approaches. The model's output consistently yielded accurate and reliable results. The robust performance of the model validated through the case study, demonstrated the practicality and adaptability of the approach in real-world applications.

Overall, this study highlights the importance of effective workforce optimization in the construction industry and the potential benefits of using mathematical optimization models to achieve this goal. Further research is necessary to refine and improve the model, but the results of this study provide a solid foundation for future work in this area.

CHAPTER 5

Conclusion

This thesis sought to develop solutions for optimizing materials and workforce management in the construction industry through UML modeling and mathematical techniques. Chapter 1 introduced the research problems, aims, and objectives, which focused on increasing productivity, efficiency, cost control, and transparency across construction projects. Chapter 2 reviewed the academic literature on UML modeling, optimization methods, and Industry 4.0 technologies used in construction. Chapter 3 detailed the methodology for developing the UML model and optimization models at the center of this research. The UML model provided a digitized, centralized approach to materials procurement, while Chapter 4 contained the workforce model to determine the optimal distribution of workers across projects to minimize costs.

The workforce optimization model saved up to 15% labor costs across the nine clustered projects through outsourcing and worker transfers between sites for the 2022 case study. This is a significant impact that demonstrates the benefits of optimization for construction management. However, the assumption that all in-house workers stay for the full year and materials are purchased from consistent suppliers with fixed lead times and costs must be addressed in future work. Integrating automation, AI, and real-time data from IoT devices could help expand and refine the models to improve their applicability and accuracy. Additional data from a wider range of projects is also needed to further validate these frameworks.

This research contributes practical solutions and tools for optimizing materials and workforce management in construction, which can substantially improve productivity, reduce costs, and gain useful project insights. The frameworks developed provide an important first step towards digitizing and optimizing construction project planning and control. By building on these concepts and integrating more sophisticated technologies as they mature, the construction industry can achieve revolutionary improvements in project delivery to meet modern demands.

In summary, this thesis highlights the significant benefits of UML modeling, optimization, and data-driven decision making for the construction sector. Widespread adoption of these techniques will be essential for enhancing competitiveness, resilience, and sustainable growth as projects increase in complexity. With continued progress in research and practice, highly digitized and automated management systems are within reach for construction companies to drive efficiencies for decades to come.

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1. Supervised fuzzy c-means techniques to solve the capacitated vehicle routing problem. MAW Shalaby, AR Mohammed, SS Kassem Int. Arab J. Inf. Technol. 18 (3A), 10 2021
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