

A BIM-ENABLED LEAN CONSTRUCTION FRAMEWORK FOR CONSTRUCTION-PHASE WASTE IDENTIFICATION AND OPTIMIZATION

MISS YUANYU HE

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF SCIENCE IN
INDUSTRIAL MANAGEMENT ENGINEERING
DEPARTMENT OF INDUSTRIAL ENGINEERING
FACULTY OF ENGINEERING
KING MONGKUT'S UNIVERSITY OF TECHNOLOGY NORTH BANGKOK
ACADEMIC YEAR 2026

COPYRIGHT OF KING MONGKUT'S UNIVERSITY OF TECHNOLOGY NORTH BANGKOK

A BIM-ENABLED LEAN CONSTRUCTION FRAMEWORK FOR CONSTRUCTION-PHASE WASTE IDENTIFICATION AND OPTIMIZATION

MISS YUANYU HE

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF SCIENCE IN
INDUSTRIAL MANAGEMENT ENGINEERING
DEPARTMENT OF INDUSTRIAL ENGINEERING
FACULTY OF ENGINEERING
KING MONGKUT'S UNIVERSITY OF TECHNOLOGY NORTH BANGKOK
ACADEMIC YEAR 2026

COPYRIGHT OF KING MONGKUT'S UNIVERSITY OF TECHNOLOGY NORTH BANGKOK

Thesis Certificate

The Faculty of Engineering, King Mongkut's University of Technology North Bangkok

Title A BIM-Enabled Lean Construction Framework for Construction-Phase Waste Identification and Optimization

By Miss Yuanyu He

Accepted by the Faculty of Engineering, King Mongkut's University of Technology North Bangkok in Partial Fulfillment of the Requirements for the Master of Science in Industrial Management Engineering

..... Dean / Head of Department

(Associate Professor Dr. Kittichai Thanasupsin)

Thesis Examination Committee

..... Advisor

(Assistant Professor Dr. Chayathach Phuaksaman)

..... Committee

(Assistant Professor Piya Rontlaong, Ph.D.)

..... Committee

(Associate Professor Siravit Swangnop, Ph.D.)

Name : Miss Yuanyu He
Thesis Title : A BIM-Enabled Lean Construction Framework for Construction-Phase Waste Identification and Optimization
Major Field : Industrial Management Engineering
King Mongkut's University of Technology North Bangkok
Thesis Advisor : Assistant Professor Dr. Chayathach Phuaksaman
Academic Year : 2026

ABSTRACT

The construction phase is characterized by a substantial presence of non-value-adding activities, such as waiting, rework, information delays, and resource conflicts. These activities do not contribute to value creation but consume significant resources, thereby constituting a fundamental cause of inefficiencies in construction projects. Traditional construction management approaches primarily rely on experience-based decision-making and ex post control, making it difficult to systematically identify and eliminate such waste at its root. In recent years, Building Information Modeling (BIM) has provided a digital and visualized means for construction management; however, a clear and systematic methodology for leveraging BIM to reduce construction-phase waste remains lacking.

Guided by Lean Construction theory, this study aims to explore methods and pathways for reducing construction-phase waste through the application of BIM. First, considering the characteristics of the construction phase, construction waste is systematically classified into nine categories: waiting; rework and defects; transportation; motion; inventory and work-in-progress; over-processing; overproduction; making-do; and information and collaboration waste. Second, the functional applications of BIM in the construction phase are analyzed to clarify its role in waste identification and prevention. A comparative analysis between BIM-enabled and non-BIM scenarios is conducted, and a mapping framework linking BIM functionalities to different types of construction-phase waste is developed.

The results indicate that BIM contributes to waste reduction primarily through two mechanisms. First, at the design stage, BIM helps eliminate the root causes of waste by identifying and resolving potential issues through clash detection, integrated design coordination, and design development support, thereby preventing design defects from propagating into the construction phase. Second, during the construction phase, BIM enhances process management through 4D simulation, collaborative platforms, and smart site technologies, effectively reducing waste caused by information delays and poor coordination.

From the perspective of construction-phase waste, this study systematically establishes the relationships between BIM functionalities and waste types and further demonstrates the practical effectiveness of BIM in reducing construction-phase waste through case-based analysis. The findings provide practical guidance for construction enterprises in selecting and implementing BIM technologies in project delivery.

This study provides a theoretical foundation for the application of BIM in reducing construction-phase waste.

(Total 1 Pages)

Keywords : Construction-phase waste, Building Information Modeling(BIM), Lean Construction, Waste identification

_____ Advisor

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to everyone who supported me throughout my master's studies in Thailand.

After nearly seven years of working in China, the fast pace of professional and daily life prompted me to reflect on my personal and professional growth. I realized the importance of continuing my education and decided to pursue a master's degree in Thailand. My familiarity with the Thai language and culture made this an especially meaningful choice. I am deeply grateful to the university for making this educational journey possible.

My two years of study have been a special and memorable part of my life. I would like to thank the dean, my advisor, the faculty members, and all university staff for their guidance and support. Their help with my studies and with academic and administrative matters made it possible for me to continue my program with greater confidence. I am especially grateful to my advisor for providing guidance and encouragement throughout my research. My advisor's support helped me stay focused and make steady progress in completing this thesis.

Beyond the classroom, my time in Thailand was enriched by the warmth and kindness I encountered in everyday interactions, including the generous compliments and encouragement that often made me feel welcome. I also gained a deeper appreciation of Thai culture through the care devoted to festivals and traditions. These experiences made my time in Bangkok memorable and meaningful beyond the classroom.

Before beginning my master's studies, I tended to believe that technical knowledge was the most important part of professional development. Through my studies, I came to appreciate the importance of management as well—the way people, resources, and processes are organized and guided toward shared goals. This change in perspective has been one of the most valuable outcomes of my master's education.

Finally, I would like to thank my classmates, friends, parents, family, and everyone who supported me during this journey. Your understanding, encouragement, and care helped me through both the challenges of studying abroad and the demands of completing this thesis. I will always cherish the knowledge, friendships, and experiences I gained during these two years.

Yuanyu He

TABLE OF CONTENTS

Page

ABSTRACT i

ACKNOWLEDGEMENTS ii

TABLE OF CONTENTS iii

LIST OF TABLES v

LIST OF FIGURES vi

LIST OF ABBREVIATIONS vii

Chapter 1 Introduction 1

1.1 Research Background 1

1.2 Problem Statement 2

1.3 Research Objectives 3

1.4 Research Questions 4

1.5 Research Significance 4

1.6 Thesis Structure 4

Chapter 2 Literature Review 6

2.1 Concept and Characteristics of Construction-Phase Waste 6

2.2 Formation Mechanism of Construction-Phase Waste 11

2.3 Applications of BIM in the Construction Phase 14

2.4 Application of Lean Construction in the Construction Phase 18

2.5 Integration of BIM and Lean Construction 22

2.6 Literature Review Summary and Research Gaps 25

chapter 3 Methodology 27

3.1 Overview of Research Methodology 27

3.2 Justification of the Research Methodology 27

3.3 Alignment between Research Questions and Methods 28

3.4 Literature Analysis Method 29

3.5 Framework Development Method 32

3.6 Case-Based Comparative Analysis 34

Chapter 4 BIM–Lean-Based Framework for Construction-Phase Waste Optimization 50

4.1 Dimension I: Information Integration – Information Visibility Mechanism 52

4.2 Dimension II: Process Optimization – Constraint Removal and Process Control Mechanism 55

4.3 Dimension III: Performance Feedback – Data-Driven Learning Mechanism 58

4.4 Dimensional Synergy and BIM–Lean Collaborative Mechanism 59

4.5 BIM–Lean Synergy for the Nine Types of Construction-Phase Waste 60

Chapter 5 Mechanism Analysis of BIM–Lean Synergy in Construction-Phase Waste Optimization 63

5.1 Functional Complementarity: Division of Roles between BIM and Lean Construction 63

5.2 Theoretical Interpretation of the Synergy Mechanism 64

5.3 Positive Feedback Loop: Why the Synergy Effect Amplifies Over Time 65

Chapter 6 Conclusions and Future Research 67

6.1 Summary of Findings and Responses to Research Questions 67

6.2 Research Contributions 68

6.3 Research Limitations 68

6.4 Future Research Directions 69

REFERENCES 70

VITA 77

LIST OF TABLES

Table **Page**

Table 2-1 Comparison of Construction-Phase Waste Types and Characteristics.....9

Table 2-2 Mechanism Analysis of BIM in Waste Identification during the Construction Phase 16

Table 2-3 Mapping of Lean Tools, Waste Types, and Effects 20

Table 3-1 Alignment between Research Questions and Research Methods.....29

Table 3-2 Detailed Breakdown of Nine Types of Construction Waste 35

Table 3-3 BIM capabilities and Limitations in Construction Waste Reduction 46

Table 4-1 Mapping between BIM Mechanisms and Waste Types 54

Table 4-2 Mapping between Lean Mechanisms and Waste Types.....57

Table 4-3 Key BIM–Lean Synergy Mechanisms for Nine Types of Construction-Phase Waste 61

พระจอมเกล้าพระนครเหนือ มหาวิทยาลัยเทคโนโลยี

LIST OF FIGURES

Figure **Page**

Figure 1-1 illustrates the integration of multi-disciplinary models in BIM 3

Figure 2- 1 Mechanism of Construction Waste Formation 13

Figure 2- 2 Framework of BIM Applications in the Construction Phase 17

Figure 2- 3 Relationship between BIM and Lean Construction 24

Figure 3-1 Multi-disciplinary BIM Model (Structure, Steel Structure, MEP, and Facade) 37

Figure 3-2 Comparison of MEP Layout Before and After Optimization.....38

Figure 3-3 Comparison of Clearance Before and After Optimization.....39

Figure 3-4 BIM Model of the Façade System 39

Figure 3-5 Detailed BIM Model of Steel Structure Connections 40

Figure 3-6 Simulation of the Steel Structure Lifting Plan 41

Figure 3-7 UAV-Based Progress Monitoring and Comparison 41

Figure 3-8 Digital Construction Platform 42

Figure 3-9 Real-Time Tower Crane Monitoring.....42

Figure 3-10 On-Site Video Surveillance.....43

Figure 4-1 Integrated BIM–Lean Framework for Construction-Phase Waste Optimization 51

LIST OF ABBREVIATIONS

BIM	Building Information Modeling
MEP	Mechanical, Electrical, and Plumbing
WIP	Work-In-Progress
RFI	Request for Information
3D	Three-Dimensional
4D	Four-Dimensional
CDE	Common Data Environment
LPS	Last Planner System
PPC	Percent Plan Complete
VSM	Value Stream Mapping
JIT	Just-In-Time
RCA	Root Cause Analysis
CI	Continuous Improvement
5S	Sort, Set in Order, Shine, Standardize, Sustain
RQ	Research Questions
CNKI	China National Knowledge Infrastructure
PDCA	Plan–Do–Check–Act
RMB	Renminbi
UAV	Unmanned Aerial Vehicle
SOP	Standard Operating Procedure
IoT	Internet of Things
AI	Artificial Intelligence

Chapter 1

Introduction

1.1 Research Background

In recent years, the construction industry has experienced a continuous increase in project scale and complexity, while issues related to construction efficiency have become increasingly prominent. A significant proportion of on-site activities are non-value-adding, including waiting, rework, and information delays, which lead to resource waste and schedule overruns, thereby constraining overall project performance (Koskela, 2000; Cabrera et al., 2023). The construction phase, as the core stage of project delivery, directly determines the overall performance and success of a project (Parsamehr et al., 2023).

Traditional construction management approaches primarily rely on experience-based decision-making and reactive control, making it difficult to identify and eliminate non-value-adding activities in a timely manner. Beyond material waste, construction sites are characterized by various forms of hidden waste, such as waiting time, rework, and information errors, which further reduce operational efficiency and increase project risks (Cabrera et al., 2023). Previous studies indicate that schedule delays are not solely caused by external disturbances, but rather stem from the accumulation of non-value-adding activities within construction processes—activities that consume time and resources without contributing to value creation.

To address these challenges, Lean Construction has been increasingly introduced into construction management. This approach focuses on eliminating waste and improving process efficiency through systematic optimization of workflows (Koskela, 2000; Landim et al., 2022). Meanwhile, Building Information Modeling (BIM), as a digital technology, enhances visualization and collaboration in construction processes through three-dimensional(3D) modeling and integrated information management (Landim et al., 2022).

However, existing studies often examine BIM and Lean Construction separately or limit their integration to the tool level, lacking a systematic understanding of their synergistic mechanisms. From a mechanism-oriented perspective, BIM primarily enhances information visibility by transforming implicit construction issues into explicit and manageable data, whereas Lean Construction focuses on constraint removal and process control to reduce non-value-adding activities (Sacks et al., 2010). These two approaches are inherently complementary: BIM addresses

the problem of visibility, while Lean Construction addresses the problem of controllability. Therefore, exploring how BIM can be leveraged under the guidance of Lean Construction theory to identify and reduce construction-phase waste is of significant importance for improving construction management performance.

1.2 Problem Statement

Despite the recognized advantages of BIM and Lean Construction in construction management, several critical issues remain unresolved.

First, the concept of construction-phase waste has not yet been consistently defined. Some studies focus primarily on material waste while overlooking non-physical forms of waste, such as waiting, rework, and information errors. This fragmented understanding limits the systematic identification and management of construction waste (Landim et al., 2022).

Second, BIM applications in the construction phase are often limited to visualization and information management. Its potential for process analysis and waste identification remains underexplored, particularly in identifying workflow conflicts and resource mismatches (Parsamehr et al., 2023).

Third, while Lean Construction emphasizes waste elimination and process optimization, its practical implementation often lacks data-driven support and real-time feedback mechanisms. This limitation reduces its effectiveness in complex and dynamic construction environments (Sacks et al., 2010).

Finally, although some studies have attempted to integrate BIM and Lean Construction, most efforts remain at a superficial level, focusing on tool integration rather than mechanism-level synergy. For example, BIM is frequently used to support construction planning without fully leveraging its capability to systematically optimize construction waste through integration with Lean principles (Landim et al., 2022).

Based on these gaps, this study raises the following central research question: How can BIM be effectively utilized, under the guidance of Lean Construction theory, to reduce construction-phase waste?

1.3 Research Objectives

Based on the identified research gaps, the overall objective of this study is as follows: This study aims to explore systematic methods and pathways for reducing construction-phase waste through the application of BIM under the guidance of Lean Construction theory.

To achieve this objective, the specific research objectives are:

To investigate how BIM can be applied to reduce typical types of construction-phase waste.

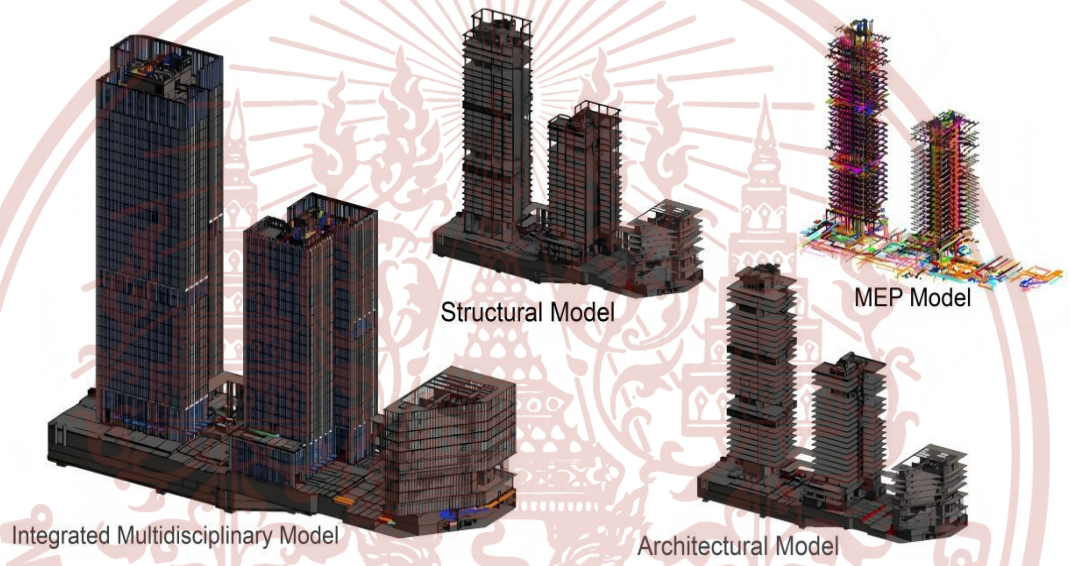


Figure 1-1 illustrates the integration of multi-disciplinary models in BIM

As shown in Figure 1-1, BIM is a 3D digital approach for integrating building information across multiple disciplines, including architecture, structure, and mechanical, electrical, and plumbing (MEP) systems. Its core principle lies in integrating these discipline-specific models into a unified digital model, enabling information sharing and coordination among project stakeholders.

In traditional practices, design information is fragmented across separate drawings, forming "information silos," which hinder the early detection of design conflicts and delay information transmission. By establishing a unified information platform, BIM enables all participants to collaborate on a shared model, allowing design conflicts to be identified and resolved before construction begins, thereby reducing rework, waiting, and information-related waste during the construction phase (Sacks et al., 2018; Landim et al., 2022).

1.4 Research Questions

Guided by Lean Construction theory, this study addresses the following research questions:

1、 What are the main types of construction-phase waste, and what are their essential characteristics?

2、What are the core functions of BIM in the construction phase, and how do these functions support waste identification and prevention?

3、 How can BIM be effectively applied to reduce typical construction-phase waste?

1.5 Research Significance

This study contributes to both theoretical development and practical application.

From a theoretical perspective, this research systematically defines and classifies construction-phase waste (Koskela, 2000; Koskela et al., 2013; Bølviken et al., 2014), thereby extending existing waste classification frameworks. Furthermore, it focuses on the application of BIM in identifying and reducing construction-phase waste, clarifying the underlying mechanisms through which BIM contributes to waste reduction and providing a new theoretical perspective for BIM-based construction management (Sacks et al., 2010; Sacks et al., 2018; Landim et al., 2022).

From a practical perspective, this study employs comparative case analysis to demonstrate the effectiveness of BIM in reducing construction-phase waste. The findings provide actionable guidance for construction enterprises in selecting and implementing BIM technologies during both design and construction stages, ultimately improving process controllability and operational efficiency (Peshkov & Guevara Rada, 2022; Parsamehr et al., 2023).

1.6 Thesis Structure

This thesis consists of six chapters, organized as follows:

Chapter 1: Introduction Presents the research background, problem statement, objectives, research questions, and significance, and outlines the overall research framework.

Chapter 2: Literature Review Reviews the concepts and classifications of construction-phase waste, BIM applications in construction, Lean Construction theory, and existing BIM–Lean integration studies, identifying research gaps.

Chapter 3: Methodology Describes the research methods, including literature analysis, comparative case study, and framework development, and outlines the research process.

Chapter 4: BIM–Lean-Based Framework for Construction-Phase Waste Optimization Develops a mapping framework linking BIM functionalities with types of construction-phase waste and their corresponding reduction pathways.

Chapter 5: Mechanism Analysis of BIM–Lean Synergy Analyzes the underlying mechanisms of BIM-enabled waste reduction from the perspectives of functional complementarity, theoretical explanation, and feedback loops.

Chapter 6: Conclusions and Future Work Summarizes the key findings, highlights contributions, discusses limitations, and suggests directions for future research.

พระจอมเกล้าพระนครเหนือ
มหาวิทยาลัยเทคโนโลยี

Chapter 2

Literature Review

2.1 Concept and Characteristics of Construction-Phase Waste

Construction-phase waste is generally defined as any non-value-adding activity that consumes resources without contributing to project value. This definition originates from lean production theory and has been widely adopted in construction research (Koskela, 2000; Ohno, 1988). Early studies primarily equated construction waste with material loss or physical debris (Bajjou & Chafi, 2022). However, such a narrow interpretation fails to capture the systemic and multi-dimensional nature of waste in construction environments.

Unlike manufacturing, construction projects exhibit higher complexity, variability, and interdependence among processes. As a result, construction-phase waste extends beyond physical inefficiencies to include losses embedded in information flows, coordination processes, and time-related disruptions. This shift reflects a broader understanding that waste in construction is not merely a material issue but a systemic phenomenon.

From a theoretical perspective, the seven categories of waste proposed by Ohno(1988)—waiting, defects, transportation, motion, inventory, over-processing, and overproduction—provide a foundational framework. However, directly applying this classification to construction contexts is insufficient due to the dynamic and fragmented nature of construction processes.

For instance, waiting waste is one of the most prevalent forms in construction, often caused by delays in materials, drawings, equipment, or preceding activities. Unlike manufacturing, where waiting is often process-driven, construction waiting is strongly influenced by planning instability and information delays, resulting in persistent workflow interruptions (Bajjou & Chafi, 2020).

Similarly, rework and defects, while conceptually aligned with manufacturing defects, have broader implications in construction. Design inconsistencies, coordination errors, and execution deviations frequently trigger cascading effects, leading to systemic inefficiencies rather than isolated defects (Michaud et al., 2021; Mitera-Kiełbasa & Zima, 2025). Specifically, Mitera-Kiełbasa and Zima (2025) identified 34 waste factors, with design errors being the most critical source of construction waste, while Michaud et al. (2021) developed a taxonomy of waste sources in BIM information flows and discussed their consequences, including rework and losses in time

and productivity.

At the resource flow level, transportation and motion waste are significantly influenced by the spatial and dynamic characteristics of construction sites. Unlike controlled manufacturing environments, construction sites involve constantly changing layouts, which amplify inefficiencies in material handling and worker movement (Kumar & Cheng, 2015; RazaviAlavi & AbouRizk, 2021).

Inventory and work-in-progress (WIP) waste also exhibit unique characteristics. Excessive accumulation of unfinished work not only occupies space but also masks underlying process inefficiencies, thereby disrupting workflow continuity.

In addition, over-processing and overproduction in construction differ from their manufacturing counterparts. Over-processing often manifests as unnecessary procedures or excessively high construction standards, while overproduction typically appears as premature execution of tasks before conditions are fully ready, increasing the risk of rework.

To address these limitations, Koskela (2004) introduced the concept of "making-do" as an additional category of waste, referring to situations where work proceeds despite insufficient resources or information. This form of waste is particularly critical in construction, as it often acts as a trigger for multiple downstream inefficiencies, including rework, delays, and quality defects.

More recent studies emphasize the role of information-related waste. In contrast to traditional lean theory, which focuses on physical processes, construction projects are highly dependent on information exchange, making information errors, delays, and coordination failures significant sources of waste (Tribelsky & Sacks, 2010; Waheed et al., 2025). Waheed, Khodeir and Fathy (2025) specifically investigated the integration of sustainability and lean approaches for architecture design management, demonstrating that information flow disruptions—such as design version inconsistencies and delayed responses to information requests—directly contribute to project inefficiencies.

Based on this analysis, construction-phase waste can be systematically classified into nine categories. Importantly, this classification is not a simple extension of traditional lean categories but is structured along two fundamental dimensions:

Process dimension (waiting, transportation, motion, inventory, over-processing,

overproduction)

Hybrid dimension (defects, making-do);

Information dimension (information waste).

Empirical evidence from a Chinese prefabricated housing project provides an example for applying this dual-dimensional classification. Cao and Guo (2025) used lean value stream analysis to identify and eliminate waste across the construction lifecycle. In their case study, on-site labor efficiency increased from 60% to 88%, while the supply-chain response delay rate decreased from 25% to 8%. The study also integrated BIM and the Internet of Things (IoT) data fusion with a Plan–Do–Check–Act (PDCA) error-control cycle to support dynamic coordination and reduce rework. Within this study's classification, supply-chain response delays can be categorized as process-related waste, rework as hybrid waste, and BIM–IoT data integration as information-related waste.

This dual-dimensional classification highlights a critical insight: BIM primarily addresses information-related waste through enhanced visibility, while Lean Construction targets process-related waste through flow optimization.

Table 2-1 Comparison of Construction-Phase Waste Types and Characteristics

Waste Type	Manifestation in Construction Phase	Causes	Typical Impacts	Differences from Traditional Lean	References
Waiting	Waiting for materials, drawings, equipment, approvals, or preceding tasks	Discontinuous processes	Schedule delays	More strongly influenced by information delays and unstable planning	Bajjou & Chafi, 2020
Defects	Construction errors, quality issues, design changes	Design errors / quality problems	Increased costs	Often leads to cascading rework chains and systemic impacts	Sacks et al., 2010; Mitera-Kiełbasa & Zima, 2025
Transportation	Repeated material handling, on-site relocation	Poor site layout	Reduced efficiency	Strongly affected by spatial constraints and site organization	Sacks et al., 2010; Toca Pérez & Bastos Costa, 2021
Motion	Frequent worker movement, searching for tools	Inefficient work organization	Time waste	Highly dependent on site layout and task design	Mitera-Kiełbasa & Zima, 2025

Table 2-1 Comparison of Construction-Phase Waste Types and Characteristics(CONTINUED)

Waste Type	Manifestation in Construction Phase	Causes	Typical Impacts	Differences from Traditional Lean	References
Inventory	Material accumulation, excessive unfinished work	Push-based production	Resource occupation	WIP disrupts workflow continuity and masks underlying issues	Mitera-Kiełbasa & Zima, 2025
Over-processing	Redundant procedures, unnecessary high construction standards	Unclear standards	Time waste	Often related to quality control or management redundancy	Marhani et al., 2022
Overproduction	Premature construction, early fabrication or installation	Poor planning control	Increased inventory	Reflects improper sequencing rather than excess quantity	Moradi & Sormunen, 2023
Making-do	Work performed under insufficient conditions	Lack of information / resources	Rework risk	acts as an upstream trigger for other wastes	Koskela, 2004

Table 2-1 Comparison of Construction-Phase Waste Types and Characteristics(CONTINUED)

Waste Type	Manifestation in Construction Phase	Causes	Typical Impacts	Differences from Traditional Lean	References
Information Waste	Information errors, poor communication, delayed decisions	Insufficient coordination	Decision errors	Belongs to information-flow waste; combination of multiple waste types	Michaud et al., 2021; Tribelsky & Sacks, 2010

Table 2-1 provides a systematic comparison of the major types of construction-phase waste. As shown in the table, different types of waste vary in their manifestations and underlying causes; however, all of them negatively affect construction efficiency and overall project performance. The first seven categories are derived from the classical framework proposed by Ohno (1988), while "making-do" originates from the extension introduced by Koskela (2004). Information waste, in contrast, represents a more recent category that has emerged from studies focusing on information flow in construction processes.

2.2 Formation Mechanism of Construction-Phase Waste

Construction-phase waste does not occur in isolation but emerges from the interaction of multiple internal elements within the construction system. Recent studies increasingly recognize that non-value-adding activities on construction sites are typically associated with unstable process organization, distorted information transmission, and imbalanced resource allocation. These factors are often coupled, forming a complex waste generation mechanism (Sacks et al., 2010). Therefore, understanding construction waste cannot be limited to surface-level typology identification but requires in-depth analysis of its formation mechanisms.

From a process perspective, construction activities often fail to achieve continuous and stable working conditions. This lack of flow directly leads to waiting, inventory accumulation, overproduction, and other such problems (Koskela, 2000). Koskela (1992), in his technical report,

was the first to conceptualize the construction system as a "flow" system, emphasizing that flow continuity is the core of construction efficiency. In practice, however, due to unreasonable task decomposition, poor process coordination, and insufficient planning reliability, different processes struggle to maintain a stable rhythm, causing resources to frequently remain idle or become accumulated during construction (Ballard & Tommelein, 2021). Typical manifestations of process instability include: idle workspaces due to lack of effective connections between processes; resource accumulation caused by premature task initiation; and construction interruptions resulting from frequent schedule adjustments.

From an information perspective, the formation of construction-phase waste is closely related to instability in information flow. Construction projects typically involve multi-stakeholder collaboration, with information being frequently transmitted among different parties. However, problems such as incomplete information, version inconsistencies, and communication delays often affect the accuracy and timeliness of construction decisions, thereby triggering various forms of waste including rework, waiting, and quality defects (Tribelsky & Sacks, 2010; Mitera-Kiełbasa & Zima, 2025).

The formation mechanism of information distortion can be understood across three stages:

Information generation stage: design errors or missing information.

Information transmission stage: inconsistent drawing versions, delayed responses to requests for information (RFI).

Information reception stage: task execution based on incorrect information.

These three stages collectively create a chain of inefficiencies that propagate throughout the construction process (Tribelsky & Sacks, 2010).

From the perspective of resources and site conditions, mismatches between resources and site conditions are also a significant cause of construction-phase waste. In practice, materials, equipment, and working conditions often fail to achieve effective alignment with construction tasks, forcing construction activities to proceed despite insufficient preparation (Koskela, 2004). This phenomenon manifests in construction management as "making-do" (working under insufficient conditions), which often results in problems being transferred to subsequent processes and triggers cascading effects including rework, defects, and reduced efficiency.

It is important to note that the above factors do not exist independently but interact dynamically to form the systemic characteristics of construction-phase waste. The formation of construction waste can be summarized as a chain reaction: "process instability ⟶ information distortion ⟶ resource mismatch". This multi-factor coupling results in significant cascading and amplifying effects in construction-phase waste. Therefore, analysis of construction-phase waste cannot be confined to a single dimension but requires a comprehensive understanding from three perspectives: process, information, and resources.

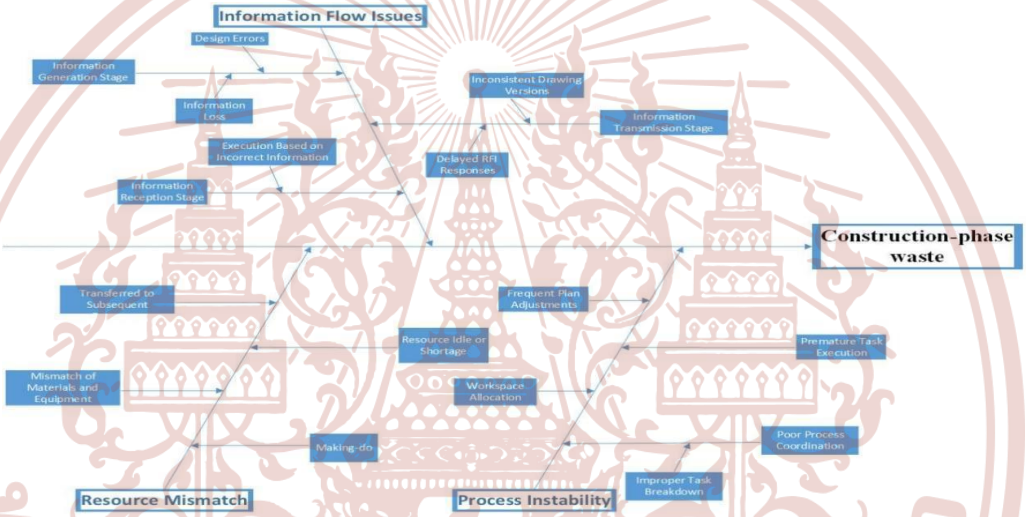


Figure 2- 1 Mechanism of Construction Waste Formation

Figure 2-1 illustrates that construction waste primarily originates from three core factors: process instability, information distortion, and resource mismatch. These factors do not operate independently; rather, they interact dynamically and reinforce each other throughout the construction process.

As construction activities progress, the interaction among these factors amplifies inefficiencies, leading to the accumulation of non-value-adding activities and the emergence of systemic waste.

In summary, the essence of construction-phase waste can be understood as the combined result of "blocked flow, distorted information, and mismatched resources" during the operation of the construction system. Process instability leads to waste from waiting and inventory; information problems trigger rework and decision delays; and insufficient resources or conditions further amplify various types of waste through "making-do" (working under insufficient preparation). This

systematic analysis indicates that no single method can effectively solve construction waste problems; instead, holistic analysis and optimization are required. This conclusion provides a theoretical foundation for subsequent BIM-based waste identification and lean optimization—BIM can enhance information transparency and process visualization, addressing the "visibility" problem, while Lean Construction can block the chain reaction of waste through process control and resource coordination, addressing the "controllability" problem.

2.3 Applications of BIM in the Construction Phase

In the development process of Building Information Modeling (BIM), its application in the construction phase is no longer limited to serving as a 3D modeling tool but has gradually evolved into a digital control platform for construction management (Sacks et al., 2018). Recent review studies generally agree that the most mature and common BIM applications in the construction phase are concentrated in four directions: 3D visualization and multi-disciplinary coordination, Four-Dimensional (4D) schedule planning and construction time management, construction process monitoring and progress verification, and integrated management of construction information and resources (Parsamehr et al., 2023). Related research further indicates that BIM primarily supports core management tasks in construction, including schedule, cost, quality, and safety management, while significantly enhancing visualization levels, improving communication and coordination, and optimizing construction scheduling (Sacks et al., 2018).

From a mechanism perspective, the core function of BIM can be summarized as an information visualization mechanism—transforming implicit construction issues into explicit, analyzable information (Sacks et al., 2010). This mechanism provides the data foundation for subsequent lean optimization.

1、 Time-Space Information Integration

4D BIM is widely recognized as a key application form most directly embedded in construction site management (Sacks et al., 2018). By linking construction schedule tasks with 3D models, 4D BIM enables dynamic simulation of the construction process, thereby improving construction logistics decision-making and project delivery efficiency (Doukari et al., 2022). This expression of time-space coupling allows construction teams to more intuitively identify process logic dependencies, construction sequence conflicts, and potential planning gaps, thereby

enhancing the feasibility and reliability of construction schedules. From a mechanism perspective, 4D BIM visualizes time-space relationships, helping construction teams identify and manage potential flow interruptions (Sacks et al., 2018; Doukari et al., 2022).

2、 Multi-Disciplinary Information Integration

In terms of quality control and rework management, one of the core applications of BIM is clash detection and construction deviation identification. Research indicates that BIM-based design clash detection can significantly reduce conflicts during the construction phase and yield quantifiable cost savings (Sacks et al., 2018; Chahrour et al., 2021). If these issues are not identified before construction, they often transform into costly rework problems during the construction process. From a mechanism perspective, clash detection makes spatial conflicts visible and helps project teams resolve them during the design stage.

3、 Construction Process Monitoring

In terms of construction execution monitoring, BIM is gradually being integrated with on-site data acquisition technologies, such as laser scanning and computer vision, to identify "planned-actual" deviations during the construction process (Bosché et al., 2015). By comparing on-site visual or scan data with BIM models, automated identification of construction progress and deviation analysis can be achieved. In complex construction scenarios such as MEP installation, it is also possible to identify installation deviations, component misalignments, and omitted processes, thereby revealing rework and efficiency losses hidden within the construction process (Bosché et al., 2014, 2015).

4、 Information Integration and Collaboration

In terms of information management and collaboration, BIM effectively reduces distortion and delays in information transmission by building a unified information platform. Research indicates that BIM-based collaborative environments can significantly reduce problems such as inconsistent drawing versions, missing information, and poor communication, thereby reducing waiting and rework caused by information errors (Jaskula et al., 2025; Seyis & Ozkan, 2024) . From a mechanism perspective, BIM achieves an "information consistency mechanism" through a Common Data Environment (CDE), establishing a single source of information (Jaskula et al., 2025).

5、 Construction Site Organization and Resource Allocation

In terms of construction site organization and resource allocation, BIM facilitates the identification of transportation path and resource mismatch problems through visual analysis of site layout and resource allocation (Kumar & Cheng, 2015; Akinci et al., 2002). Furthermore, by linking component information with construction schedules, BIM can also identify problems such as material accumulation, resource mismatches, and excessive work-in-progress, thereby reducing inventory-related waste (Bortolini et al., 2019).

Table 2-2 Mechanism Analysis of BIM in Waste Identification during the Construction Phase

BIM Function	Identifiable Waste Types	Identification Mechanism	Corresponding Problem Manifestation	References
3D Visualization & Multi-disciplinary Coordination	Rework/Defects, Information Waste	Spatial Conflict Visualization	Drawing conflicts, installation errors	Chahrour et al. (2021)
4D BIM Schedule Simulation	Waiting, Overproduction	Time-Space Information Visualization	Process conflicts, workspace overlaps	Doukari et al. (2022)
Construction Progress Monitoring	Waiting, Rework, Inventory	Planned-Actual Deviation Identification	Schedule delays, repeated construction	Bosché et al. (2015)
BIM Information Integration Platform	Information Waste, Waiting	Information Consistency Mechanism	Information errors, communication delays	Jaskula et al. (2025)
Site Layout & Construction Simulation	Transportation, Motion	Spatial Layout Visualization	Material re-handling, path conflicts	Bortolini et al. (2019)

Table 2-2 Mechanism Analysis of BIM in Waste Identification during the Construction Phase

(CONTINUED)

BIM Function	Identifiable Waste Types	Identification Mechanism	Corresponding Problem Manifestation	References
Construction Resource & Component Management	Inventory, Overproduction	Resource Status Visualization	Material accumulation, excessive WIP	Bortolini et al. (2019)

Table 2-2 illustrates how Building Information Modeling integrates spatial, temporal, and informational dimensions of construction processes through functionalities such as visualization, information integration, and schedule simulation, thereby enabling information visibility.

Specifically, 4D BIM is primarily used to identify waiting-related issues and process conflicts within construction workflows. Clash detection focuses on identifying design conflicts that may lead to rework and defects. Information integration, supported by unified data environments, addresses information-related waste by ensuring consistency and accessibility of project data.

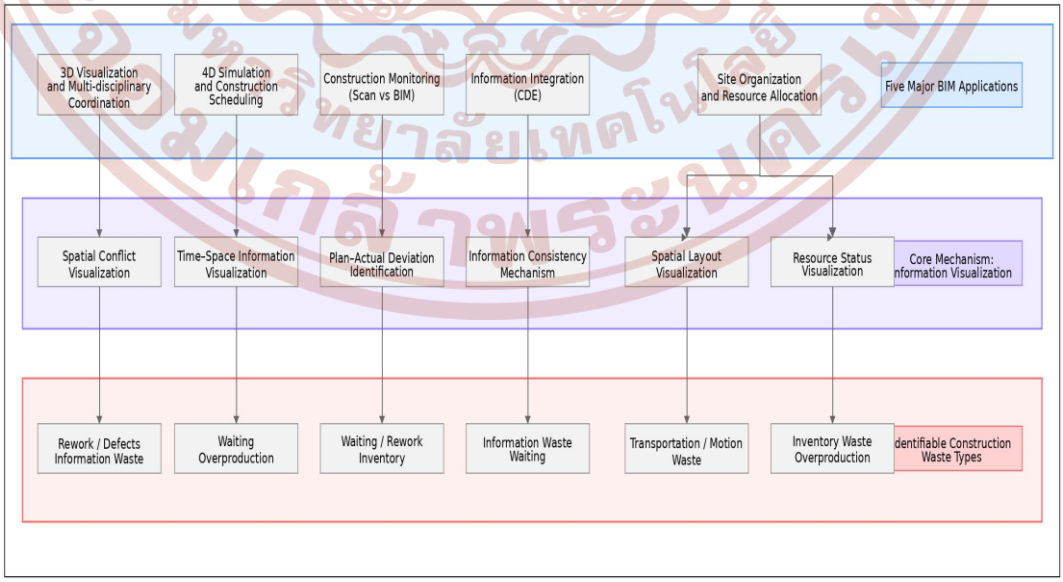


Figure 2- 2 Framework of BIM Applications in the Construction Phase

Figure 2-2 presents the main applications of BIM during the construction phase, including.

3D visualization

Multi-disciplinary coordination

4D schedule simulation

Information integration

These functionalities provide both visual and data-driven support for construction management, enabling early identification of potential issues and improving decision-making processes.

By making construction processes more transparent and analyzable, BIM allows problems to be identified and addressed proactively rather than reactively.

This framework demonstrates that BIM serves as a foundational technology for transforming fragmented construction information into an integrated and actionable system, thereby supporting systematic waste identification.

2.4 Application of Lean Construction in the Construction Phase

Under the guidance of Lean Construction principles, construction management has gradually shifted from traditional experience-driven practices to a systematic approach centered on process optimization and value creation (Koskela, 2000). Recent studies consistently demonstrate that the application of Lean Construction in the construction phase can significantly enhance overall project performance, particularly in terms of improved productivity, waste reduction, enhanced construction quality, and increased reliability of project delivery (Melo et al., 2017; Ballard & Tommelein, 2021).

From a mechanism perspective, the core function of Lean Construction can be summarized as a combination of constraint removal and process control, which aims to reduce non-value-adding activities and improve the stability of construction systems (Melo et al., 2017; Ballard & Tommelein, 2021).

1、 Last Planner System (LPS) and Constraint Removal

In terms of improving production efficiency, Lean Construction enhances workflow continuity and stability by minimizing non-value-adding activities and optimizing construction processes. Studies on the LPS indicate a strong positive correlation between planning reliability

and project performance. As the Percent Plan Complete (PPC) increases, construction efficiency and project execution outcomes improve accordingly (Kim et al., 2015).

The fundamental mechanism of LPS lies in constraint removal. Before tasks are scheduled, LPS ensures that all necessary preconditions are satisfied, allowing only ready tasks to be executed, thereby effectively preventing the "making-do phenomenon identified by Koskela (2004), where work proceeds despite insufficient resources or information (Ballard, 2000). Recent research demonstrates that integrating LPS with BIM can significantly reduce tasks performed under making-do conditions and minimize construction waste (Karaz et al., 2024).

2、 Value Stream Mapping (VSM) and Process Optimization

VSM is a key tool for identifying non-value-adding activities in construction processes (Rother & Shook, 2003). By mapping the entire workflow and distinguishing between value-adding and non-value-adding activities, VSM enables the systematic elimination of redundant procedures, unnecessary approvals, and inefficient process steps. Research indicates that VSM implementation can effectively reduce lead time and material waste in construction projects (Vilventhan et al., 2019; Rosenbaum et al., 2014).

The essence of VSM lies in process transparency, making waste visible and measurable, thereby facilitating targeted process improvement (Rother & Shook, 2003; Rosenbaum et al., 2014).

3、 Just-in-Time (JIT) and Supply–Demand Matching

JIT production focuses on synchronizing resource supply with actual demand to minimize inventory and resource waste. Its core principle is to deliver materials only when needed, avoiding early supply and accumulation.

By integrating BIM models with construction schedules, JIT can achieve precise, demand-driven material delivery, ensuring that resource flows are aligned with construction activities (Ocheoha & Moselhi, 2013). Research on prefabricated construction demonstrates that BIM-enabled tracking systems can achieve real-time visibility of logistics status and enable JIT delivery coordination between factories and construction sites (Zhong et al., 2017; Ocheoha & Moselhi, 2013).

The fundamental mechanism of JIT is supply–demand matching, which ensures that resources are provided in the right quantity at the right time.

4、 Standardized Work and Process Consistency

Standardized work improves consistency in construction operations by unifying construction methods, workflows, and quality standards. This reduces variability caused by human factors and minimizes operational errors.

When rework occurs, Lean Construction emphasizes root cause analysis (RCA) to identify the underlying causes of problems. Combined with continuous improvement (CI), this approach helps prevent the recurrence of similar issues.

The essence of standardized work lies in achieving process consistency, transforming individual experience into systematic and repeatable practices (Fireman et al., 2018).

5、 5S Management and Spatial Organization

5S management (Sort, Set in order, Shine, Standardize, Sustain) improves site organization by promoting a cleaner and more orderly work environment.

A case study of 5S implementation at a construction site reported improved workflow, reduced material waste and non-value-adding activities, and a more organized and safer workplace (Anjos & Oliveira, 2018). This suggests that workplace organization can help create a more structured and efficient construction site.

Table 2-3 Mapping of Lean Tools, Waste Types, and Effects

Lean Tool	Main Function	Corresponding Waste Types	Mechanism	Effect	References
Last Planner System (LPS)	Improve planning reliability	Waiting, Overproduction	Constraint removal	Reduces waiting, improves execution efficiency	Kim et al., 2015; Karaz et al., 2024
Value Stream Mapping (VSM)	Identify non-value-adding activities	Waiting, Motion, Transportation	Process optimization	Optimizes workflow, reduces waste	Vilventhan et al., 2019; Rosenbaum et al., 2014

Table 2-3 Mapping of Lean Tools, Waste Types, and Effects(CONTINUED)

Lean Tool	Main Function	Corresponding Waste Types	Mechanism	Effect	References
Just-in-Time (JIT)	Optimize resource supply	Inventory, Waiting	Supply-demand matching	Reduces inventory and material waste	Ocheoha & Moselhi, 2013
Continuous Improvement (CI)	Continuously optimize construction processes	Defects	Process consistency	Improves quality, reduces rework	Zhang et al., 2012
5S Management	Optimize site layout	Transportation, Motion	Spatial reorganization	Reduces transportation and motion waste	Anjos & Oliveira, 2018

Table 2-3 demonstrates how Lean Construction exerts an integrated effect in the construction phase through a range of management tools.

At a fundamental level, these tools can be interpreted as different types of process control mechanisms, each targeting specific sources of inefficiency within construction workflows.

Specifically:

The LPS enables constraint removal, ensuring that tasks are executed only when prerequisite conditions are satisfied.

VSM enhances process transparency, making non-value-adding activities visible within construction workflows.

JIT establishes supply–demand matching, aligning resource delivery with actual construction needs.

Standardized work ensures process consistency, reducing variability and improving quality

stability.

5S management achieves spatial order restructuring, optimizing site layout and minimizing unnecessary movement.

Together, these mechanisms form a systematic approach to process control, enabling Lean Construction to reduce non-value-adding activities and improve overall construction performance.

Despite its advantages, Lean Construction also faces practical challenges. Researchers suggest that the lack of data support and visualization tools limits the effectiveness of Lean methods in complex construction environments. Fragmented coordination, resistance to cultural change, and misalignment of contract systems remain significant barriers to Lean implementation across multi-stakeholder projects (Moradi & Sormunen, 2024).

This limitation highlights the necessity of integrating Lean Construction with digital technologies such as BIM, enabling a complete cycle from waste identification to waste elimination. Studies demonstrate that integrating LPS with BIM can achieve significant cost reduction and completion rate improvement (Karaz et al. (2024). The synergistic integration of Lean Construction with BIM and sustainability can overcome common challenges related to safety, reliability, productivity, collaboration, and quality in construction projects (Moradi & Sormunen, 2024).

2.5 Integration of BIM and Lean Construction

In recent years, researchers have increasingly recognized the inherent complementarity between Building Information Modeling (BIM) and Lean Construction, leading to a growing body of studies exploring their integrated application in construction management. Sacks et al. (2010) conducted a matrix-based analysis and identified 56 interactions between BIM functionalities and Lean principles, the majority of which were found to be positively synergistic. This seminal work established a systematic theoretical foundation for BIM–Lean integration. Subsequent studies have further validated the effectiveness of this synergy in practical construction contexts (Dave et al., 2013; Pedo et al., 2021).

From a mechanism perspective, the complementarity between BIM and Lean Construction can be understood in terms of their distinct but interrelated functional roles. BIM primarily enhances information visibility by transforming implicit construction issues into explicit,

analyzable data, thereby addressing the problem of "visibility." In contrast, Lean Construction focuses on constraint removal and process control, addressing the problem of "controllability" (Sacks et al., 2010; Dave et al., 2013; Pedo et al., 2021). When integrated, BIM and Lean Construction enable a dual-mechanism system that simultaneously improves visibility and controllability, forming the basis for systematic waste reduction in construction processes.

1、 BIM-Enabled LPS

The LPS is a core planning and control tool in Lean Construction, whose effectiveness depends on accurate and timely information regarding task status and constraints. Research indicates that integrating BIM with LPS enables automatic updating of task progress, visualization of constraints, and dynamic monitoring of PPC, thereby improving planning reliability (Sacks et al., 2010; Dave et al., 2013; Schimanski et al., 2020).

For example, through 4D BIM models, construction teams can visually identify unmet preconditions for tasks, allowing for more accurate selection of "ready-to-execute" activities during weekly planning. This integration shifts LPS from experience-based planning to data-driven decision-making, significantly enhancing workflow reliability (Schimanski et al., 2020).

2、 BIM-Enabled VSM

VSM is widely used to identify non-value-adding activities in construction processes. However, traditional VSM relies heavily on manual observation and estimation, limiting its accuracy.

Studies show that integrating BIM with VSM allows for the extraction of detailed process data, including task durations, resource flows, and waiting times, directly from BIM models (Dantas Filho et al., 2017). This enables the development of more precise and data-driven value stream maps, improving the identification and quantification of waste.

As a result, waste identification evolves from subjective judgment to objective, data-supported analysis, enhancing the effectiveness of process optimization.

3、 BIM-Enabled Pull Production and JIT

The implementation of pull production and JIT systems relies on accurate demand forecasting and real-time status tracking. Research indicates that BIM can support these requirements by linking component information with construction schedules, enabling precise,

demand-driven resource management (Sacks et al., 2010; Ocheoha & Moselhi, 2013).

For instance, when a BIM model indicates that a component is approaching installation, procurement or delivery processes can be automatically triggered, ensuring timely material supply. This integration minimizes inventory levels and reduces the risks associated with premature production and material accumulation (Ocheoha & Moselhi, 2013).

4、 BIM-Enabled CI

CI depends on the systematic collection and analysis of problem-related data (Liker, 2004; Koskela, 2000). Studies suggest that BIM can function as an effective data platform for CI by recording deviations, rework events, and delays throughout the construction process (van der Veen et al., 2021; Pedo et al., 2021).

Through BIM-based visualization and traceability, construction teams can retrospectively analyze process inefficiencies and identify root causes more effectively. This capability enhances the feedback loop within construction systems, enabling continuous learning and process refinement.

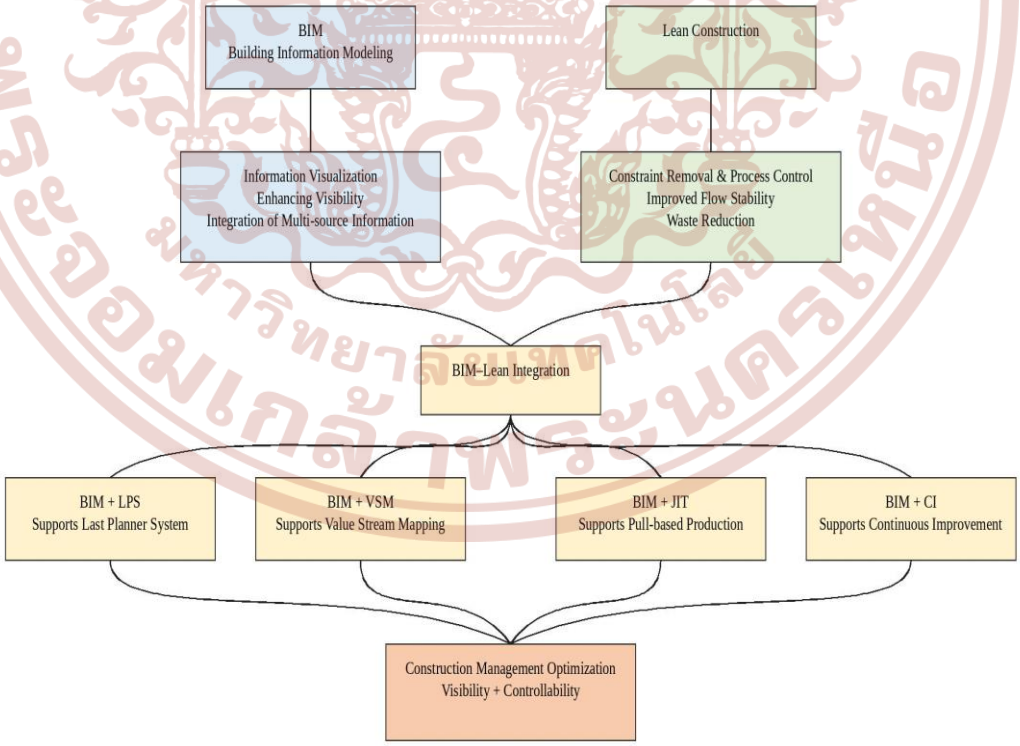


Figure 2- 3 Relationship between BIM and Lean Construction

Figure 2-3 illustrates the relationship between Building Information Modeling (BIM) and Lean Construction. BIM primarily supports problem identification and information integration by enabling information visualization, thereby enhancing the visibility of construction processes. In contrast, Lean Construction focuses on process optimization and waste reduction through mechanisms such as constraint removal and process control. Through their complementary and integrated application, BIM and Lean Construction jointly contribute to the systematic optimization of construction management.

Overall, the integration of BIM and Lean Construction establishes a closed-loop mechanism in which construction waste is first identified through enhanced information visibility and subsequently reduced through process optimization and control.

2.6 Literature Review Summary and Research Gaps

A systematic review of the existing literature reveals that significant progress has been made in the areas of construction-phase waste, BIM applications, Lean Construction, and their integration. However, several critical limitations remain, highlighting the need for further research.

First, the classification of construction-phase waste remains inconsistent. Different studies adopt varying definitions and frameworks, with some still confined to the traditional seven waste categories derived from manufacturing. Such approaches often fail to fully capture the unique characteristics of construction environments. Although Koskela (2004) introduced "making-do" as an eighth category, information and collaboration-related waste have yet to be widely recognized as independent categories, limiting the comprehensiveness of existing classification systems.

Second, the depth of integration between Building Information Modeling and Lean Construction remains insufficient. Most studies focus on tool-level integration, treating BIM as an information support system and Lean Construction as a management methodology, without fully exploring their synergistic mechanisms. Although Sacks et al. (2010) identified 56 interactions between BIM functionalities and Lean principles, these interactions have not been further developed into a systematic and operational integration framework.

Third, there is a lack of comprehensive and systematic frameworks. Existing research often focuses on specific application scenarios, such as schedule management or quality control, rather than addressing construction-phase waste from a holistic perspective. Few studies have developed

integrated frameworks that cover the entire process of waste identification, analysis, optimization, and feedback. Although recent studies have proposed BIM–Lean integrated frameworks, they tend to focus on macro-level perspectives and fail to provide detailed analysis of specific waste types and corresponding optimization strategies.

Fourth, mechanism-based analysis remains underdeveloped. Many studies emphasize what has been implemented and what outcomes have been achieved, but provide limited explanation of why these approaches are effective. The underlying mechanisms through which BIM and Lean Construction jointly influence the formation and reduction of construction-phase waste have not been sufficiently clarified.

In response to the identified gaps, this study takes a system-oriented perspective on construction-phase waste and develops a BIM-enabled framework for waste identification and optimization. Compared with existing research, the main contributions of this study are as follows. First, a mechanism-oriented perspective is adopted to clarify the core functions of BIM and their roles in waste identification and prevention. Second, a mapping framework is established between BIM functionalities and construction-phase waste types, forming a complete pathway from waste identification to waste reduction. Third, for the nine categories of construction-phase waste, specific BIM-enabled identification methods and corresponding optimization pathways are systematically defined. This framework aims to bridge the gap between waste identification and optimization while addressing the lack of systematization in existing studies.

Chapter 3

Methodology

3.1 Overview of Research Methodology

This study aims to explore systematic approaches for reducing construction-phase waste through the application of Building Information Modeling, with a primary focus on theoretical integration and mechanism-based analysis. Accordingly, a qualitative research approach based on literature analysis is adopted (Creswell & Creswell, 2018; Snyder, 2019).

Qualitative research is particularly suitable for exploratory studies that involve complex phenomena, evolving conceptual definitions, and the development of theoretical frameworks (Creswell & Creswell, 2018). In the context of this study, the concept, classification, and formation mechanisms of construction-phase waste have not yet reached full consensus within the literature. In addition, the integrated application of BIM and Lean Construction remains at a developmental stage, with limited availability of well-established and systematic frameworks. Furthermore, existing research provides limited structured guidance on how BIM can be systematically applied to identify and reduce construction-phase waste. Given these conditions, a qualitative, literature-based approach provides an appropriate foundation for theory development and framework construction (Snyder, 2019).

Specifically, this study conducts a systematic review of existing literature on construction-phase waste, BIM applications, and Lean Construction practices, synthesizing and comparing different perspectives across studies (Snyder, 2019). Based on this synthesis, the major categories of construction-phase waste are identified, and their formation mechanisms are analyzed. Building on these insights, the functional characteristics of BIM and Lean Construction are integrated to develop a mapping framework that links BIM functionalities with specific types of construction-phase waste. In addition, comparative case-based analysis is employed to illustrate how BIM contributes to waste reduction in practical construction scenarios (Creswell & Creswell, 2018).

3.2 Justification of the Research Methodology

The selection of literature-based qualitative analysis and conceptual framework development in this study is grounded in several key considerations.

First, the nature of the research questions is theory-driven. The three core research questions

(RQ1–RQ3) primarily address “what” and “how” aspects—namely, the types of construction-phase waste, the role of Building Information Modeling in waste identification, and the ways in which BIM can be applied to reduce such waste. These types of questions are inherently exploratory and conceptual, making them well-suited to theory-based analysis rather than purely empirical investigation.

Second, construction-phase waste exhibits strong systemic complexity. It involves multiple interacting dimensions, including processes, information, and resources, which are closely interrelated. A literature-based approach enables the integration of diverse perspectives and findings across studies, facilitating a comprehensive and system-level understanding of construction-phase waste. Compared with single case studies, this approach provides broader theoretical generalizability.

Third, existing research on BIM applications in the construction phase remains fragmented. Many studies focus on individual BIM functionalities, such as clash detection, 4D simulation, and site layout modeling, without establishing a systematic framework for waste identification and reduction. Through literature synthesis, this study extracts common patterns, identifies research gaps, and consolidates dispersed knowledge into a coherent and structured framework.

Fourth, the adopted methodology enhances transparency and traceability. By clearly defining literature selection criteria, analytical procedures, and framework development steps, the research process follows a structured and logical pathway that improves methodological clarity and reproducibility.

3.3 Alignment between Research Questions and Methods

To ensure methodological rigor and logical consistency, this study establishes a clear alignment between the research questions and the corresponding research methods, as presented in Table 3-1.

Table 3-1 Alignment between Research Questions and Research Methods

Research Question	Research Method	Analytical Content	Corresponding Sections
RQ1: What are the main types of construction-phase waste?	Literature-based inductive analysis	Classification and definition of waste; formation mechanisms	2.1, 2.2
RQ2: What are the core functions of BIM in the construction phase, and how do these functions support waste identification and prevention?	Literature analysis	Identification of BIM functionalities; analysis of mechanisms of action	2.3, 2.5, 4.1
RQ3: How can BIM be effectively applied to reduce typical construction-phase waste?	Theoretical analysis + Comparative analysis	Mapping between BIM functionalities and waste types; case-based comparison	4.1, 4.2, 4.3, 4.4, 4.5, 3.6

As shown in Table 3-1, each research question is addressed through a specific methodological approach, forming a coherent and structured research pathway. RQ1 and RQ2 are primarily addressed through literature-based analysis, which provides the theoretical foundation for identifying construction-phase waste types and understanding the role of Building Information Modeling in waste identification.

RQ3 is addressed through a combination of theoretical analysis and comparative analysis. By integrating conceptual reasoning with case-based comparison, this study demonstrates how BIM can be effectively applied to reduce construction-phase waste in practical scenarios.

This alignment ensures that the research design remains systematic, logically consistent, and directly linked to the study objectives.

3.4 Literature Analysis Method

This study adopts a structured literature analysis approach to systematically review research on construction-phase waste, BIM applications, Lean Construction, and their integration. The

literature analysis process consists of three main stages: literature search, literature screening, and literature analysis and synthesis. This structured process ensures both comprehensive coverage of relevant studies and methodological rigor in the analysis.

3.4.1 Literature Search

Relevant literature was retrieved from multiple authoritative academic databases, including Web of Science (Core Collection), Scopus, Google Scholar, and the China National Knowledge Infrastructure (CNKI). To enhance the completeness and depth of the review, a backward citation tracking approach (snowballing) was also employed to identify influential and foundational studies from the reference lists of highly relevant publications.

A structured keyword system was developed based on the core research themes, including construction waste, BIM, and Lean Construction. To improve search coverage and accuracy, synonyms and related terms were incorporated. For example, "construction waste" was expanded to include "process waste" and "production waste," while "BIM" was expanded to include "Building Information Modeling" and "4D BIM."

Based on these keywords, Boolean logic was applied to construct the search query, where AND was used to connect different research domains and OR was used to include synonymous terms. The search strategy is as follows:

Text

("construction waste" OR "process waste" OR "production waste") AND ("BIM" OR "Building Information Modeling" OR "4D BIM") AND ("lean construction") AND ("waste identification" OR "waste reduction") AND ("framework" OR "integration")

This search strategy enables the identification of studies at the intersection of BIM, Lean Construction, and construction-phase waste, while accommodating variations in terminology.

In addition, foundational studies in Lean Construction (e.g., Koskela, 2004; Ballard, 2000) and key BIM literature (e.g., Sacks et al. 2018; Sacks et al., 2010) were included through targeted reference tracking to ensure theoretical completeness.

3.4.2 Literature Screening

The literature screening process was conducted in two stages.

Stage 1: Title and Abstract Screening

Following the initial search, studies were screened based on titles and abstracts using the following inclusion criteria: (1) the study is directly related to construction-phase waste, BIM, or Lean Construction; (2) the research context is within the construction phase of building projects; and (3) the publication type is a peer-reviewed journal article, review paper, or conference paper.

Exclusion criteria include: (1) studies focused on design or operation phases rather than construction; (2) studies addressing BIM technology development without management application; and (3) studies with weak relevance to the research topic.

Stage 2: Full-Text Review

Studies that passed the initial screening were further evaluated through full-text review. Priority was given to studies that: (1) provide clear classifications or empirical analysis of construction waste; (2) offer detailed descriptions or evaluations of BIM applications in the construction phase; (3) present systematic discussions of Lean Construction tools; and (4) explore the integration of BIM and Lean Construction.

This two-stage screening process ensures that the selected literature is both relevant and representative of the research domain.

3.4.3 Literature Analysis and Synthesis

The selected literature was analyzed using a combination of inductive and comparative approaches.

Inductive Analysis

Inductive analysis was used to identify common patterns and synthesize key concepts from literature. By integrating findings from empirical studies such as Bajjou and Chafi (2020) and drawing on the foundational waste categories proposed by Ohno (1988) and the "making-do" concept introduced by Koskela (2004), this study consolidates existing knowledge to identify nine major categories of construction-phase waste.

Comparative Analysis

Comparative analysis was conducted to examine the roles of Building Information Modeling and Lean Construction in the construction phase. For instance, BIM demonstrates strong capabilities in enhancing information visibility, while Lean Construction is more effective in constraint removal and process optimization. This comparison clarifies their complementary roles

and functional distinctions within an integrated framework.

Through the combined use of inductive and comparative analysis, this study establishes a solid theoretical foundation for the subsequent development of a BIM-enabled framework for construction-phase waste identification and optimization.

3.5 Framework Development Method

Building upon the literature analysis, this study further adopts a conceptual framework development approach to design the collaborative mechanism between Building Information Modeling and Lean Construction.

3.5.1 Applicability of Conceptual Framework Development

Conceptual framework development is a widely used approach in management research, particularly suitable for exploratory studies where theoretical foundations are still evolving and relationships among variables are complex (Jabareen, 2009; Miles et al., 2014).

The primary outcome of this study is a 3D collaborative framework consisting of information integration, process optimization, and performance feedback, involving multiple interrelated constructs, including BIM mechanisms, Lean mechanisms, construction waste, and project performance. Given this complexity, a conceptual framework approach is appropriate for structuring and integrating these elements (Jabareen, 2009).

This study adapts Jabareen's (2009) eight-phase methodology into a five-step procedure tailored to the objectives of this study:

1、 Concept Mapping

Key concepts and their sources are identified, including BIM functionalities, Lean tools, construction-phase waste types, and performance indicators.

2、 Concept Categorization

Concepts are grouped and structured into hierarchical levels, forming three core dimensions: information integration, process optimization, and performance feedback.

3、 Concept Integration

Overlapping concepts are consolidated and clearly defined. BIM functionalities are unified under the mechanism of "information visibility," while Lean tools are categorized under "constraint removal and process control."

4、 Concept Systematization

Relationships among concepts are structured into a network, establishing a closed-loop mechanism of identification ⟶ optimization ⟶ feedback.

5、 Framework Validation （Theoretical Consistency Check）

The internal consistency of the framework is examined through subsequent mechanism analysis.

3.5.2 Framework Development Procedures

The conceptual framework in this study is developed through the following steps:

Step 1: Definition of Core Concepts and Boundaries

Based on the literature review, nine categories of construction-phase waste are defined. BIM functionalities (e.g., 4D simulation, clash detection, CDE, and component status visualization) are identified as enabling an information visibility mechanism, while Lean Construction tools (e.g., LPS, standardized work, 5S, and JIT) are defined as supporting a constraint removal and process control mechanism.

Step 2: Analysis of Conceptual Relationships

The relationships between BIM functionalities and waste types are analyzed in terms of identification capability (e.g., 4D simulation ⟶ waiting waste), while Lean tools are analyzed in terms of optimization capability (e.g., LPS ⟶ reduction of waiting waste).

This analysis establishes a mapping relationship among waste types, BIM mechanisms, and Lean mechanisms.

Step 3: Design of the Collaborative Mechanism

Based on the identified relationships, a BIM–Lean collaborative mechanism is developed. The core mechanism is conceptualized as an information–decision transformation chain, consisting of:

BIM-based information visualization ⟶ constraint identification ⟶ Lean decision-making ⟶ behavioral adjustment ⟶ waste reduction

This process is further embedded within a PDCA cycle to enable continuous improvement.

Step 4: Framework Structuring

The framework is organized into a 3D structure:

Information Integration Dimension (BIM-driven) – enabling information visibility

Process Optimization Dimension (Lean-driven) – enabling constraint removal

Performance Feedback Dimension (Jointly driven) – enabling data-driven learning

These dimensions are interconnected through a PDCA cycle, forming a dynamic and iterative system.

Step 5: Operationalization of Framework Components

The framework is applied to the nine categories of construction-phase waste. For each waste type, BIM-based identification pathways, Lean-based optimization strategies, and their collaborative relationships are explicitly defined.

3.5.3 Framework Validation Logic

As this study is exploratory and theory-oriented, the validity of the proposed framework is assessed in terms of logical coherence and theoretical consistency rather than empirical testing.

Logical Coherence

Each component of the framework is characterized by clearly defined inputs, processes, and outputs, with traceable cause–effect relationships across stages.

Theoretical Consistency

The framework is grounded in established theoretical foundations, including Lean Construction theory (Koskela, 2000; Ballard, 2000) and BIM–Lean integration studies (Sacks et al., 2010). All design decisions are supported by prior research or logical derivation.

This framework represents a theory-building contribution. Future studies may further evaluate and refine the framework through empirical case studies or quantitative validation.

3.6 Case-Based Comparative Analysis

To visually demonstrate the role of BIM technology in reducing waste during the construction phase, this study takes a university construction project as a case example to show the actual application effects of BIM technology. The project adopted BIM technology throughout both the design and construction phases, including multi-disciplinary modeling, clash detection, 4D schedule simulation, collaboration platform, and smart site system. The following sections illustrate through comparative analysis how BIM reduces waste during the construction phase.

3.6.1 Detailed Breakdown of Nine Types of Construction Waste

Before showing how BIM works, let us first list the specific problems that occur on real construction sites. Each waste type is broken down into several concrete examples.

Table 3-2 Detailed Breakdown of Nine Types of Construction Waste

Waste Category	Specific On-Site Examples
1. Waiting	① Waiting for materials: rebar, concrete not arriving on time ② Waiting for drawing updates: design changes not communicated to workers in time ③ Waiting for previous process: waterproofing not dry, cannot proceed to next step ④ Waiting for equipment: tower crane occupied by other crews ⑤ Waiting for approval: process inspection and sign-off delayed
2. Defects	① Clash of pipes: water pipe hits air duct, requiring cutting and rework ② Wrong pre-drilled holes: steel structure bolt holes misaligned with rebar ③ Insufficient clearance: headroom too low after ceiling installation ④ Installation error: curtain wall panels placed in wrong position ⑤ Welding defect: fails non-destructive testing, requires re-welding
3. Transportation	① Repeated handling: rebar moved from storage →processing area → installation point, multiple transfers ② Long on-site travel: concrete mixer truck travels long distance from gate to pouring point ③ Path conflict: transport vehicles blocking each other ④ Poor temporary storage: materials unloaded far from where they are used, requiring secondary handling
4. Motion	① Walking long distances to get tools or materials ② Searching for tools: no fixed place for tools ③ Unnecessary bending/turning: improper workbench height ④ Repetitive movements due to poor layout

Table 3-2 Detailed Breakdown of Nine Types of Construction Waste (CONTINUED)

Waste Category	Specific On-Site Examples
5. Inventory	① Material stacking: rebar, blocks piled up, occupying workspace ② Semi-finished product accumulation: processed but uninstalled steel components stacked excessively ③ Precast components: delivered but not installed for weeks ④ Excess materials in warehouse
6. Over-processing	① On-site cutting and drilling: holes that should be factory pre-drilled are cut on site using gas torch ② Redundant processes: same area reworked multiple times due to quality issues ③ Over-standard requirements: unnecessarily high standards for non-critical areas
7. Overproduction	① Premature construction: crews mobilized before workspace is ready ② Early fabrication: precast components produced months in advance, occupying space and capital ③ Over-ordering: materials purchased based on maximum estimate, resulting in leftover waste
8. Making-do	① Forcing work with incomplete drawings: missing detail drawings, working by guess ② Material substitution: specified rebar not available, using alternative specifications ③ Covering before inspection: concealed work covered without inspection ④ Assigning unfamiliar workers: lack of proper technical briefing

Table 3-2 Detailed Breakdown of Nine Types of Construction Waste (CONTINUED)

Waste Category	Specific On-Site Examples
9. Information Waste	① Inconsistent drawing versions: different crews using different versions of drawings ② Change orders not communicated to all parties ③ Slow problem feedback: taking a photo and sending via WeChat, no follow-up closure ④ Information silos: owner, designer, contractor each using their own systems

3.6.2 Case Analysis of BIM Reducing Construction-Phase Waste

The following sections analyze how BIM reduces construction-phase waste based on the actual application of BIM in the project.

The BIM application records and cost data of this project are not publicly available. Therefore, all cost data presented in this section are based on Shenzhen's current construction pricing standards and are provided for reference only. Actual project costs may vary depending on site conditions, contract terms, and market prices. The standards cited in this section include:

Consumption Standard for Installation Engineering (SJG 74.8-2025),

Consumption Standard for Prefabricated Construction Engineering (SJG 172-2024),

Consumption Standard for Construction Machinery Shift (SJG 174-2024).

1、 Multi-Disciplinary Model Integration and Clash Detection

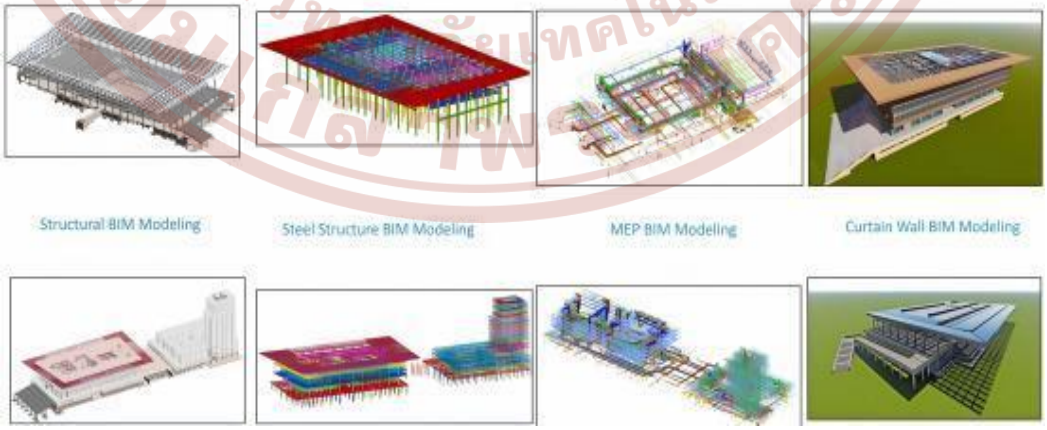


Figure 3-1 Multi-disciplinary BIM Model (Structure, Steel Structure, MEP, and Facade)

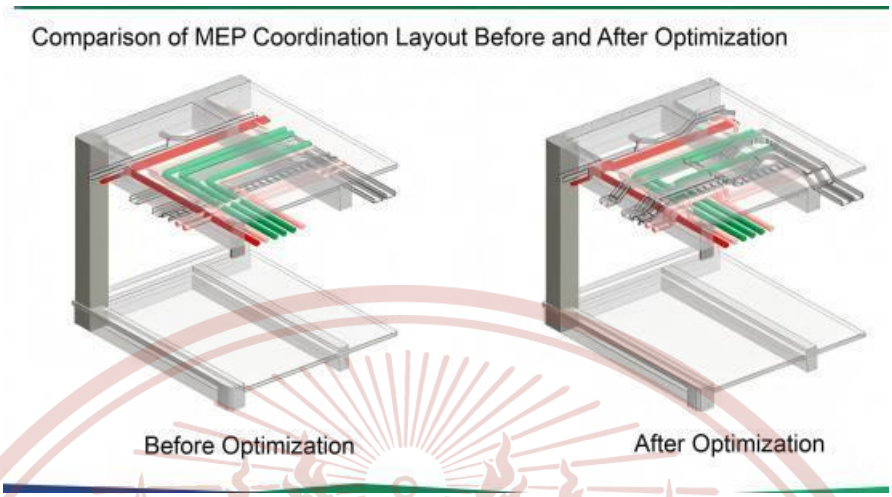


Figure 3-2 Comparison of MEP Layout Before and After Optimization

Figure 3-1 shows the integration of BIM models for four disciplines: structure, steel structure, MEP, and curtain wall. During the design phase, 3D models of different disciplines were integrated into a unified digital environment, and clash detection software was used to automatically identify spatial conflicts between pipes, as well as between pipes and structures. Figure3-2 shows a comparison of MEP coordination layout in a certain area before and after optimization.

BIM enables clash issues among disciplines to be resolved in advance by adjusting the 3D model before construction, avoiding rework waste caused on-site demolition and alteration, while also reducing material waste due to incorrect cutting

Assuming that the clash detection identifies a conflict between a DN100 galvanized steel pipe and other pipelines, requiring the galvanized steel pipe to be relocated, Based on consumption standard for installation engineering (SJG 74.8-2025) under the item for indoor galvanized steel pipe installation (threaded connection), DN80 $<$ DN $\leq$ 100, the full-cost reference unit price in August 2023 was Renminbi (RMB) 1,709.52 per 10 m, equivalent to approximately RMB 171 per meter. This price includes labor, materials, machinery, management fees, profit, temporary measures, statutory fees, and taxes. The actual cost may vary depending on project conditions.

2、 Clearance Analysis and Optimization

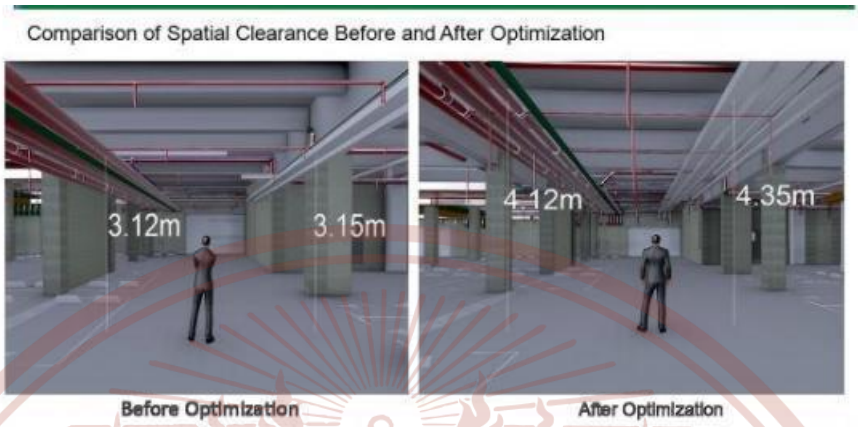


Figure 3-3 Comparison of Clearance Before and After Optimization

Figure 3-3 shows a comparison of corridor clearance before and after optimization. Using the BIM model to perform point-by-point analysis of clearance height for each functional area, areas that do not meet design requirements can be identified in advance. Designers adjust pipe elevations or beam layouts to complete clearance optimization within the model.

BIM enables clearance insufficiency issues to be discovered and resolved before construction, avoiding rework waste caused by demolition and alteration after construction.

Insufficient clearance may result in rework involving several activities, such as ceiling removal, pipeline relocation, material disposal, and reinstallation. The rework cost needs to be calculated by applying the relevant pricing items for each engineering activity. Therefore, the actual comprehensive cost should be calculated based on the specific quantities of work and applicable pricing items, and the actual cost may vary depending on project conditions.

3、 Detailed Design and Prefabrication

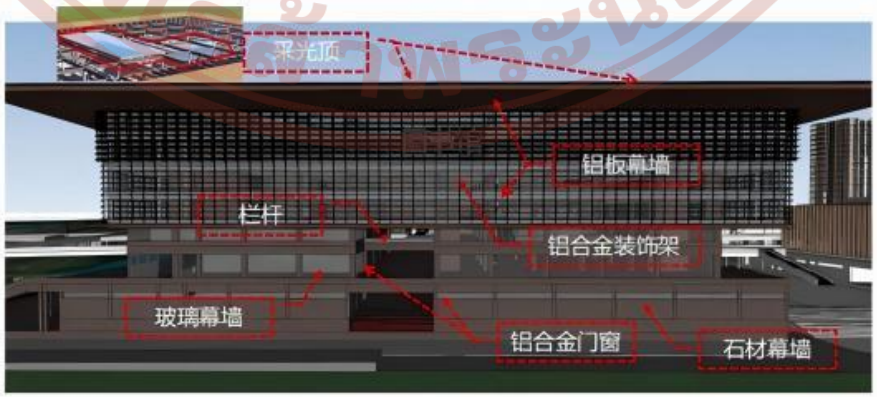


Figure 3-4 BIM Model of the Façade System

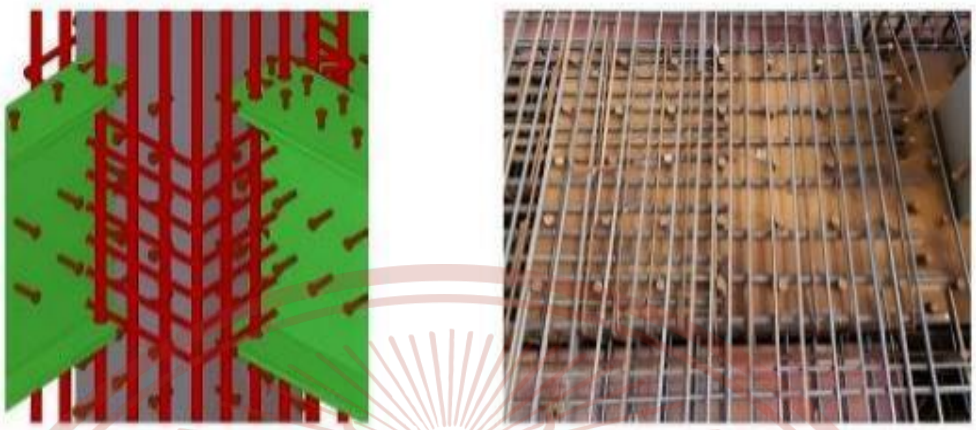


Figure 3-5 Detailed BIM Model of Steel Structure Connections

Figure 3-4 shows the BIM model of the curtain wall system. The model directly generates fabrication drawings for each panel, which are prefabricated in the factory and installed on site according to numbered positions. Figure 3-5 shows the precise positioning of rebar connection sleeves, beam-column rebar penetrations, welded connection plates, and other locations in the steel structure BIM detailed model, with holes reserved directly during component fabrication, eliminating on-site cutting and drilling.

BIM enables components to be accurately prefabricated in the factory according to model data, avoiding over-processing waste caused by on-site cutting and drilling, while also reducing rework waste and material waste caused by misaligned holes.

assuming that the holes for the beam-column reinforcement are made on site, Based on Consumption Standard for prefabricated construction engineering（SJG 172-2024） Section 2.3.11,“On-site Opening and Sealing of Components,” the August 2023 full-cost reference unit price for on-site opening with a hole area of $0 < S \leq 0.5m^2$ was RMB 612.99 per opening. When combined with the actual labor and consumable costs, the actual cost may vary depending on project conditions.

4、 4D Construction Simulation and Plan Validation

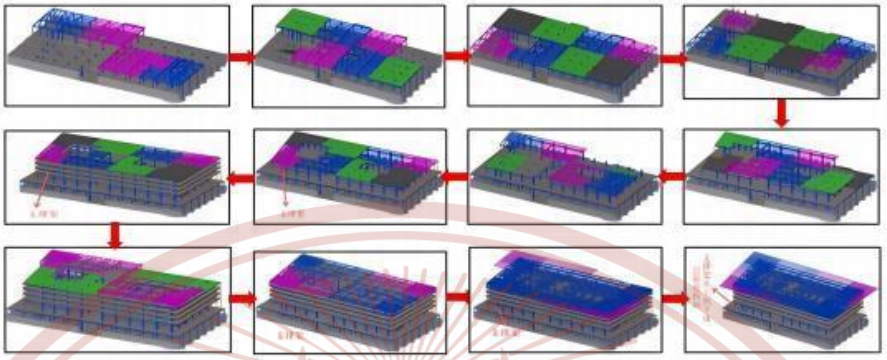


Figure 3-6 Simulation of the Steel Structure Lifting Plan

Figure 3-6 shows a 4D simulation of the steel structure lifting sequence for the library. The construction schedule is linked with the BIM model to dynamically simulate the lifting sequence of each component, crane position, and swing radius. The simulation can identify potential collisions between the crane boom and already installed components in advance, allowing optimization of the lifting sequence.

BIM enables the lifting plan to be validated in a virtual environment, avoiding waiting waste caused by on-the-fly adjustments and rework waste caused by component damage.

Based on Consumption standard for civil engineering construction machinery (SJG 174-2024), the August 2023 reference shift price for a 3,150 kN·m self-erecting tower crane was RMB 1,926.50 per shift. In addition, idle labor costs may occur when workers are waiting for the equipment. The actual cost may vary depending on project conditions.

5、 Dynamic Progress Tracking



Figure 3-7 UAV-Based Progress Monitoring and Comparison

Figure 3-7 shows Unmanned Aerial Vehicle (UAV) aerial images. By comparing the actual aerial photos with the 4D planned model, delayed areas can be visually identified. Compared with traditional methods relying only on Gantt charts and manual reporting, this approach provides objective, visual deviation data, enabling the project team to take timely corrective actions.

BIM combined with UAV aerial imaging enables progress deviations to be detected early, reducing waiting waste caused by schedule delays and overproduction waste caused by last-minute schedule acceleration.

Early detection of schedule delays can help avoid work stoppages in subsequent activities. Delays may also cause labor and equipment to remain idle, disrupt the planned construction sequence, and require additional resource coordination. If the delayed activity is on the critical path, it may also affect the overall project completion time.

6、 Collaboration Platform and Smart Site



Figure 3-8 Digital Construction Platform

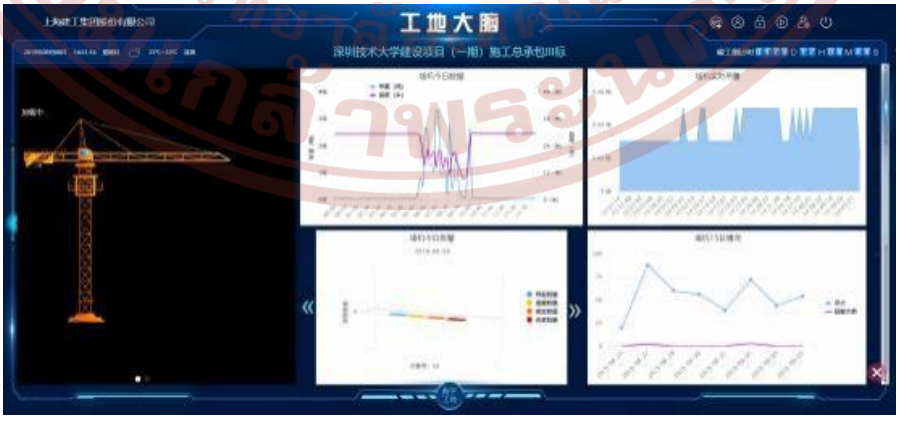


Figure 3-9 Real-Time Tower Crane Monitoring



Figure 3-10 On-Site Video Surveillance

Figure 3-8 shows the "Site Brain" integrated platform, Figure 3-9 shows real-time tower crane monitoring data, and Figure 3-10 shows video surveillance footage. The platform centralizes data such as crane load, height, alarm information, site video, and environmental monitoring, achieving real-time visualization of construction site status.

The BIM collaboration platform unifies drawing versions and synchronizes information in real time, reducing information waste (inconsistent drawing versions, communication delays, difficulty in issue tracking). The smart site system makes equipment idle status and material accumulation visible, reducing waiting waste.

While information waste is difficult to quantify using construction pricing standards, the value of information consistency and real-time visibility lies in enabling proactive management and preventing errors before they result in physical waste.

When information flows smoothly, many problems simply do not occur. Unified drawings, traceable issues, and all project participants working from the same information, BIM can help reduce rework and waiting caused by information errors and communication gaps.

3.6.3 Types of Construction-Phase Waste That BIM Can Reduce and Its Boundaries

The core principle of BIM in reducing construction waste lies in information integration and visualization. It transforms fragmented and implicit information in traditional construction management (such as spatial positions of different disciplines, process sequences, component status, drawing versions, etc.) into integrated and visual digital information, enabling problems to be identified and resolved during the design or construction preparation stage, thereby preventing them from entering the on-site execution stage.

1、 Waiting Waste

BIM can link the construction schedule with the 3D model through 4D construction simulation, dynamically displaying the time logic and space occupancy of each process, allowing managers to identify process conflicts in advance and adjust schedules, thereby reducing waiting caused by incomplete previous processes or occupied equipment. The smart site system also helps reduce equipment idle waiting by displaying real-time status of tower cranes and other equipment. However, BIM cannot control external factors such as material waiting caused by supplier delays or drawing waiting caused by slow drawing production from design institutes.

2、 Defects Waste

Through clash detection that automatically identifies spatial conflicts between models of different disciplines, and clearance analysis that checks the height of functional areas point by point, BIM enables issues such as pipe clashes, insufficient clearance, and misaligned pre-drilled holes to be discovered and corrected during the design stage, thus avoiding rework caused by on-site demolition and alteration. However, for defects caused by operational skills or human errors such as welding defects and installation errors, BIM can provide precise positioning information but cannot replace workers' skill levels or on-site supervision.

3、 Transportation Waste

Using site layout simulation (which can be combined with 4D), BIM can display transportation paths and stockpile locations at different construction stages, optimize layout plans, and reduce secondary handling caused by path conflicts or unreasonable temporary storage. However, BIM cannot intervene in external factors such as off-site traffic congestion or transport vehicle breakdowns.

4、 Motion Waste

By optimizing workspace layout through site layout models and marking tool storage points and material stockpiles in the model to form standardized layout drawings, BIM helps reduce ineffective movements caused by workers walking long distances to get tools or materials, or tools not having fixed positions. However, BIM cannot refine to the level of individual movements for ergonomic issues such as unnecessary bending or turning, nor for personal operating habits.

5、 Inventory Waste

Using component status labeling (e.g., green = installed, yellow = delivered but not installed, gray = not yet delivered), BIM can visually display the status of each component, exposing material stacking and semi-finished product accumulation issues, and providing data support for managers to adjust installation sequences. However, for waste caused by factory scheduling issues (e.g. accumulation of precast components) or warehouse management chaos, which involve supply chain and warehousing processes, BIM can only provide delivery information but cannot intervene in factory scheduling or warehousing operations.

6、 Over-processing Waste

Detailed design models directly generate precise fabrication drawings (such as steel structure hole positions, curtain wall panel dimensions), enabling components to be prefabricated in the factory according to the drawings and installed directly on site, thus avoiding over-processing caused by on-site cutting and drilling. However, for redundant processes caused by repeated rework due to quality issues, BIM can provide quality standards but cannot control construction quality.

7、 Overproduction Waste

Through 4D construction simulation that verifies the start time of each process and determines whether the workspace is ready, BIM helps optimize construction sequences and reduce overproduction caused by premature construction (crews mobilized before the workspace is ready). However, for waste influenced by procurement strategies and contract incentives, such as over-ordering and premature pouring, BIM can provide accurate quantity takeoffs but cannot automatically constrain procurement behavior.

8、 Making-do

Through the CDE collaboration platform ensuring unified release of all drawings and

changes, preventing information gaps, and marking prerequisite constraints (materials, drawings, workspace, personnel, equipment) for each task in the model, BIM can assist in determining whether a task is "ready to execute," reducing problems caused by forcing work with incomplete drawings or material substitution. However, for site management discipline issues such as covering before inspection or assigning unfamiliar workers, BIM cannot enforce management behavior.

9、 Information Waste

Establishing a CDE as a single source of truth, where all drawings, changes, and issue reports are uniformly stored and synchronized, and an online issue tracking system enables a closed-loop management of raised ⟶ assigned ⟶ resolved ⟶ closed, BIM thereby eliminates fragmented information problems such as inconsistent drawing versions, slow problem feedback, and information silos. However, for issues involving organizational behavior such as change orders not communicated to all parties (human oversight) or decision delays (long approval processes), BIM can push information but cannot ensure that every individual reads it, nor can it shorten organizational decision-making processes.

Table 3-3 BIM capabilities and Limitations in Construction Waste Reduction

Waste	BIM Directly Supports	BIM Limitations
Waiting	Identifies schedule conflicts, workspace conflicts, and equipment occupation through 4D simulation	Cannot directly control supplier delays or external material delivery
Defects	Detects pipe clashes, insufficient clearance, and incorrect pre-drilled hole positions	Cannot prevent workmanship errors or replace on-site quality supervision
Transportation	Optimizes on-site transportation routes, site layout, and temporary storage	Cannot control external traffic conditions or vehicle breakdowns
Motion	Optimizes workspace layout and locations of tools and materials	Cannot directly control individual working habits or ergonomic behavior

Table 3-3 BIM capabilities and Limitations in Construction Waste Reduction (CONTINUED)

Waste	BIM Directly Supports	BIM Limitations
Inventory	Visualizes component status and identifies material/WIP accumulation	Cannot directly control factory scheduling or warehouse management
Over-processing	Supports accurate fabrication and reduces unnecessary on-site cutting and drilling	Cannot directly prevent redundant work caused by poor workmanship or management
Overproduction	Supports construction sequencing and quantity take off	Cannot directly control procurement decisions, contract incentives, or management behavior
Making-do	Checks task readiness through information and prerequisite constraints	Cannot enforce site management discipline or workers 'compliance
Information Waste	Integrate information through CDE, version control, and issue tracking	Cannot ensure people read or act on information, or directly shorten organizational approval processes

The core contribution of BIM lies in transforming waste in the "information" and "spatial" dimensions into visible and controllable data, eliminating a large amount of rework, waiting, and information waste during the design and construction preparation stages. For waste related to "human behavior," "external supply chain," and "organizational processes," BIM can only provide data support but cannot directly eliminate it.

3.6.4 Comparative Analysis: With BIM vs. Without BIM

This section compares the differences in construction management between scenarios with BIM and without BIM, in order to explain why BIM can reduce waste during the construction phase.

1、 Timing of Problem Identification

Without BIM: Design information of different disciplines is scattered across separate drawings. Problems such as pipe clashes, insufficient clearance, and wrong pre-drilled holes are

often discovered by on-site workers only during the construction phase. By that time, concrete has already been poured and steel components have already been fabricated, so problems can only be resolved through rework, demolition, and alteration.

With BIM: Models of different disciplines are integrated into a unified environment during the design phase. Rule-based checks such as clash detection and clearance analysis are completed before construction. Problems are identified and corrected during the design stage, preventing them from entering the construction phase.

2、 Approach to Problem Resolution

Without BIM: Problems discovered during the construction phase are typically addressed through remedial measures such as "on-site cutting, re- installation, chiseling and redoing." Such approaches not only consume additional labor and materials but can also delay subsequent processes, causing cascading waiting.

With BIM: Problems are resolved in a virtual environment by adjusting the model: pipe routes are optimized on the computer, clearance height is improved in the model, and pre-drilled holes are precisely positioned in fabrication drawings. On-site construction is executed according to the optimized plan, requiring no demolition or alteration.

3、 Information Collaboration Efficiency

Without BIM: Drawings are distributed as paper or electronic files. After a version update, it is difficult to ensure that all crews are synchronized. Change orders are communicated through meetings, phone calls, or WeChat, making them prone to omission or misunderstanding. Problem feedback relies on manual photos and record-keeping, making tracking difficult.

With BIM: All drawings, changes, and issue records are centralized in a CDE. All project participants work based on a single source of information. Drawing versions are unified, and changes are synchronized in real time. Issues are submitted, assigned, resolved, and closed online, forming a closed-loop management system.

4、 Resource Utilization Efficiency

Without BIM: Material procurement is often based on experience-based estimates, easily leading to over-ordering or premature delivery causing site accumulation. Steel components, curtain walls, etc., require on-site cutting and drilling, generating material waste. Construction

progress relies on Gantt charts and manual reporting. Process conflicts are difficult to detect in time, resulting in equipment idle time and labor idle time.

With BIM: The model can directly generate accurate quantity takeoffs, providing a basis for JIT procurement. Detailed design drawings guide factory prefabrication, enabling direct on-site installation and reducing material waste. 4D construction simulation identifies process conflicts in advance, optimizes resource allocation, and reduces equipment idle time and waiting.

5、 Waste Control Effectiveness

Without BIM: Waste such as rework, waiting, information errors, and over-processing occurs repeatedly during the construction process and is difficult to quantify or trace. Managers often react passively after problems occur, lacking systematic preventive measures.

With BIM: Foreseeable rework-type waste such as spatial conflicts, insufficient clearance, and wrong hole positions is eliminated during the design stage. Information-type waste such as inconsistent drawing versions and information silos is systematically resolved through the collaboration platform. Waiting-type waste such as process conflicts and equipment occupation is proactively avoided through 4D simulation. For waste that BIM cannot directly resolve, such as supply chain issues and human behavior, the data support provided by BIM lays the foundation for subsequent Lean management.

The case analysis above shows that the essence of using BIM is to shift construction management from "reactive remedy" to "proactive prevention." Through information integration and visualization, BIM enables problems to be identified before they occur and resolved in a virtual environment, thereby reducing rework, waiting, information waste, and over-processing. Although BIM cannot replace management decision-making or on-site supervision, it provides a reliable data foundation and visualization tools for construction waste reduction.

Chapter 4

BIM–Lean-Based Framework for Construction-Phase Waste Optimization

To achieve systematic identification and optimization of construction-phase waste, this study develops an integrated conceptual framework combining Building Information Modeling and Lean Construction.

Unlike traditional studies that primarily focus on tool-level applications, this framework adopts a mechanism-oriented perspective, defining BIM as an information visualization and data integration mechanism, and Lean Construction as a process control and constraint management mechanism. Through their interaction, the framework enables systematic reduction of construction-phase waste.

Framework Structure and Core Dimensions

The proposed framework consists of three core dimensions:

Information Integration, Process Optimization, Performance Feedback.

These dimensions are interconnected through a closed-loop mechanism: waste identification $\longrightarrow$ optimization $\longrightarrow$ performance feedback. This closed-loop structure enables continuous improvement in construction processes.

Theoretical Basis of the Framework

As discussed in Chapter 2, construction-phase waste is categorized into nine types and is primarily driven by three underlying mechanisms:

Process instability, Information distortion, Resource mismatch.

Building on this foundation, the proposed BIM–Lean framework establishes a systematic mapping between waste types, BIM-based identification mechanisms, and Lean-based optimization strategies. For each type of waste, the framework defines a structured pathway that integrates BIM-enabled identification (visibility) and Lean-based optimization (control).

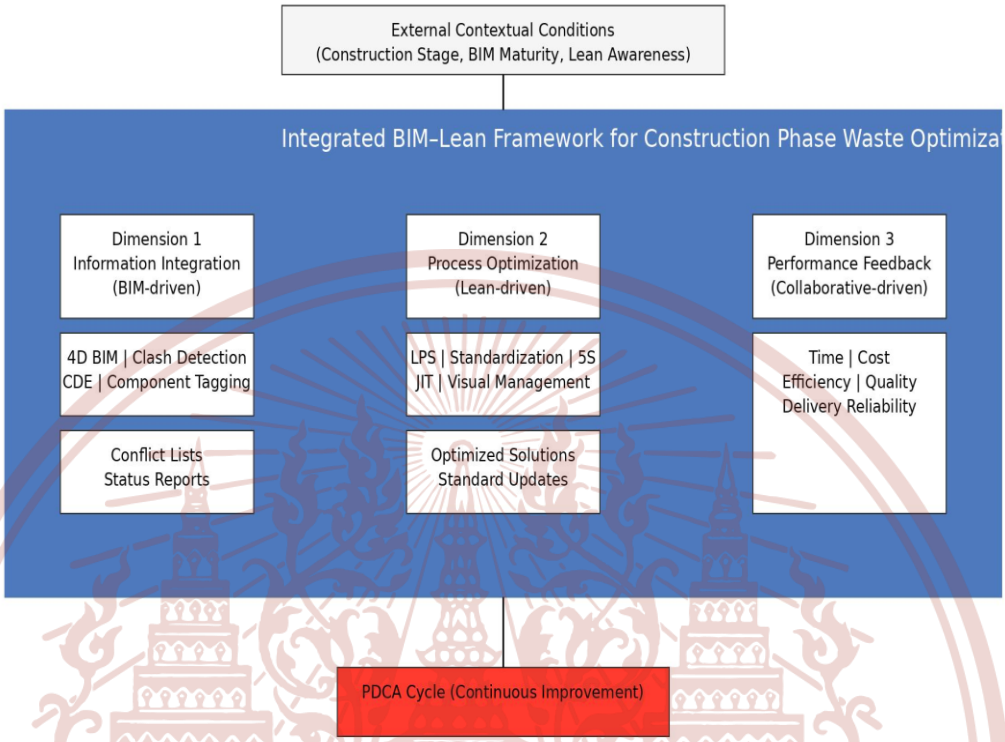


Figure 4-1 Integrated BIM–Lean Framework for Construction-Phase Waste Optimization

Figure 4-1 illustrates the overall structure of the proposed framework. The framework is organized into three interrelated dimensions:

Information Integration (BIM-driven): This dimension focuses on making construction issues visible by transforming implicit information into explicit, analyzable data.

Process Optimization (Lean-driven): This dimension focuses on constraint removal and workflow stabilization to eliminate non-value-adding activities.

Performance Feedback (Jointly driven): This dimension enables data-driven learning by integrating feedback from construction performance into future decision-making.

These three dimensions are interconnected through a PDCA cycle, forming a dynamic system that continuously improves construction performance and systematically reduces waste.

The proposed framework establishes a dual-mechanism system in which BIM enhances visibility for waste identification, while Lean Construction ensures controllability for waste elimination, thereby enabling a continuous and systematic reduction of construction-phase waste.

4.1 Dimension I: Information Integration – Information Visibility Mechanism

From a mechanism perspective, construction-phase waste largely originates from information opacity, where critical construction information—such as process logic, design conflicts, and resource status—is not effectively represented or shared (Sacks et al., 2010). When problems remain invisible, effective managerial intervention becomes difficult or even impossible.

As noted by Koskela (2000), construction systems should be understood as flow systems, in which disruptions can only be managed if the state of flow is made visible.

In this context, Building Information Modeling serves as a unified information platform that enables an information visibility mechanism, transforming implicit construction issues into explicit, analyzable data through model integration and visualization (Sacks et al. 2018; Sacks et al., 2010). During the construction phase, this mechanism is realized through the following technological pathways.

4.1.1 Time–Space Information Visualization

Waiting waste fundamentally reflects flow interruptions, which often arise from mismatches between time and space, for example, when a task requires a workspace that is still occupied by preceding activities. Traditional scheduling tools, such as Gantt charts, rely heavily on experience-based interpretation and are unable to effectively reveal such hidden conflicts.

Through the integration of construction schedules with 3D models, 4D BIM enables the coupling of time and space (Doukari et al., 2022), allowing three major sources of waiting waste to be visualized:

Process conflicts, Unreleased workspaces, Unavailable resources.

The core technical principle of 4D BIM lies in task–object mapping, where each construction task is linked to corresponding model components. As the model evolves along the timeline, the construction sequence is visually represented, enabling project teams to identify logical dependencies and potential conflicts among tasks. (Doukari et al., 2022)

This mechanism transforms flow interruptions from invisible conditions into manageable entities, providing a critical basis for subsequent process optimization.

4.1.2 Spatial Conflict Visualization

Rework and defect-related waste are often caused by multi-disciplinary design conflicts. In

traditional workflows, architectural, structural, and MEP information is distributed across separate drawings, and conflicts are typically identified only during construction, resulting in costly rework (Sacks et al. 2018).

BIM enables the integration of multi-disciplinary models within a unified environment and applies clash detection to identify spatial conflicts before construction begins (Sacks et al. 2018; Chahrour et al., 2021). The typical process includes:

Importing multi-disciplinary models into detection software, defining clash rules (e.g., hard clashes, clearance clashes), Running detection and generating clash reports. (Chahrour et al., 2021)

These reports provide detailed information on conflict locations, involved components, and conflict types, allowing design teams to resolve issues prior to construction.

This mechanism achieves spatial conflict visualization, enabling problems to be addressed during the design phase rather than being transferred to the construction phase as rework.

Importantly, research suggests that the value of BIM lies not in identifying all clashes, but in prioritizing those with the greatest impact on construction schedule and resource allocation (Chahrour et al., 2021).

4.1.3 Information Consistency Mechanism

Information and collaboration waste often arises from inconsistent drawing versions, delayed RFI responses, and insufficient cross-disciplinary coordination. The underlying issue is the absence of a unified information source, leading to decisions being made based on inconsistent data.

BIM addresses this challenge by establishing a CDE, which serves as a single source of truth for all project participants.

This mechanism ensures that all stakeholders access and operate on consistent and up-to-date information, thereby reducing information distortion and communication delays.

Studies indicate that BIM-based collaborative environments significantly reduce issues such as inconsistent drawings, missing information, and ineffective communication, thereby minimizing waiting and rework caused by information errors.

4.1.4 Status Information Visualization

Inventory and WIP waste often result from the lack of visibility into material and component

status. Project managers may not clearly understand which materials have been delivered, installed, or remain in storage.

BIM enables status information visualization by assigning visual indicators to components, typically categorized as:

Green: Installed

Yellow: Delivered but not installed

Gray: Not yet delivered

An increasing number of "yellow" components indicates higher levels of WIP accumulation, signaling potential inventory waste.

This mechanism enables resource status visibility, providing a data foundation for JIT and pull-based production systems.

4.1.5 Summary of the Information Integration Dimension

Table 4-1 Mapping between BIM Mechanisms and Waste Types

BIM Mechanism	**Technical Implementation**	**Identified Waste Types**
Time-space information visualization	4D BIM	Waiting, Overproduction
Spatial conflict visualization	Clash detection	defects
Information consistency	Common Data Environment (CDE)	Information waste
Status information visualization	Component status labeling	Inventory
Spatial layout visualization	Site layout simulation	Transportation, Motion

In summary, the core function of the information integration dimension is to transform "invisible problems" into "actionable information."

By enhancing information visibility across time, space, and resource dimensions, BIM provides a critical data foundation for subsequent Lean-based process optimization.

4.2 Dimension II: Process Optimization – Constraint Removal and Process Control Mechanism

If the information integration dimension addresses the question of whether problems can be identified, the process optimization dimension addresses how these problems can be effectively eliminated.

According to Lean Construction theory, construction systems should be conceptualized as production flow systems, where the primary objective is to minimize non-value-adding activities and enhance flow stability.

Lean Construction achieves this objective through a set of systematic mechanisms, including:

Constraint removal mechanisms, Process consistency mechanisms, Spatial organization mechanisms, Supply–demand matching mechanisms.

These mechanisms enable targeted optimization strategies for different types of construction-phase waste.

4.2.1 Constraint Removal Mechanism

Construction waste, particularly waiting waste, fundamentally arises when tasks are initiated before all required conditions are satisfied. This phenomenon is referred to in Lean Construction as "making-do," where work proceeds despite insufficient resources or information, often transferring problems to downstream processes.

The LPS establishes a constraint removal mechanism through systematic constraint analysis. The LPS process consists of four hierarchical planning levels:

Master Schedule– overall project-level planning.

Phase Schedule– medium-term planning based on construction phases.

Weekly Work Plan– short-term executable planning, forming the core of LPS.

PPC– a performance metric that measures the reliability of plan execution.

The key principle of constraint analysis is to identify and eliminate all prerequisite conditions before task execution, including:

Availability of materials, Completion and confirmation of drawings, Completion of preceding activities, Availability of workspace, Availability of labor and equipment.

Only when all constraints are satisfied is a task released for execution. This mechanism effectively prevents "making-do" situations and reduces downstream waiting, rework, and process disruptions.

4.2.2 Process Consistency Mechanism

Rework and defect-related waste often originate from inconsistencies in construction processes. Variations in execution methods across teams and workers lead to quality fluctuations and increased error rates.

Standardized work establishes a process consistency mechanism by transforming individual experience into systematic and repeatable procedures. Key practices include:

Development of standard operating procedures (SOP), Definition of quality control points for critical activities, Standardization of tools, materials, and workflows.

When defects occur, Lean Construction emphasizes RCA to identify underlying systemic issues rather than addressing only surface-level problems. Combined with continuous improvement practices, this approach reduces recurrence of defects.

This mechanism ensures stable and consistent process execution, thereby minimizing rework and defect-related waste.

4.2.3 Spatial Organization Mechanism

Transportation and motion waste are primarily caused by inefficient spatial arrangements on construction sites, such as poorly located material storage areas, disorganized tool placement, and congested pathways.

The 5S methodology establishes a spatial organization mechanism to optimize site layout and reduce unnecessary movement. The five steps of 5S include:

Sort– removing unnecessary materials and reducing clutter,

Set in Order– organizing materials and tools based on usage frequency,

Shine– maintaining clean and unobstructed workspaces,

Standardize– establishing consistent layout and operational standards,

Sustain– maintaining improvements through regular monitoring.

This mechanism restructures spatial order, transforming construction sites from disorganized environments into efficient and controlled workspaces, thereby reducing transportation and motion

waste.

4.2.4 Supply–Demand Matching Mechanism

Inventory and overproduction waste are typically caused by mismatches between resource supply and construction demand. Materials may arrive too early and accumulate on-site, or arrive too late, causing delays.

JIT and pull-based production systems establish a supply–demand matching mechanism, ensuring that resources are delivered only when needed.

Unlike traditional push systems, where materials are supplied based on predefined schedules regardless of actual readiness, pull systems are driven by downstream demand. Implementation strategies include:

Buffer inventories ("supermarkets") to handle variability, Kanban systems to trigger replenishment, Takt-based material delivery aligned with construction rhythm.

When integrated with Building Information Modeling, component information can be linked with construction schedules to enable precise, demand-driven material delivery. For example, when a component is identified in the BIM model as approaching installation, material delivery can be automatically triggered.

This mechanism ensures synchronization between resource flows and construction activities, reducing both inventory accumulation and waiting.

4.2.5 Summary of the Process Optimization Dimension

Table 4-2 Mapping between Lean Mechanisms and Waste Types

Lean Mechanism	**Tool Implementation**	**Optimized Waste Types**
Constraint removal	LPS	Waiting, Overproduction, Making-do
Process consistency	Standardized work, Root Cause Analysis (RCA)	defects, Over-processing

Table 4-2 Mapping between Lean Mechanisms and Waste Types (CONTINUED)

Lean Mechanism	Tool Implementation	Optimized Waste Types
Spatial reorganization	5S management	Transportation, Motion
Supply-demand matching	JIT, Pull production, Kanban system	Inventory, Overproduction
Information flow optimization	Visual management, Daily coordination	Information waste

In summary, the core function of the process optimization dimension is to transform identified problems into executable control strategies, thereby stabilizing construction flows.

Through constraint removal, process standardization, spatial organization, and supply–demand synchronization, Lean Construction provides systematic pathways for eliminating construction-phase waste and improving operational efficiency.

4.3 Dimension III: Performance Feedback – Data-Driven Learning Mechanism

The improvement of construction performance is not the result of a single technology or tool, but rather the outcome of the synergistic enhancement of information transparency and process stability.

4.3.1 Pathways for Performance Improvement

Through the integration of Building Information Modeling and Lean Construction, construction performance is improved across five key dimensions:

Schedule Reduction– By minimizing waiting, rework, and overproduction, workflow continuity is enhanced.

Cost Reduction– By reducing resource waste and rework, overall project costs are better controlled.

Efficiency Improvement– By optimizing processes and eliminating non-value-adding activities, labor productivity is increased.

Quality Enhancement– Through early problem identification and standardized processes, construction quality becomes more stable.

Improved Delivery Reliability– Through effective planning and constraint management, project delivery becomes more predictable and reliable.

4.3.2 PDCA Closed-Loop Mechanism

The PDCA cycle is widely applied in Lean Construction as a continuous improvement tool, with its core function being the optimization of system performance through feedback mechanisms (Liker, 2004).

When combined with BIM-based data support, PDCA evolves into a data-driven learning mechanism, enabling dynamic and iterative optimization.

The PDCA cycle consists of four stages:

Plan– Optimization objectives and strategies are formulated based on BIM models and historical data, such as PPC, rework rates, and inventory levels.

Do– Optimization measures are implemented, while BIM platforms are used to monitor progress and information flows in real time.

Check– Actual progress is compared with planned outcomes through BIM models, and performance indicators (e.g., PPC, rework rates, inventory levels) are collected and analyzed.

Act– Deviations are analyzed, and corrective actions are implemented by adjusting construction logic, resource allocation, and Lean strategies. Improved practices are standardized for future application.

Optimization results—such as improvements in PPC, reductions in rework rates, and changes in inventory levels—are continuously fed back into the BIM model to update schedules, refine resource allocation, and correct model information.

This feedback mechanism enables the construction system to evolve through continuous cycles, shifting from reactive control to proactive optimization. Each iteration enhances the system's resilience, resulting in cumulative improvement over time.

4.4 Dimensional Synergy and BIM–Lean Collaborative Mechanism

The core strength of the proposed framework lies in the synergy between BIM and Lean Construction. The three dimensions do not operate independently; rather, they form an integrated system through the following mechanisms (Sacks et al., 2010).

4.4.1 Functional Complementarity Mechanism

BIM and Lean Construction establish a stable division of roles in construction waste management:

BIM dominates information integration (information dimension), Lean Construction dominates process optimization (process dimension).

They operate on different but complementary aspects of the construction system:

BIM excels in handling spatial and informational complexity, Lean Construction excels in managing temporal and process-related dynamics.

4.4.2 Information–Decision Transformation Mechanism

The key to effective integration lies in the transformation chain between information and decision-making:

BIM Information ⟶ Constraint Identification ⟶ Lean Decision-Making ⟶Behavioral Change ⟶ Waste Reduction.

In practical terms, outputs generated by BIM must directly serve as inputs for Lean optimization:

Conflict lists generated from 4D simulations inform LPS constraint removal, Clash detection reports guide adjustments in standardized work, Component status visualization supports JIT-based pull planning.

When these interfaces function effectively, BIM and Lean Construction evolve from a simple combination of tools into a functionally integrated system.

4.4.3 Closed-Loop Optimization Mechanism

Through the PDCA cycle, the framework establishes a continuous improvement loop:

Identification ⟶ Optimization ⟶ Feedback ⟶ Re-identification.

This mechanism enables the construction system to transition from passive control to proactive optimization, equipping it with learning capability.

The proposed BIM–Lean framework establishes a synergistic system in which BIM enhances visibility for problem identification, Lean Construction ensures controllability for process optimization, and PDCA enables continuous learning, thereby forming a closed-loop mechanism for systematic waste reduction.

4.5 BIM–Lean Synergy for the Nine Types of Construction-Phase Waste

Based on the proposed framework, the key principles for the identification and optimization of the nine categories of construction-phase waste are summarized in Table 4-3.

Table 4-3 Key BIM–Lean Synergy Mechanisms for Nine Types of Construction-Phase Waste

Waste Type	BIM Mechanism (Information Integration)	Lean Mechanism (Process Optimization)	Synergy Relationship
Waiting	Time-space information visualization (4D BIM)	Constraint removal (LPS)	Conflict list ⟶ Constraint removal ⟶ Model update
defects	Spatial conflict visualization (Clash detection)	Process consistency (Standardized work)	Clash report ⟶ Design adjustment ⟶ Standardization
Transportation	Spatial layout visualization (Site layout simulation)	Spatial reorganization (5S management)	Path visualization ⟶ Layout optimization ⟶ JIT delivery
Motion	Workspace area visualization	Spatial reorganization (5S management)	Movement analysis ⟶ Workstation optimization ⟶ Standardization
Inventory	Status information visualization (Component labeling)	Supply-demand matching (JIT, Kanban system)	Status tracking ⟶ Demand trigger ⟶ JIT supply
Over-processing	Process visualization	Process consistency (VSM, process simplification)	Process mapping ⟶ Value-added analysis ⟶ Redundancy elimination
Overproduction	Time-space information visualization (4D BIM)	Constraint removal + Supply-demand matching (LPS, Pull production)	Sequence verification ⟶ Condition check ⟶ Task release

Table 4-3 Key BIM–Lean Synergy Mechanisms for Nine Types of Construction-Phase Waste (CONTINUED)

Waste Type	BIM Mechanism (Information Integration)	Lean Mechanism (Process Optimization)	Synergy Relationship
Making-do	Construction condition visualization	Constraint removal (LPS, Constraint management)	Condition check ⟶ Release decision ⟶ Condition tracking
Information waste	Information consistency (CDE)	Information flow optimization (Visual management)	Information integration ⟶ Clash detection ⟶ Process standardization

As shown in Table 4-3, the management of each type of construction-phase waste follows a consistent closed-loop logic:

BIM-based information visibility ⟶ Lean-based constraint removal ⟶Collaborative feedback and improvement

Specifically, Building Information Modeling is responsible for transforming implicit waste into explicit and analyzable information through visualization and data integration. Based on this information, Lean Construction translates identified issues into targeted optimization actions through process control and constraint management.

The outcomes of these optimization actions are then fed back into the BIM model through a PDCA cycle, enabling continuous updating of construction plans, resource allocation, and process logic.

This iterative feedback mechanism ensures that the system evolves dynamically, allowing construction processes to continuously improve across successive cycles.

Across all nine waste categories, the BIM–Lean integration establishes a unified operational logic in which BIM enables visibility for problem identification, Lean Construction ensures controllability for process optimization, and PDCA facilitates continuous learning, thereby forming a closed-loop system for systematic waste reduction.

Chapter 5

Mechanism Analysis of BIM–Lean Synergy in Construction-Phase Waste Optimization

This chapter examines the underlying mechanisms that explain the effectiveness of the proposed BIM–Lean framework from three perspectives: functional complementarity, theoretical interpretation, and positive feedback loops.

5.1 Functional Complementarity: Division of Roles between BIM and Lean Construction

The synergy between Building Information Modeling and Lean Construction is fundamentally rooted in their complementary functions. BIM primarily supports information integration, while Lean Construction focuses on process optimization. This division is not arbitrary but is determined by the inherent capability boundaries of the two approaches.

5.1.1 Capability Boundary Analysis

The core capability of BIM lies in visualization and information integration. It transforms implicit construction issues—such as process conflicts, design errors, and resource mismatches—into explicit and analyzable information. However, BIM does not inherently alter workflows or make decisions.

As highlighted by Koskela (2000), a fundamental challenge in construction systems is the visibility of flow. BIM directly addresses this challenge by making the state of construction processes observable.

In contrast, Lean Construction focuses on process optimization and planning control. Through tools such as the LPS, standardized work, and JIT, Lean Construction improves workflow reliability and eliminates non-value-adding activities. However, its effectiveness depends on accurate and timely input data.

Ballard (2000) emphasizes that the effectiveness of LPS relies on accurate identification of constraints. In the proposed framework, BIM provides information that can support this process.

Therefore, the division of roles—BIM for information integration and Lean Construction for process optimization—is a natural outcome of their capability boundaries.

As demonstrated in Table 4-1 and 4-2, this division applies consistently across different types of construction-phase waste:

BIM performs the role of identification (visibility),

Lean Construction performs the role of optimization (controllability)

5.1.2 Information–Decision Transformation Chain

Effective collaboration between BIM and Lean Construction depends on seamless information exchange. The output generated by BIM must serve as inputs for Lean decision-making, while optimization outcomes must be fed back into the BIM model.

This interaction can be conceptualized as an information–decision transformation chain:

BIM Information Visualization ⟶ Constraint Identification ⟶ Lean Decision-Making ⟶ Behavioral Change ⟶ Waste Reduction

For example, in the case of waiting waste:

4D BIM enables time–space visualization and identifies process conflicts; these conflict lists are then used in LPS to identify constraints; LPS adjusts the construction plan accordingly; and on-site execution follows the optimized plan, reducing waiting time.

This chain reveals the essence of BIM–Lean synergy: BIM identifies problems, while Lean Construction resolves them. Their effectiveness depends on the continuity of this transformation process.

5.2 Theoretical Interpretation of the Synergy Mechanism

5.2.1 System Theory Perspective: Joint Enhancement of Visibility and Controllability

From a systems theory perspective, the performance of a construction system depends on both the timely identification of problems and the effectiveness of corrective actions.

BIM enhances system visibility by making process states, conflicts, and deviations observable. Lean Construction enhances system controllability by providing structured methods for resolving identified issues.

When used independently:

BIM results in visible but uncontrollable systems,

Lean Construction results in controllable but insufficiently observable systems,

When integrated, they simultaneously enhance visibility and controllability, forming a

complete governance capability for construction systems.

5.2.2 Information Theory Perspective: Optimization of Information Quality and Response Efficiency

From an information theory perspective, system performance depends on the quality and speed of information processing.

In traditional construction environments, information is fragmented across multiple channels, leading to inconsistent drawings, redundant data, and conflicting information. This increases the cost of information processing and reduces decision quality.

BIM addresses this issue by supporting the establishment of a CDE, ensuring a single source of truth and improving information accuracy.

In terms of response efficiency, traditional processes involve multiple layers of communication, resulting in delayed problem resolution. Lean Construction improves responsiveness through visual management, daily coordination practices, and PPC tracking, reducing the time between problem identification and resolution.

BIM improves information quality, while Lean Construction enhances response efficiency. Their integration shortens the information-to-action cycle and enables proactive rather than reactive management.

5.3 Positive Feedback Loop: Why the Synergy Effect Amplifies Over Time

5.3.1 Logic of the Positive Feedback Loop

A key feature of BIM–Lean integration is the existence of a positive feedback loop.

On one hand, BIM provides increasingly accurate information to Lean Construction:

Real-time data on resource availability, Status of preceding tasks, Workspace readiness.

As information accuracy improves, Lean decision-making becomes more precise, reducing waiting and overproduction.

On the other hand, Lean Construction improves the reliability of execution plans through constraint removal and process control. This improved reliability enhances the accuracy of BIM-based simulations and predictions.

These two directions reinforce each other, forming a self-strengthening loop.

With each iteration:

System performance improves, Data accuracy increases, Decision quality is enhanced.

This cumulative improvement represents a positive feedback mechanism, where the combined effect of BIM and Lean Construction exceeds the sum of their individual contributions.

5.3.2 Preconditions and Boundaries of the Positive Feedback Loop

It is important to note that this positive feedback loop does not occur automatically. Its effectiveness depends on two key conditions:

Timely updating of BIM models. Outdated models lead to inaccurate information, resulting in flawed decision-making.

Proper implementation of Lean practices. If LPS data is unreliable or standardized work is poorly enforced, process reliability cannot be improved, undermining the feedback loop.

In severe cases, inaccurate execution results may contaminate BIM data, leading to negative feedback cycles.

Therefore, active management intervention is required to maintain and reinforce the positive feedback loop, which is achieved through the PDCA cycle.

The BIM–Lean integrated framework achieves systematic waste reduction by combining visibility, controllability, and learning capabilities, forming a self-reinforcing system that continuously improves construction performance.

Chapter 6

Conclusions and Future Research

6.1 Summary of Findings and Responses to Research Questions

Guided by Lean Construction theory, this study investigates the problem of construction-phase waste and explores how Building Information Modeling can be utilized to reduce such waste. The findings are summarized in response to the three research questions.

Regarding RQ1: What are the main types of construction-phase waste?

This study extends the traditional understanding of construction waste beyond material loss. From a Lean Construction perspective, construction-phase waste is systematically categorized into nine types: waiting, defects, transportation, motion, inventory, over-processing, overproduction, making-do and information waste. This classification reflects the inherent complexity and systemic nature of construction processes.

Regarding RQ2: How does BIM support waste identification?

The findings indicate that BIM supports waste identification by transforming implicit problems into explicit and analyzable information through functions such as clash detection, 4D simulation, collaborative platforms, site simulation, and component status visualization.

For instance, in the university construction project case study, clash detection identified pipeline conflicts during the design phase, preventing them from propagating into construction. In addition, the integration of 4D simulation and UAV monitoring enabled dynamic tracking of construction progress. These examples demonstrate the practical effectiveness of BIM in enhancing visibility and enabling early problem identification.

Regarding RQ3: How can BIM be used to reduce construction-phase waste?

This study reveals that the effectiveness of BIM in reducing construction-phase waste is based on two key mechanisms:

Upstream problem elimination during the design phase– through clash detection, MEP coordination, and design development, preventing defects from entering the construction stage.

Process optimization during the construction phase– through 4D simulation, collaborative platforms, and smart site technologies, reducing waste caused by information delays and coordination inefficiencies.

Comparative analysis shows that projects using BIM can identify and resolve issues at earlier stages, enabling smoother execution during construction. In contrast, projects without BIM often encounter these issues only during construction, resulting in rework, waiting, and material waste.

This comparison highlights the underlying mechanism through which BIM reduces construction-phase waste by shifting problem identification upstream and improving process coordination.

6.2 Research Contributions

The contributions of this study can be summarized in three aspects:

Theoretical Contribution

This study systematically defines the concept and classification of construction-phase waste from a Lean Construction perspective, extending the traditional seven waste categories by incorporating making-do and information-related waste. In addition, it explains the underlying logic through which BIM reduces construction-phase waste—namely, by enabling upstream problem prevention and downstream process optimization. This provides a new theoretical perspective on the application of BIM in construction management.

Methodological Contribution

This study adopts a systematic literature analysis approach to synthesize existing research on construction waste, BIM, and Lean Construction. It further employs case-based comparative analysis to demonstrate the practical effectiveness of BIM in reducing waste. Based on these analyses, a mapping framework linking BIM functionalities with construction-phase waste is developed, clearly identifying pathways for waste identification and reduction.

Practical Contribution

This study shows that effective application of BIM can shift problem identification from the construction phase to the design phase, thereby reducing rework, waiting, transportation, and inventory-related waste. The findings provide practical guidance for construction organizations in selecting and implementing BIM technologies in project management.

6.3 Research Limitations

Despite its contributions, this study has several limitations:

1、 Limited case representativeness– The case project involved relatively The case project

involved relatively extensive and integrated BIM applications. Therefore, the findings may not be fully representative of projects with different BIM implementation levels, and broader validation across different project types and BIM implementation contexts is needed.

2、 Lack of quantitative analysis– The analysis primarily relies on qualitative evaluation. Quantitative indicators—such as changes in rework rates, schedule duration, and cost savings—were not systematically measured.

3、 Uneven depth of analysis across waste types– This study focuses more on key waste categories such as defects, waiting, and information waste, while other categories (e.g., transportation, motion, inventory) are less extensively analyzed.

6.4 Future Research Directions

Based on these limitations, future research may focus on the following areas:

1、 Expanding the scope of empirical studies– Future studies may include a wider range of project types and BIM implementation levels to validate the generalizability of the findings and identify context-specific conditions.

2、 Developing quantitative evaluation frameworks– Establishing measurable indicators—such as rework rates, waiting time ratios, and inventory turnover—would enable more rigorous assessment of BIM effectiveness through before-and-after comparisons.

3、 Integration with emerging technologies– Future research may explore the integration of BIM with emerging technologies such as digital twins, the IoT), and artificial intelligence (AI), enabling real-time waste identification and predictive optimization.

REFERENCES

1.Akinci, B., Fischer, M., & Kunz, J. (2002). Automated generation of work spaces required by construction activities. Journal of construction engineering and management, 128(4), 306-315.

2. Bajjou, M. S., & Chafi, A. (2020). Identifying and Managing Critical Waste Factors for Lean Construction Projects. Engineering Management Journal, 32(1), 2–13.

3.Bajjou, M. S., & Chafi, A. (2022). Exploring the critical waste factors affecting construction projects. Engineering, Construction and Architectural Management, 29(6), 2268-2299.

4. Ballard, G. & Tommelein, I. (2021) 2020 Current Process Benchmark for the Last Planner® System of Project Planning and Control. In Lean Construction Journal pp. 53-155.

5. Ballard, H. G. (2000). The Last Planner system of production control [Doctoral dissertation, University of Birmingham]. University of Birmingham eTheses Repository.

6. Bølviken, T., Rooke, J., & Koskela, L. (2014). The Wastes of Production in Construction – a TFV Based Taxonomy. In B. T. Kalsaas, L. Koskela, & T. A. Saurin (Eds.), 22nd Annual Conference of the International Group for Lean Construction (pp. 811–822).

7.Bortolini, R., Formoso, C. T., & Viana, D. D. (2019). Site logistics planning and control for engineer-to-order prefabricated building systems using BIM 4D modeling. Automation in Construction, 98, 248-264.

8.Bosché, F., Ahmed, M., Turkan, Y., Haas, C. T., & Haas, R. (2015). The value of integrating Scan-to-BIM and Scan-vs-BIM techniques for construction monitoring using laser scanning and BIM: The case of cylindrical MEP components. Automation in construction, 49, 201-213.

9.Bosché, F., Guillemet, A., Turkan, Y., Haas, C. T., & Haas, R. (2014). Tracking the built status of MEP works: Assessing the value of a Scan-vs-BIM system. Journal of computing in civil engineering, 28(4), 05014004.

10.Cabrera, O., Tejeda, J., Llontop, J., Mendoza, P., Alvarez, J. C., & Demirkesen, S. (2023). A validation model to reduce non-contributory time based on Lean tools: Case of a construction company in Perú. Cogent Engineering, 10(1), 2236838.

11. Cao, X., & Guo, G. (2025). Research on lean construction management of prefabricated buildings: A management innovation pathway for coordinating industrialization and on-site customization [in Chinese]. Heilongjiang Science, 16(20), 141–143.

12. Chahrour, R., Hafeez, M. A., Ahmad, A. M., Sulieman, H. I., Dawood, H., Rodriguez-Trejo, S., Kassem, M., Naji, K. K., & Dawood, N. (2021). Cost-benefit analysis of BIM-enabled design clash detection and resolution. Construction Management and Economics, 39(1), 55–72.

13.Creswell, J. W., & Creswell, J. D. (2017). Research design: Qualitative, quantitative, and mixed methods approaches (5th ed.). Sage publications.

14. Dantas Filho, J. B. P., Barros Neto, J. de P., & Angelim, B. M. (2017). Mapeamento do fluxo de valor de processo de construção virtual baseado em BIM [Value stream mapping of a BIM based virtual construction process]. Ambiente Construído, 17(4), 343–358.

15. Dave, B., Boddy, S., & Koskela, L. (2013). Challenges and Opportunities in Implementing Lean and BIM on a Infrastructure Project. In C. T. Formoso, & P. Tzortzopoulos (Eds.), 21th Annual Conference of the International Group for Lean Construction (pp. 741–750).

16.Doukari, O., Seck, B., & Greenwood, D. (2022). The creation of construction schedules in 4D BIM: A comparison of conventional and automated approaches. Buildings, 12(8), 1145.

17. Fireman, M. C., Saurin, T. A., & Formoso, C. T. (2018). The Role of Slack in Standardized Work in Construction: An Exploratory Study. In 26th Annual Conference of the International Group for Lean Construction (pp. 1313–1322).

18.Jabareen, Y. (2009). Building a conceptual framework: philosophy, definitions, and procedure. International journal of qualitative methods, 8(4), 49-62.

19. Jaskula K, Kifokeris D, Papadonikolaki E, Rovas D (2025), "Common data environments in construction: state-of-the-art and challenges for practical implementation". Construction Innovation: Information Process Management, Vol. 25 No. 5 pp. 1522–1541

20. Karaz, M., Teixeira, J. M. C., & Amaral, T. G. d. (2024). Mitigating Making-Do Practices Using the Last Planner System and BIM: A System Dynamic Analysis. Buildings, 14(8), 2314.

21.Kim, S. C., Kim, Y. W., Park, K. S., & Yoo, C. Y. (2015). Impact of measuring operational-level planning reliability on management-level project performance. Journal of Management in Engineering, 31(5), 05014021.

22.Koskela, L. (2000). An exploration towards a production theory and its application to construction. VTT Technical Research Centre of Finland.

23.Koskela, L. (2004). Making-do—The eighth category of waste. In S. Bertelsen & C. T. Formoso (Eds.), Proceedings of the 12th Annual Conference of the International Group for Lean Construction.

24. Koskela, L., Bølviken, T., & Rooke, J. (2013). Which Are the Wastes of Construction? In C. T. Formoso, & P. Tzortzopoulos (Eds.), 21th Annual Conference of the International Group for Lean Construction (pp. 3–12).

25.Kumar, S. S., & Cheng, J. C. (2015). A BIM-based automated site layout planning framework for congested construction sites. Automation in construction, 59, 24-37.

26.Landim, G. L., Rocha, L. M., Nogueira, R. N., & Barros Neto, J. P. (2022). The synergies between lean and BIM: a practical and theoretical comparison. In Proceedings of the 30th Annual Conference of the International Group for Lean Construction (IGLC30) (pp. 611-622).

27.Liker, J. K. (2004). The Toyota way: 14 management principles from the world's greatest manufacturer. McGraw-Hill.

28.Marhani, M. A., Jaapar, A., Bari, N. A., & Shaari, S. M. (2022). Reducing over-processing construction waste by using lean construction tools in the Malaysian construction industry. In IOP Conference Series: Earth and Environmental Science, 1067(1), 012048.

29.Melo, M., Deschamps, F., & da Costa, S. E. G. (2017). Application of Lean Construction–A Systematic Literature Review. Journal of Lean Systems, 2(3), 02-21.

30.Michaud, M., Meyer, J., Forgues, D., & Ouellet-Plamondon, C. (2021). A taxonomy of sources of waste in BIM information flows. Buildings, 11(7), 291.

31.Miles, M. B., Huberman, A. M., & Saldaña, J. (2014). Qualitative Data Analysis: A Methods Sourcebook, (3rd ed.). SAGE Publications.

32.Mitera-Kiełbasa, E., & Zima, K. (2025). Optimising construction efficiency: A comprehensive survey-based approach to waste identification and recommendations with BIM and lean construction. Sustainability, 17(9), 4027.

33.Moradi, S., & Sormunen, P. (2023). Revisiting the concept of waste and its causes in construction from analytical and conceptual perspectives. Construction Management and Economics, 41(8), 621-633.

34.Moradi, S., & Sormunen, P. (2024). Integrating lean construction with BIM and sustainability: A comparative study of challenges, enablers, techniques, and benefits. Construction Innovation, 24(7), 188-203.

35. Ocheoha, I. A., & Moselhi, O. (2013). Impact of building information modeling on just-in-time material delivery. In Proceedings of the 30th International Symposium on Automation and Robotics in Construction (pp. 793–801).

36.Parsamehr, M., Perera, U. S., Dodanwala, T. C., Perera, P., & Ruparathna, R. (2023). A review of construction management challenges and BIM-based solutions: Perspectives from the schedule, cost, quality, and safety management. Asian Journal of Civil Engineering, 24(1), 353-389.

37. Pedo, B., Tezel, A., Koskela, L., Whitelock-Wainwright, A., Lenagan, D., & Nguyen, Q. A. (2021). Lean Contributions to BIM Processes: The Case of Clash Management in Highways Design. In Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC) (pp. 116–125).

38. Peshkov, V. V., & Rada, L. T. G. (2022). Improvement of organization and management of construction production based on BIM technologies and lean construction. AIP Conference Proceedings, 2434(1), 080011.

39. RazaviAlavi, S., & AbouRizk, S. (2021). Construction Site Layout Planning Using a Simulation-Based Decision Support Tool. Logistics, 5(4), 65.

40.Rosenbaum, S., Toledo, M., & González, V. (2014). Improving environmental and production performance in construction projects using value-stream mapping: Case study. Journal of Construction Engineering and Management, 140(2), 04013045.

41. Rother, M., & Shook, J. (2003). Learning to see: Value stream mapping to create value and eliminate muda (Version 1.3). Lean Enterprise Institute.

42.Sacks, R., Eastman, C., Lee, G., & Teicholz, P. (2018). BIM handbook: A guide to building information modeling for owners, designers, engineers, contractors, and facility managers. John Wiley & Sons.

43.Sacks, R., Koskela, L., Dave, B. A., & Owen, R. (2010). Interaction of lean and building information modeling in construction. Journal of construction engineering and management, 136(9), 968-980.

44.Schimanski, C. P., Marcher, C., Pasetti Monizza, G., & Matt, D. T. (2020). The Last Planner® system and building information modeling in construction execution: From an integrative review to a conceptual model for integration. Applied Sciences, 10(3), 821.

45.Seyis, S., & Ozkan, S. (2024). Benefits and challenges of implementing the common data environments in the construction phase of BIM-based projects. Journal of Construction Engineering and Management, 150(8), 04024091.

46.Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. Journal of business research, 104, 333-339.

47.Tribelsky, E., & Sacks, R. (2010). Measuring information flow in the detailed design of construction projects. Research in engineering design, 21(3), 189-206.

48. Van der Veen, S., Dallasega, P., & Hall, D. (2021). Data-driven continuous improvement process framework for railway construction projects. In Proceedings of the 38th International Symposium on Automation and Robotics in Construction (pp. 857–863). International Association for Automation and Robotics in Construction.

49.Vilventhan, A., Ram, V. G., & Sugumaran, S. (2019). Value stream mapping for identification and assessment of material waste in construction: A case study. Waste Management & Research, 37(8), 815-825.

50.Waheed, W., Khodeir, L., & Fathy, F. (2025). Investigation of sustainability and lean approaches for efficient architecture design management. Results in Engineering, 27, 105847.

51.Zhang, D., Haas, C. T., Goodrum, P. M., Caldas, C. H., & Granger, R. (2012). Construction small-projects rework reduction for capital facilities. Journal of Construction Engineering and Management, 138(12), 1377-1385.

52. Zhong, R. Y., Peng, Y., Xue, F., Fang, J., Zou, W., Luo, H., Ng, S. T., Lu, W., Shen, G. Q. P., & Huang, G. Q. (2017). Prefabricated construction enabled by the Internet-of-Things. Automation in Construction, 76, 59–70.

VITA

Name	Click or tap here to enter text.
Thesis Title	Click or tap here to enter text.
Major Field	Click or tap here to enter text.
Biography	Click or tap here to enter text.

