

An Expert-Informed BIM and Lean Decision Framework for Material Waste at Mechanical System Interfaces in Industrial Facilities

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Article Info

Article history:

Received June 22, 2026

Revised August 23, 2026

Accepted August 28, 2026

Keywords:

Material Waste,
Building Information
Modeling,
Lean Construction,
Mechanical System Interfaces,
Industrial Facilities,
Construction Life Cycle,
Expert Survey

ABSTRACT

Material waste in industrial facilities can arise at the interfaces between mechanical equipment, service routes, supporting structures, installation, maintenance, and dismantling. This exploratory study develops an expert-informed framework that maps potential waste drivers to Building Information Modeling (BIM) coordination and lean planning decisions. A literature review identified 35 candidate drivers, which were consolidated into 23 questionnaire factors covering design, construction, operation and maintenance, and demolition. Twenty expert responses were obtained, of which 14 were retained in the reported analysis. The resulting factors provide a preliminary checklist for examining issues such as equipment access, component selection, service coordination, material handling, and design for disassembly. An illustrative mechanical equipment and pipe-routing scenario shows how BIM information and lean work planning could be used to address these risks. The study does not measure discarded material or test whether the proposed approach reduces waste. Its interpretation is limited by the small, retained panel, unavailable item-level rankings, and uncertainty about the units used in parts of the statistical analysis. Validation requires project-level records of material quantities, returns, discarded mass, and rework.

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1. Introduction

The construction sector is one of the largest contributors to economic development in both developed and developing countries. The construction industry pervades the majority of economic sectors. Despite its significance to society, building activities have an impact on the natural environment (Fuentes et al., 2013). The construction industry is traditionally bifurcated into two major branches: residential construction and industrial, commercial, and institutional buildings. Industrial construction, a highly specialized, niche-building approach, refers to the design, installation, and maintenance of the structural and mechanical components in power plants, refineries, factories, and mines. Industrial construction projects often include a broad range of professions and disciplines (e.g., civil, steel structure, plumbing, electrical, and mechanical) and are fraught with danger. The intricately intertwined engineering and construction procedures raises the need for more technical and complex management of the project (Hu & Mohamed, 2014; A. Meshref et al., 2022). It has been envisaged that construction process for these projects is inefficient and influences in too much waste of materials (Horman & Kenley, 2005).

After classifying waste into seven forms (Fumihito et al., 1994; Pichtel, 2014; Womack & Jones, 2003), waste can

be defined as any action that consumes resources without contributing value, i.e., waste is the loss of any resource - materials, time (people and equipment), and capital - due to activities that incur direct or indirect costs but add no value to the final product from the client's perspective (Formoso et al., 2002).

It's important to industrial facilities to have reliable and safe operation and maintenance with complex mechanical systems, such as process piping, HVAC networks, pumps, vessels, compressors, ductwork, utility lines, supports and equipment, etc. Each of these systems needs to be fit in a very congested area, while allowing for structural requirements, electrical services, instrumentation, fire protection, access routes, maintenance clearances, lifting paths, and operational safety requirements (Sarhan et al., 2017). A simple coordination mistake, for example if a pipe route crosses a steel brace, or there is not enough space around the equipment can have serious downstream implications such as field changes, equipment scrap, delays, rework and disruptions to commissioning activities. A major problem in the industrial construction is material waste in mechanical-system interfaces. This waste is often in the areas of poor mechanical equipment to support connections, service routes, foundations, access, adjacent trades, installation sequences, and future maintenance needs. For instance, ductwork or piping based on uncoordinated drawings could need cutting, resizing, rerouting or replacement after being found to clash upon installation. Such changes require more material, manpower, time and energy and create unnecessary construction waste. BIM research has shown that design mistakes, underutilization of materials, poor communication, and planning failures are all significant factors that can cause construction waste and inefficiency. Building Information Modeling (BIM) creates a virtual and collaborative environment where problems can be noticed and worked out before any structures are built. BIM combines together geometric, technical, scheduling and asset information in the same model to allow all stakeholders to visualize mechanical systems within the context of structural, architectural, electrical, plumbing, fire-protection, and process elements. Some of the major features of BIMs are federated model coordination, clash detection, rule-based checking, quantity extraction, constructability review, and 4D sequencing (Azhar, 2011; Eastman et al., 2011; Sepasgozar et al., 2021). These tools can detect hard clashes, clearance conflicts, routing issues, un-reachable valves, poor maintenance areas and installation restrictions prior to materials being delivered to site, or manufactured. Electronic conflict resolution can keep project teams from reworking, ordering materials unnecessarily, and getting more accurate fabrications. But BIM is not the solution for the elimination of waste. Even a clash free model can result in material loss if they are fabricated too early, delivery is poorly timed, installation sequences are impractical, materials are over producible or the responsibility for decisions at interfaces is not clear. Lean construction principles are complementary to BIM and address systematically the elimination of waste, the reliability of construction processes, the planning of production, and continuous learning. There are multiple types of waste identified in lean construction—defects, overproduction, waiting, unnecessary transportation (information and materials), excess inventory, excess motion, over-processing, and underutilization of human expertise. In industrial mechanical works these forms of waste are well interconnected; if there is an interface conflict, it can simultaneously result in faulty products, waiting for reworked drawings, too much material ordering, unnecessary handling, and rework (Erik Eriksson, 2010).

Combining BIM and lean construction is a more effective solution than using either of the two separately for reducing material waste. BIM gives teams a visual and data-driven source of potential interface issues, lean practices will organize the way teams prioritize, solve, verify and learn from the issues. For instance, BIM-enabled quantity control can help to more accurately estimate materials, clash detection can help to prevent fabrication mistakes and lean tools like pull planning, just-in-time delivery, standardized work and value stream mapping can help to streamline material and installation workflows (Mesa et al., 2021). This integration enables better and faster decision-making processes for when materials are to be procured, fabricated, delivered and installed, and when they are in a design state, have access to and/or can be sequenced by them and are coordinated with others involved in the process. Although the effectiveness of BIM–lean integration is widely understood, adoption of BIM in industrial facilities is still fragmented. Previous studies often focus on BIM coordination, clash detection, lean planning or material-waste management as independent techniques without involving interfacing aspects of a decision process. Industrial projects are also unique in the sense that mechanical systems are placed in an environment with low design space and low design freedom, and fabrication tolerances, installation logistical needs, equipment maintenance, safety requirement, and process-operability condition should be all considered simultaneously. We need therefore a decision framework to enable project teams to identify material-waste risks at mechanical-system interfaces, establish the pertinent BIM evidence, and choose appropriate lean actions prior to when waste becomes embedded in procurement and construction practice (Koskela et al., 2002; A. N. Meshref et al., 2022). To meet this need, an expert-informed BIM and lean decision framework has been developed that incorporates practical expertise from mechanical engineers, BIM coordinators, construction managers, procurement specialists, fabrication workers and site supervisors. But expert input is crucial as many risks associated with the interfaces cannot be captured by automated clash detection.

For example, a mechanically viable route might be hard to fabricate, may have challenging access for maintenance, is not safe for installation or may produce excessive off-cuts and rework. The framework can align specific waste drivers with the design (like late changes), lack of clearance details, sequencing of work, quantity and quality of work installed, etc.) to specific BIM and lean interventions.

Modifications to the design, unwanted material scraps, non-recyclable/reusable materials, packaging waste, and design/detail errors contribute to construction waste (Faniran & Caban, 1998). For example, construction waste has become a major problem due to the massive creation and the enormous environmental effects (Li & Zhang, 2013). It has been estimated that thirty-five percent of the world's solid waste comprises construction and demolition debris (Solís-Guzmán et al., 2009). In this regard, the methods to minimize construction waste is a strategy for avoiding, eliminating, or decreasing waste during the design phase (Crittenden & Kolaczowski, 1995; Osmani, 2013; Riemer & Kristoffersen, 1999). Prevention includes any activities that may reduce the amount of construction waste, such as eliminating waste before it enters the waste stream and minimizing waste creation at the source (Baldwin et al., 2009; Hobbs, 2008; Osmani et al., 2008). Early design stages are responsible for considerable construction waste (Bossink & Brouwers, 1996; Ekanayake & Ofori, 2000a; Faniran & Caban, 1998; Rounce, 1998). Choosing appropriate design factors may influence approximately 33 percent of the waste directly (Hassan & Alashwal, 2025). The (UK) Waste and Resources Action Program (WRAP) has identified five key principles that design teams can adopt during the design process to reduce waste as fundamental design decisions like building material, sharpness of form, size, and complexity are more likely to significantly impact waste, there is a greater opportunity for waste reduction at the design phase than in later stages.

In this regard, there is plenty of factors that influence in reducing construction waste throughout the design phase and other building phases that should be considered in the initiation of the project. Hence, the research raises the question of which factors are primarily affecting the reduction of construction waste that should be taken into consideration at the design phase as it predicts the amount of construction waste before it occurs on the construction life cycle, and then can be managed, re-evaluated and avoided. Not only the design phase has crucial factors that may reduce construction waste but, there is other successive phases starting with construction, maintenance and demolishing of the project, that have several aspects of waste reduction according to literature. Accordingly, the research question tries to determine the degree of importance of the factors in the building life cycle that influences in the reduction of construction waste.

Although the construction industry has considerable challenges, it is possible to manage some of them using effective tactics and processes, such as lean construction and BIM. Lean concepts were proposed in order to accomplish effective transformation towards better project management and enhance the construction process's efficiency. Lean may be difficult to be applied in building projects due to the nature of its complex construction activities and components at different levels, notably during the design phase. It is often believed that utilizing a 3D modeling software along with (BIM) techniques will inevitably assist all project participants in visualizing the whole building process early in the design phase, incorporating with the use of lean concepts in construction projects as well (Eastman et al., 2011). Additionally, BIM implementation gives considerable advantages to the construction sector by boosting productivity and quality while reducing costs and project monitoring, resulting in enhanced project performance.

BIM is defined as the process of developing, storing, preserving, transferring, and disseminating building information that is operable and reusable (Vanlande et al., 2008). It involves creating and implementing a computer-generated model to reproduce a project's planning, design, construction, and operation phases (Azhar et al., 2008). BIM is the process of creating and using a computer-generated model to duplicate the planning, design, construction, and operation of a building facility. BIM can be considered a source of data, object- oriented, intelligent, and parametric digital representation of building facilities (America, 2005). It is a spatial and data transmission technology that can be integrated efficiently and systematically with identification and data collection technologies in the architectural, Engineering, and construction (AEC) industry. In this regard, BIM represents both of the physical and functional characteristics of a specific building (Abouhamad & Abu-Hamd, 2021; Hagedorn et al., 2023; Han et al., 2021; Wong et al., 2020; Zoghi & Kim, 2020).

The lean construction concept has been derived from the lean manufacturing concept, and refers to the Toyota Production System (Bajjou et al., 2017; Sarhan et al., 2017). The implementation of the lean thinking has been regarded as a key feature in the building industry and has been termed as "the new production philosophy" in the construction industry (Koskela, 1992). This term was created by the International Group for Lean Construction during a conference held in Finland in its first implementation in 1993 (Alarcón, 1997). In this respect, Lean construction is "a strategy of structuring manufacturing processes in order to maximize the value while minimizing waste of resources, time and labor. The term "lean construction" has a variety of definitions, ranging from a broad definition

that incorporates all design and building processes to particular definitions focusing on specific production tasks and tool applications by contractors (Awad et al., 2021; Emmitt, 2007).

The current research aims to examine the views of experts (owner, consultant, and contractor) to determine the degree of relative importance and Inferential statistical analysis among the factors of construction waste generation during the construction life cycle of industrial projects (design, construction, maintenance, and demolition). To reduce construction waste in the construction life cycle of industrial projects, and in particular to reduce demolition waste at the end of the lifespan of industrial projects trying to prevent the waste in the demolition process, whether in materials, cost or time. This study aims to present an expert-based approach to the decision-making framework to minimize material wastes at mechanical-system interfaces in industrial plants. The framework is designed to detect waste sources early, determine the readiness and reliability of information for mechanical design and coordination, and to help teams choose the right BIM-enabled and lean-based actions. The proposed approach aims to help to achieve more accurate fabrication, better material planning, minimize rework, scrap and improve inter-disciplinary coordination, and a more sustainable manufacturing of industrial mechanical systems.

In this regard, the demolition phase should be considered during the design phase trying to recover the elements, and materials of the buildings when it will be demolished to be used again after being treated in other buildings, transferring these buildings, or to recycle the elements and materials resulting from the demolition process. Accordingly, the successive construction phases should be considered in the light of BIM and Lean concepts during the selection of factors causing waste in the construction life cycle of industrial projects.

The paper is structured as follows: Section 2 describes Literature Review, Section 3 discusses Research methodology, Section 4 presents Statistical the results of analysis and Section 5 discuss the results of the statistical analysis and section 6 summarizes the conclusions.

2. Literature Review

2.1 Reuse, Recycle, Reduce

The 3R Principle, which advocates reducing, reusing, and recycling garbage, has been adopted by the United Kingdom, Europe, North America, and numerous Asian countries (Allwood et al., 2011). The 3R Principle was adopted in building construction primarily for its advantages to the environment and the economy (Coventry et al., 1999). The environmental benefit includes extending the lifespan of landfills, decreasing the environmental impact of the processes used to extract raw materials and create new materials, reducing the use of raw materials, extending the life of natural resources, and lowering environmental pollution that is harmful to human health and wellbeing. Increasing business prospects, cutting project costs, lowering the risk of litigation involving construction waste, and demonstrating a commitment to minimizing the environmental effect of construction are just a few of the benefits from an economic standpoint (Addis, 2012; Dajadian & Koch, 2014). In this respect, research studies proposed several methods to minimize Construction and demolition waste by reducing, reusing, and recycling (C&D) waste (Jaillon et al., 2009; Medibodi et al., 2014; Nouh et al., 2021; Porwal & Hewage, 2012; Yu et al., 2012).

2.2 Construction Waste

Construction waste encompasses any materials diverted from their primary intended use within a project whether transported off-site or repurposed for landfilling and recycling due to surpluses, damage, technical non-compliance, or as inherent by-products of the building process." (Ekanayake & Ofori, 2000b). Waste generated during construction, renovation, and demolition projects, such as site clearing, road construction, building, land excavation, remodeling, and demolition, is known as construction and demolition (C&D) waste (Luangcharoenrat et al., 2019; Nouh et al., 2021; Shen et al., 2004; Spišáková et al., 2021).

2.3 Construction Waste Components (Material Waste – Time Waste – Cost Waste)

There are two primary categories of construction waste; the first is the materials waste, which includes excess ordering, improper handling, excess output, improper storage, and manufacturing flaws. The second is time waste, which includes waiting times, clarification requests, interruptions, changes in information, information rework, inefficient work, delays in scheduled operations, and anomalous equipment wear (Garas et al., 2001). Additionally, it has been anticipated that cost waste results from various types of both time and material waste on construction projects. In the Dutch construction industry, solid waste accounts for between 1% and 10% of all purchased construction materials, or about 9% of the total amount of materials purchased (Bossink & Brouwers, 1996). Since materials make up more than half of the cost of a building project, at least 20% of the material purchased will often remain unused at

the conclusion of every project (Yuan, 2012). In this regard, it is notable to review the cost of waste that will affect the competitive edge of contractors, making their survival more difficult in such a competitive environment (Islam et al., 2024). It could be concluded that a broader view of waste management is needed to minimize both materials and resources waste such as equipment and labor (Formoso et al., 2002).

2.4 Categories of Construction Waste

The notion of (Construction and demolition) C&D of waste generation includes a number of different waste sources that arises throughout the project construction from start to completion. There are six distinctive sources of waste including procurement, design, materials handling, residual, operation, and others aspects (Bossink & Brouwers, 1996). In that respect, a braoded view for the classification of waste variables were grouped together under the following categories: a) Procurement; b) Design and documentation; c) Operational attributes; d) Materials handling; transportation and storage; e) Environmental and other conditions, and f) Site Management and practices (Ekanayake & Ofori, 2000b; Gavilan & Bernold, 1994). Accordingly, an evaluation for the construction waste according to the following sources: (1) design (i.e. detail error, blueprint error, and design changes); (2) procurement (i.e. ordering error and shipping errors); (3) materials handling (i.e. improper storage/ handling and deterioration); (4) operation (i.e. equipment malfunctions, human errors, accidents, catastrophes, and weather changes); (5) residual (e.g. un reclaimable non -consumables and leftover scrap); and other factors (Gavilan & Bernold, 1994). In another perspective, Conceptual planning and feasibility studies, design and engineering, construction, operation, and maintenance are some of the aspects that make up a project's life cycle (Kartam, 1996; Wang et al., 2009). It has been noted that a project life cycle consists of five phases which are the feasibility phase, design phase, construction phase, maintenance phase, and dismantling phase (Alshubbak et al., 2009; Liu et al., 2011).

According to the above-mentioned definitions, it could be concluded that the construction life cycle of industrial projects could be divided into four phases: design, construction, maintenance & operation, and demolition.

2.5 Factors for Construction Waste During Construction Phases (Design, Construction, Maintenance, and Demolition)

The building design starts with a methodology which is the methods architects and engineers are using to achieve preferred shapes and functions in the design process. Therefore, proper design approaches generate a successful design conceptual framework and effective design strategies which will prevent mistakes in the future. Despite the fact that traditional on-site construction methods have a lot of criticism and are a subject of wide debate, the use of modern construction techniques (MMC), such as (off-site construction, modular construction, and open building approach) proved several substantial advantages especially in time savings (Erik Eriksson, 2010; Latham Sir, 1994). Furthermore, it is also offering precise cost estimation and a proper time framework and thus enhances building performance (Pan et al., 2007). Additionally, the selection of Structure types (steel- precast concrete- composite - wood - in situ concrete) is of particular importance in the project initiation. In that sense, the proper selection of material types with a high percentage of recycled resources should be utilized (Poon et al., 2001). Hence, it would be profitable to select Building operations that may result in the admission of reusable materials in the construction to reduce the demand for new materials (del Río Merino et al., 2010). It could be noted that, the selection of joints and connections type as bolted joints to be used instead of the chemical ones like gluing and nailing gives the opportunity for future reuse (Crowther, 2005; Guy et al., 2006; Webster & Costello, 2005). Along with that, all construction components should be dimensionally coordinated, one of the prominent examples is the foundations' type that could be retracted from the earth later. Building components that can be swapped out to eliminate the number of components and connectors (Chini & Balachandran, 2002; Crowther, 2005; Guy & Ciarimboli, 2008; Webster & Costello, 2005).

The material waste is often produced on the interfaces of mechanical equipment, structural elements, service routes, installation activities, maintenance access, and dismantling needs in the industrial equipment. Given that mechanical systems need to be coordinated within constrained areas, minute design or installation errors can cause cutting, rerouting, re-sizing, re-working, and material scrapping, they propose, making these interfaces especially susceptible. Researchers also indicate that poor interface coordination is not just a drafting related challenge but a management challenge in which various engineering, procurement, fabrication, and construction organizational groups fail to communicate effectively, do not follow up on design changes quickly enough, provide mutually conflicting quantities, and don't clearly define their respective roles (Akanbi et al., 2018; Othman & Saad, 2024; Sacks et al., 2020; Yang et al., 2025). According to researchers, the introduction of Building Information Modeling (BIM) technology can help to minimize material waste by aiding the visualization, coordination, clash detection, quantity takeoff, and constructability review before materials are fabricated or delivered. They recommend that project

stakeholders can use BIM to flag hard clash and clearance clash issues, inaccessible equipment, routing issues, and equipment installation limitations digitally to minimise the need for changes in the field and waste of materials (Riley & Cotgrave, 2018). It is also suggested by researchers that using BIM can also aid in accurate materials estimation and procurement due to extracting quantities directly from coordinated models, thereby avoiding overordering, excess stock or fabricating mistakes. According to researchers, lean construction aims to create the maximum value with the least waste, such as defects, waiting, overproduction, unnecessary transportation, excess inventory, excess motion, over-processing and underutilised human expertise. They propose that creation of flow of materials and installation activities in construction projects can be improved by implementing lean methods like pull planning, just-in-time delivery, Standardization, Value stream mapping, and Continuous improvement. As related to mechanical systems, lean practices can be used for ensuring materials are only procured, fabricated, delivered and installed once design information, access, sequencing, and coordination are sufficiently mature. Researchers clarify that BIM and Lean Construction have more waste reduction potential when combined together than when applied individually (Zihni et al., 2022). They argue that BIM provides the evidence and data of interface issues and lean principles prioritize, resolve, verify and learn around interface issues. Researchers also state that BIM can be a lean management tool by enhancing collaboration, transparency, planning precision, and process efficiency for all project stakeholders. Moreover, they propose that systematic and structured integration of BIM–lean may help in obtaining earlier decision-making, minimising rework, boosting productivity, and optimising sustainability results for the architecture, engineering and construction sector. Researchers state that the challenges faced by industrial facilities are fundamentally different from those in non-industrial applications, as mechanical systems have to comply with the requirements of operation, safety, maintenance, access and processes as well as installation constraints. They propose that clash detection is not enough – because a technically viable mechanical route may be hard to fabricate, unsafe to install, too inaccessible for maintenance, or it may give birth to off-cuts and rework. Hence, the authors recommend that the expertise of mechanical engineers, BIM coordinators, construction managers, procurement experts, fabricators, and site supervisors should be leveraged to pinpoint context-specific waste issues and determine the right interventions. Existing research studies mostly focus on BIM coordination, lean planning and material waste management as distinct activities, instead of on an integrated interface-based decision process (Kabirifar et al., 2020). They propose that there is a need for a structured decision framework that links waste drivers, e.g., late design changes, lack of clearance data, poor sequence of installation, lack of quantities, and lack of coordination together with targeted BIM-enabled and lean-based actions. The researchers recommend that this new BIM and lean decision framework that is enhanced by an expert system could aid in the earlier identification of waste risks, better reliability of fabrication, better material planning, less rework and material scrap, and more sustainable delivery of mechanical systems in industrial facilities.

In relation to the construction phase, the nature of the building form and its purpose, the construction process itself, the project timetable, the size/scale of the project, site circumstances, and the surrounding environment, all these factors are of important consideration while the project initiation on-site which could be described as massively complex (Xia & Chan, 2012). Accordingly, the entire approach to a specific project, especially the needed resources and planning, as well as the tools and methodologies, is being determined based on the degree of complexity. Environmentally, it could be noted that each building project is unique and difficult, requiring a significant amount of processes and thus has a direct impact on the quantity of waste created by construction operations (Haponava & Al-Jibouri, 2012). In this regard, pre-construction preparations were the primary cause of waste during the building phase, and several additional elements contribute to waste during the construction process. Moreover, waste can be created throughout the building process as a result of poor coordination and control (Alwi et al., 2002b; Khanh & Kim, 2014; Muhwezi et al., 2012; Nagapan, Rahman, Asmi, Memon, & Zin, 2012), poor construction technique selection (Bossink & Brouwers, 1996; Wan et al., 2009), and reworks (Bekr, 2014; Oko John & Emmanuel Itodo, 2013). It could be inferred that, that the most common issues mentioned during the building phase are ordering errors and poor workmanship, indicating that each element has a substantial role in waste generation throughout the construction process because ordering errors result in an overabundance or scarcity of orders. And as a result, over-ordering can result in an overabundance of supplies and waste (Agyekum et al., 2012). Contrarily, a shortfall of orders may result in insufficient material availability, halting building operations on the job site, and thus the material has to be reordered, which will extend the time it takes to receive items from the supplier and by far extend the project deadlines (Nagapan, Rahman, Asmi, Memon, & Latif, 2012). Regarding labor, poor craftsmanship is a significant contributor to construction waste throughout the construction period. Moreover, unskilled labor, insufficient tools and equipment, and/or a bad working environment can all contribute to poor craftsmanship (Gavilan & Bernold, 1994). It is also important to note that poor craftsmanship may be caused, in some situations, by aggressive inspector supervisors and project managers (Nagapan, Rahman, Asmi, Memon, & Latif, 2012). As a result, poor craftsmanship will result in

worker conflict due to deviations from the original goal (Wan et al., 2009). Finally, it may lead to abandoned work, especially during the construction/renovation stage (Tam et al., 2007).

Building maintenance is inevitably needed to protect financial assets and also maximizing building functionality. In that sense, the organization will decide to employ some type of strategic maintenance plan to maximize building maintenance's economic value and technical efficacy. It should be noted that for that maintenance development plans should consider the following factors: Life expectancy of the structure, the use of the building, Timeframes for significant fabric, and service repairs and thus it will affect the chosen materials and components and their individual and collective life periods. Because each building must meet a certain standard of conditions, not all structures must be maintained in the same way (Riley & Cotgrave, 2018). This raises the need to prepare a proper plan and consult specialists in relation to building maintenance over time, as it brings along life span of the building and in turn reduces the need for demolishing and as a result reduces its effect on the environment. Building demolition is considered, in some situations, the only option of decision -making. Relevant legislation and scientific research identify several elements influencing demolition waste generation (DWG). It could be noted that (DWG) is governed by some internal and external factors, the former being factors such as a building's age (Poon, 1997), type (Wang et al., 2004) and geometrical features (Shi & Xu, 2006; Wang et al., 2004), and the latter factors such as demolition methods (i.e., deconstruction, wrecking ball, or implosion) (Kibert et al., 2000; Kourmpanis et al., 2008; Chi Sun Poon, Ann Tit Wan Yu, Siu Ching See, et al., 2004), demolition length (Yuan et al., 2011), surrounds (Hendriks & Janssen, 2001). Ironically, there is a shortage of comprehensive understanding and accurate knowledge about (DWG), particularly concerning these internal and external aspects. Beyond the fact that Demolition is the process of reversing the building process, as well as a process of disassembling and removing a structure or subsections. In that sense, the construction may be demolished or deconstructed in order to utilize and recycle additional materials. The demolition can be regarded as a complex process due to the vast number of criteria that determine the demolition process itself taking into account that every type of structure is unique. Regarding the appropriate choice of demolition technique, the choice is based on the demolition engineer's expertise, abilities, and understanding (Abdullah & Anumba, 2002; McDonald & Smithers, 1998). The choice of demolition procedures has been influenced by six primary factors and various sub-criteria. The primary criteria are the structural qualities, site circumstances, demolition cost, previous experience, time, and possibilities for reuse and recycling. Accordingly, eight factors must be considered, including the structural form of the structure, the size of the construction, the location of the building, the authorized degree of annoyance, the scope of destruction, the use of the building, safety, and the demolition time (Kasai, 1988). It could be inferred that demolition is such a complex process needs a specialized framework to prevent the waste of resources and give the opportunity for materials recycling.

According to the above-mentioned analysis, table (1) shows the 35 factors that cause the generation of construction waste in the construction life cycle (CLC) of industrial projects (design, construction, maintenance, and demolition). Then a questionnaire was structured focusing on the degree of relative importance according to the experts' opinions. It ends up with 23 factors that were listed in the table (2) with a full description.

Table 1(a): Factors for Construction Waste Generation During Construction Phases of the Industrial Projects (Design, Construction, Maintenance, and Demolition).

Cluster	Code	Criteria	Literature
Design Phase	dp1	Structure Type	(Riley & Cotgrave, 2018)
	dp2	Material Type	(Chini & Balachandran, 2002; Crowther, 2005; del Río Merino et al., 2010; Guy & Ciarimboli, 2008; Guy et al., 2006; Poon et al., 2001; Webster & Costello, 2005)
	dp3	Method of Construction	(Erik Eriksson, 2010; Jaillon et al., 2009; Latham Sir, 1994; Pan et al., 2007)
	dp4	Element Type	(Chini & Balachandran, 2002; Crowther, 2005; Guy & Ciarimboli, 2008; Guy et al., 2006; Webster & Costello, 2005)
	dp5	Foundation Type	(WRAP, 2009)
	dp6	Section Type	(Osmani et al., 2008)
	dp7	Joint and Connection Type	(Crowther, 2005; Guy et al., 2006; Webster & Costello, 2005)

Table 1 (b): Factors for Construction Waste Generation During Construction Phases of the Industrial Projects (Design, Construction, Maintenance, and Demolition).

Cluster	Code	Criteria	Literature
Construction Phase	cp1	Design Change	(Bossink & Brouwers, 1996; Osmani et al., 2008), (Alwi et al., 2002a, 2002b; Bossink & Brouwers, 1996; Ekanayake & Ofori, 2004; Faniran & Caban, 1998; Garas et al., 2001; Lu et al., 2011; Polat & Ballard, 2004; C.S. Poon et al., 2004; Chi Sun Poon, Ann Tit Wan Yu, Sze Wai Wong, et al., 2004; Tam et al., 2007; Wahab & Lawal, 2011; Wan et al., 2009; Wang et al., 2008; Yamany et al., 2024)
	cp2	Design Errors	(Alwi et al., 2002a, 2002b; Bossink & Brouwers, 1996; Chandrakanthi et al., 2002; Ekanayake & Ofori, 2004; Garas et al., 2001; Osmani et al., 2006; Polat & Ballard, 2004; C.S. Poon et al., 2004)
	cp3	Complex Design	(Ekanayake & Ofori, 2004; Polat & Ballard, 2004; C.S. Poon et al., 2004; Xia & Chan, 2012)
	cp4	Poor Quality in Design and Specification	(Alwi et al., 2002b; Wang et al., 2008; Xia & Chan, 2012)
	cp5	Rework	(Bekr, 2014; Oko John & Emmanuel Itodo, 2013)
	cp6	Poor Information Quality	(Garas et al., 2001; C.S. Poon et al., 2004; Wang et al., 2008; Xia & Chan, 2012)
	cp7	Inappropriate Equipment	(Gavilan & Bernold, 1994)
	cp8	Effect of Weather	(Alwi et al., 2002a, 2002b; Bossink & Brouwers, 1996; Ekanayake & Ofori, 2004; Polat & Ballard, 2004; Tam et al., 2007; Wahab & Lawal, 2011)
	cp9	Accidents	(Bossink & Brouwers, 1996; Ekanayake & Ofori, 2004; Polat & Ballard, 2004; Tam et al., 2007)
	cp10	Wrong Material Storage	(Alwi et al., 2002b; Bossink & Brouwers, 1996; Garas et al., 2001; Lu et al., 2011; Najafpoor et al., 2014; Chi Sun Poon, Ann Tit Wan Yu, Sze Wai Wong, et al., 2004; Tam et al., 2007; Wahab & Lawal, 2011; Wan et al., 2009; Wang et al., 2008)
	cp11	Damage during Transportation	(Bossink & Brouwers, 1996; Garas et al., 2001), (Ekanayake & Ofori, 2004; Lu et al., 2011; C.S. Poon et al., 2004; Wahab & Lawal, 2011; Wang et al., 2008)
	cp12	Poor Site Management	(Bossink & Brouwers, 1996; Ekanayake & Ofori, 2004; Garas et al., 2001; Lu et al., 2011; Polat & Ballard, 2004; Wahab & Lawal, 2011; Wan et al., 2009; Wang et al., 2008), (Haponava & Al-Jibouri, 2012)
	cp13	Poor Work Man Ship	(Gavilan & Bernold, 1994; Nagapan, Rahman, Asmi, Memon, & Latif, 2012; Tam et al., 2007), (Alwi et al., 2002b; Bossink & Brouwers, 1996; Polat & Ballard, 2004; Wan et al., 2009)
	cp14	Waiting Time	(Nagapan, Rahman, Asmi, Memon, & Latif, 2012)
	cp15	Unstructured Movement and Nonproductive Site Plane	(Alwi et al., 2002b; Bossink & Brouwers, 1996; Khanh & Kim, 2014; Muhwezi et al., 2012; Nagapan, Rahman, Asmi, Memon, & Zin, 2012)
	cp16	Ordering Errors	(Agyekum et al., 2012; Bossink & Brouwers, 1996), (Ekanayake & Ofori, 2004; Garas et al., 2001; Lu et al., 2011; Najafpoor et al., 2014; Polat & Ballard, 2004; C.S. Poon et al., 2004; Chi Sun Poon, Ann Tit Wan Yu, Sze Wai Wong, et al., 2004; Tam et al., 2007; Wang et al., 2008)

Table 1 (c): Factors for Construction Waste Generation During Construction Phases of the Industrial Projects (Design, Construction, Maintenance, and Demolition).

Cluster	Code	Criteria	Literature
Maintenance and Operation Phase	mop1	Cost	(Riley & Cotgrave, 2018)
	mop2	Time	(Riley & Cotgrave, 2018)
	mop3	Information About Building	(Riley & Cotgrave, 2018)
	mop4	Material Used	(Riley & Cotgrave, 2018)
	mop5	The Condition of the Building	(Riley & Cotgrave, 2018)
Demolition Phase	dep1	Structure Design Characteristic	(Abdullah & Anumba, 2002; Jaillon et al., 2009; Kasai, 1988; Poon, 1997; Poon et al., 2001; Shi & Xu, 2006; Wang et al., 2004)
	dep2	Site Condition	(Abdullah & Anumba, 2002; del Rio Merino et al., 2010; Hendriks & Janssen, 2001; Kasai, 1988)
	dep3	Cost	(Abdullah & Anumba, 2002; del Rio Merino et al., 2010)
	dep4	Past Experience	(Abdullah & Anumba, 2002; del Rio Merino et al., 2010; McDonald & Smithers, 1998)
	dep5	Reuse – Recycle	(Abdullah & Anumba, 2002; del Rio Merino et al., 2010; Kasai, 1988)
	dep6	Time	(Abdullah & Anumba, 2002; Kasai, 1988; Yuan et al., 2011)
	dep7	Demolition Method	(Abdullah & Anumba, 2002; Kabirifar et al., 2020; Kasai, 1988; Kibert et al., 2000; Kourmpanis et al., 2008; Poon, 1997; Chi Sun Poon, Ann Tit Wan Yu, Siu Ching See, et al., 2004)

2.6 Construction Waste in the Construction Life Cycle (Design, Construction, Maintenance, and Demolition)

It has been claimed that waste could be generated at any stage of the construction, from conception to design, construction, and operation of the built facility, and can be caused by one or a combination of several variables (Gavilan & Bernold, 1994). In this respect, the study tried to accumulate these factors into four categories: design, construction, maintenance and operation, and demolition to conclude a framework to minimize the construction waste in the construction life cycle of the industrial projects integrated with BIM and Lean concepts for both quantitative and qualitative factors.

Before starting the building process, the first step is to create construction project designs. It is notable that there are two factors contribute to construction waste: the mindset of the designer ignores the probability of construction waste. One of the prominent reasons of waste in the design phase is the minimum order for specific objects from suppliers, specifying an excessive number of materials and sizes for a construction project may result in the much more demand of substantial quantities of material and by a result increase the project cost. Furthermore, the design could be amended during the construction time resulting in several unusable materials and thus much more waste. It could be noted that the absence of perfect shop drawings can lead in too much cutting or fitting shape or sizes of an installed materials may result in waste if standard sizes. On the hand, the lack of awareness of the standard size of real building materials on the market can also increase waste (Haponava & Al-Jibouri, 2012). It could be inferred that the inaccurate specifications can lead in too much materials demand and then changes in the materials which result in waste.

During the construction phase, the design and documentation are essential to be reviewed in the building phase, which is the most significant process, since the most recognized causes of waste arise during this period. It has been claimed that construction waste is created mostly during site operations and rarely appears at the first phases (Osmani et al., 2006), therefore, a considerable attention has to be paid in the start of the construction of the project to alleviate waste as much as possible.

Maintenance is the process of maintaining a building in order to provide its original designated function and has several definitions according to literature. British Standard 3811 defines building maintenance as "a combination of all actions used to maintain or restore an item to an acceptable condition." It can also be defined as "work performed to keep, restore, or improve every facility, i.e., every part of the building, its services, and surroundings, to a currently acceptable standard and to sustain the utility and value of the facility" in recognition of the significance of including a reasonable element of improvement" (Arditi & Nawakorawit, 1999). It could be inferred that maintenance is the appropriate tool that can restore the building to its original condition.

Regarding the demolition phase, it would be profitable to limit the production of end-of-life waste, and these

decisions could be determined in the design phase (Chen et al., 2006; Cheng & Ma, 2012; Yuan et al., 2011). It is notably to consider and waste quantification during demolition as it has played a major role in calculating disposal costs (Cochran et al., 2007; Masudi et al., 2012; Wu et al., 2014). In this respect, end-of-life activities generate a substantial amount of waste. Accordingly, this massive amount of non-recyclable waste will increase the effect on the environment.

Recent academic advancements in mitigating material waste within Egypt's industrial construction sector highlight a progressive shift from foundational digital coordination toward highly automated, predictive technologies. Early 2025 research underscored the critical need to address material inefficiencies at the conceptual design stage, proposing multidimensional strategies where Building Information Modeling (BIM) facilitates clash detection and prefabrication to prevent costly design iterations, while simultaneously integrating Lean construction philosophies such as Value Stream Mapping and just-in-time logistics to systematically eliminate non-value-adding activities across the supply chain. Building directly upon these paradigms, the latest 2026 literature pivots toward intelligent, real-time interventions by embedding Artificial Intelligence within BIM environments to predictively optimize supply pipelines, an approach proven to significantly curtail material surplus in complex domestic mega-projects. Concurrently, the frontier of this research introduces the synergy of Digital Twins and Lean 4.0 methodologies, utilizing IoT sensors to continuously synchronize the physical site with its digital counterpart, thereby enabling live monitoring and localized "waste-to-value" recycling loops throughout the facility's entire lifecycle. Collectively, these four studies trace a cohesive evolutionary roadmap for the Egyptian market, moving from proactive digital design frameworks to dynamic, AI-assisted operational management to achieve unprecedented resource efficiency. The convergence of advanced digital frameworks and lean methodologies represents a transformative shift in the pursuit of a sustainable built environment, specifically regarding the mitigation of construction waste. Current research underscores that addressing waste must begin during the conceptual phase, where a multidimensional design strategy can preemptively reduce debris generation within architectural practices. This proactive approach is significantly enhanced by the synergistic integration of Building Information Modeling (IM) and Lean Construction principles, which streamline workflows and minimize non-value-added activities throughout a project's lifecycle. Furthermore, the advent of Industry 4.0 has introduced sophisticated tools such as Digital Twins and Artificial Intelligence-driven big data analytics, enabling real-time material monitoring and high-precision waste forecasting for complex industrial infrastructure. By synthesizing these technological advancements—ranging from predictive AI models to live Lean 4.0 monitoring systems the construction industry can transition from reactive waste management to a data-centric, circular economy model that optimizes resource efficiency and environmental stewardship in rapidly developing markets.

3. Research Methodology

The research adopted appropriate statistical tools to conclude the degree of importance of the factors causing the waste of construction. then testing the reliability of these factors and the design of the survey using the SPSS and other related software's to validate the accuracy of the results, this can illustrate as follows:

3.1 Data Processing

A web-based questionnaire form was used to collect information from contractors, owners, and consultants. The completed surveys may be sent in, transformed automatically, and saved in Excel worksheets. The questionnaire was developed using the following factors:

1- A complete list of 35 factors influencing construction waste (CLC) has been compiled from the literature. Based on the recommended method of classification (Wambeke et al., 2011), (a) Elements that were only appropriate for particular projects and activities were eliminated and (b) components with similar characteristics can be grouped together. The selected elements have been redefined and reduced to 23 construction waste factors.

According to the methodology of this research, the factors that are arithmetic mean three and less than three were ignored, and these s were grouped into four categories: design, construction, maintenance & operation, and demolition, according to their sources, as shown in Table (2).

2- Academics and construction practitioners estimated the degree of importance for each factor that causes construction waste in the construction life cycle for the mentioned industrial projects in a questionnaire measuring the degree of relative importance to ensure the understanding and appropriateness of the content.

3- Respondents were asked to rate the questionnaire. Table (2) lists the individual factors in terms of their effect on construction waste in all phases of the project. The level of constraint is measured on a 5-point Likert scale, with 5 denoting very high, 4 denoting high, 3 denoting neutrals, 2 denoting low, and 1 denoting negligible.

4- To evaluate the validity of the survey's design and content, a prototype survey was created. A sample of 14 construction industry experts were given the questionnaires, and the overall internal consistency reliability coefficients

were 0.65, which is considered satisfactory in statistical analysis.

Table 2: Waste Factors Were Grouped into Four Categories: (Design, Construction, Maintenance & Operation, and Demolition), As Shown.

Criteria	Criteria Description
Design Phase	
Structure Type	There are many different types of structures, including(steel, precast concrete, composite, wood, and in situ concrete).
Material Type	Utilizing sustainable reusable, recyclable materials, specify building materials with a long life span, specify durable materials. Also to avoid secondary finishes, toxic, hazardous, composite materials. Additionally, to consider material handling and specify the lightweight materials.
Method of Construction	Traditional buildings or pre-cast buildings are used.
Element Type	The number and type of elements are minimized, and interchangeable building elements are used to ensure proper dimensional coordination.
Foundation Type	Using a retractable foundation from the ground or a traditional foundation.
Section Type	Design sections are optimized to reduce the amount of material used, and thus construction & demolition waste generation is eliminated.
Joint and Connection Type	Bolted joints are utilized instead of chemical ones such as gluing and nail joints. To use the joints and connectors that can endure repeated use.
Construction Phase	
Design Change	Lack of communication between contractors and designers, and clients during the design phase
Design Errors	Designers' lack of understanding of the nature and quality of the project leads to design errors
Complex Design	The design was not optimized to use less materials.
Wrong Material Storage	Materials were not kept in a safe place on the property to guard against damage before it happened and excessive inventories, which led to materials waste and monetary waste.
Poor Workmanship	Poor qualification of teamwork and unskilled workers, and poor labor productivity.
Waiting Time	Operational downtime frequently stems from a misalignment between material flow stabilization, workload balancing, and the synchronization of disparate labor teams or mechanical assets.
Unstructured Movement and Non Productive Site Plan	Poor planning and organization of work on the site.
Maintenance and Operation Phase	
Cost For Maintenance	The cost of the maintenance operation is highly if compared with the refurbishment cost
Time For Maintenance	Probable periods for major repair activity for fabric and services are linked to the selection of materials, components and The allowable time between recognition of the required maintenance or repair a specific item
Information About Building	Intended building life span, life to a major change of use, lack of knowledge about the technical condition of the components which installed a long time ago or applied cutting edge technologies can make the maintenance period longer than planned
Materials	suitable material for different maintenance types and refurbishment
Demolition Phase	
Structure Design	height – type - stability – degree of demolition – use of the structure - period of construction
Characteristic	Contract stakeholder awareness of specified techniques, availability of plant & equipment and expertise
Past Experience	
Reuse – Recycle	Level of reuse and recycling for materials, waste, and components.
Time for Demolition	Time for site preparation and actual demolition.
Demolition Method	Machines employ hydraulic crushers along the boom arm or to use a wrecking ball implosion when utilizing top-down hand techniques.

3.2 Design of Sample Size

The required sample size can be statistically calculated according to the equation of Marzouk et al. (2014), as follows:

$$n = \frac{\left(z_{\alpha/2}\right)^2 * p * (1-p)}{d^2} \quad (1)$$

Where; n is the sample size, $z_{\alpha/2}$ is the critical value from statistical tables, P is the percentage of the target sample population to the total population, and d is the accepted error percentage.

Where: the size of a sample is (N), by using $z_{\alpha/2} = 1.645$ When the Statistical value equals 1.645, (P) is used as a percentage of the target population, and (d) is used as a percentage of 10% for the acceptable error.

3.3 Statistical Analysis Tests

The research uses statistical techniques (Cronbach's Alpha, explanatory factor analysis, Pearson correlation, Kruskal Wallis test) to verify the validity of the experts' opinions using SPSS 24 software.

Cronbach's Alpha for measuring Reliability.

Kruskal -Wallis test for comparing means of experts' opinions.

Explanatory Factor Analysis for checking the validity of the expert's opinions.

Pearson Correlation Coefficients for studying the relation among opinions.

3.3.1. Reliability Analysis

Reliability analysis can be used to assess the dependability of measuring scales. According to the extent to which a test or technique produces comparable results under consistent conditions in all situations (Yin, 1994). If the scale's dependability is inadequate, (Cronbach) suggests that individual components within the scale be re-examined and amended or fully altered if needed. In this regard, the reliability test is critical when using derivative variables in later predictive studies. Hence, it could be noted that the scale is more internally dependable if the alpha value is close to 1 - preferable to 0.8 or higher (Bryman & Cramer, 2005). Considering that dependability is less than 0.6 to be poor, 0.6-0.7 to be acceptable, and greater than 0.8 to be excellent (Sekaran & Bougie, 2010). Therefore, the research tried to unfold these statistical analysis methods to gauge the results with certainty.

3.3.2. The Kruskal-Wallis Test

The Kruskal-Wallis H test serves as a robust non-parametric alternative to the one-way analysis of variance (ANOVA), specifically designed to determine whether statistically significant differences exist between three or more independent groups when the underlying data does not meet the assumptions of normality. Unlike parametric methods that rely on mean values, this rank-based test evaluates the distribution of a single continuous or ordinal variable across multiple populations by converting raw scores into ranks, thereby accommodating skewed data and outliers that might otherwise distort the results. Consequently, it is an essential analytical tool in empirical research for validating the consistency of expert opinions or experimental outcomes across diverse, unrelated samples, providing a rigorous mathematical basis for rejecting the null hypothesis and ensuring that any observed variations are not merely the result of random chance. It is a rank-based one-way analysis of variance, which can be used with ordinal or rank data. It is a two-group Mann-Whitney U (Wilcoxon rank) test that has been extended. In addition, it is considered a non-parametric variation of the one-way ANOVA and is a more generalized version of the Mann-Whitney U test (Kruskal & Wallis, 1952). Furthermore, the Kruskal-Wallis test also examines the null hypothesis that many independent samples from the same population are coming from the same source (Harlow, 1980; Kruskal & Wallis, 1952). It could be inferred that the Kruskal-Wallis test is a non-parametric null hypothesis test used in statistics to verify whether various groups of people have different opinions on a given subject.

3.3.3. Exploratory Factor Analysis

Factor analysis is a multivariate statistical method utilized in psychology, education, and, more recently, health-related fields. Many scholars have employed it in construction management (Ahadzie, 2007; Bassioni, 2004; Li et al., 2005). Especially paramedics can use factor analysis to develop, refine, and assess tests, scales, and measures for use in education and clinical settings. The first need for factor analysis is being preferable approach for evaluating self-reporting surveys because it allows many variables to be reduced to a smaller number of variables (also could be termed as factors). Second, it identifies underlying dimensions between measurable variables and latent conceptions,

allowing for theory development and proper refinement. Finally, it shows that self-reporting measures have construct validity (Williams et al., 2010). It could be concluded this is the appropriate statistical method .in reducing the number of variables to ensure better results.

3.3.4. Pearson's Correlation Analysis

Pearson's correlation coefficient functions as a sophisticated statistical instrument designed to quantify the magnitude and direction of the linear association between two distinct datasets. Within the context of academic research, this metric is indispensable for evaluating the degree of interdependence among variables, allowing investigators to ascertain whether a change in one factor consistently corresponds with a predictable shift in another. By providing a standardized numerical output, typically ranging from -1.0 to +1.0, it enables a rigorous assessment of data consistency and relationship strength, which is essential for validating conceptual frameworks and ensuring the reliability of empirical findings. Consequently, the application of this correlation analysis serves as a foundational step in inferential statistics, facilitating the identification of significant patterns that support more informed and evidence-based decision-making in complex project environments. The interval or ratio level, linear relationship, and bivariate normal distribution assumptions must all hold for its computation and subsequent significance testing. It is used to analyze sample data as a sign that two quantitative variables have a linear relationship (Matthews & Ross, 2010). It also can be used to test the null hypothesis that the variables X and Y have no relationship. Pearson's R is a number that runs from -1 to +1 and is not expressed in any unit of measurement. There is no connection between the variables if the correlation value is 0 (LeBlanc, 2004). The bivariate correlations process was used to determine pair-wise relationships for a collection of variables in a matrix. This study determined the degree and direction of the correlation between ordinal variables using Pearson's correlation. It should be noted that for a significant correlation when analyzing the amount of correlation between factors or variables: 0.19 and less is considered very low; 0.20 to 0.39 is considered low; 0.40 to 0.69 is considered modest; 0.70 to 0.89 is considered high, and 0.90 to 1.00 is considered quite high (Cohen & Holliday, 1982).

4. Assembling Statistical Analysis Results

4.1 Reliability Analysis

The research started the questionnaire with 20 experts' opinions, and then some opinions were excluded in order to reach the acceptable bound of reliability (0.65) according to the following Table (3).

Table 3: According to Cronbach's Alpha after Exclusion.

Experts	Cronbach's Alpha after exclusion
Expert 12	0.206
Expert 10	0.291
Expert 2	0.368
Expert 15	0.423
Expert 7	0.475
Expert 6	0.518

According to Table (3), the research had to exclude six experts (2, 6, 7, 10, 12, and 15) to raise the value of Cronbach's Alpha to the acceptable bound.

Table 4: The Reliability of the Experts' Opinions.

Reliability Statistics	
Cronbach's Alpha	N of Items
0.65	14

According to Table (4), there is acceptable reliability in the experts' opinions where the value of Cronbach's Alpha =0.65, which is greater than 0.6.

4.2 Exploratory Factor Analysis

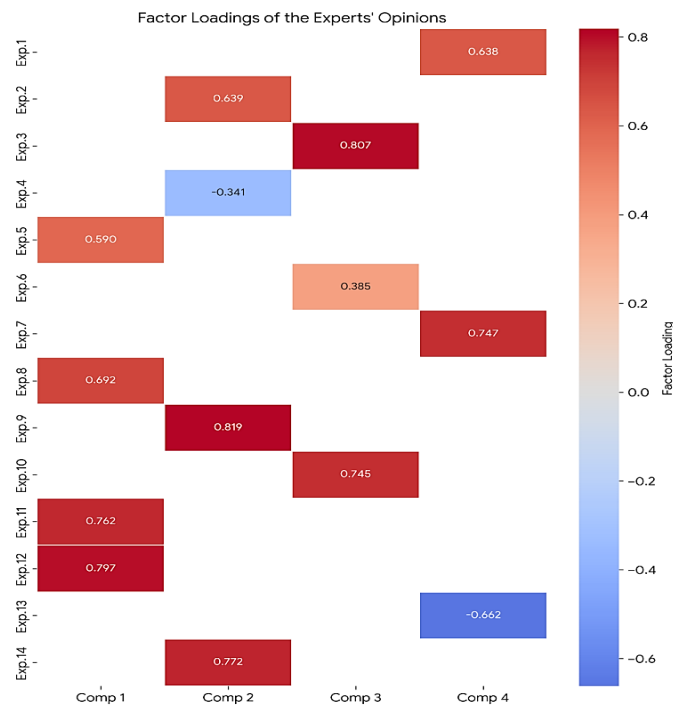
The research used explanatory factor analysis to verify the validity of experts' opinions according to Tables (5) and (6).

Table 5: The Number of Extracted Components.

Component	Initial Eigenvalues			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	2.514	17.958	17.958	2.408	17.202	17.202
2	2.315	16.537	34.495	2.118	15.126	32.328
3	1.736	12.402	46.897	1.922	13.727	46.055
4	1.584	11.315	58.212	1.702	12.157	58.212

Extraction Method: Principal Component Analysis.

According to Table (5), the four common factors managed to absorb 58% (>50%) of the variations between experts' opinions, so there is a factor validity.

**Figure 1:** Factor Loadings of the Experts' Opinions.**Table 6:** Factor Loadings of the Experts' Opinions.

Experts	Component			
	1	2	3	4
Exp.1				0.638
Exp.2		0.639		
Exp.3			0.807	
Exp.4		-0.341		
Exp.5	0.590			
Exp.6			0.385	
Exp.7				0.747
Exp.8	0.692			
Exp.9		0.819		
Exp.10			0.745	
Exp.11	0.762			
Exp.12	0.797			
Exp.13				-0.662
Exp.14		0.772		
Extracted Variation	17.2%	15.1%	13.7%	12.1%

According to Figure (1) and Table (6), it could be concluded that:

The first component explains 17.2% of the variations between experts' opinions, including the following opinions (5,8,11,12), where the values of factor loadings are higher than 0.3.

The second component managed to explain 15.1% of the variations between experts' opinions, including the following opinions (2,4,9,14) where the values of factor loadings are higher than 0.3.

The third component explains 13.7% of the variations between experts' opinions, including the following opinions (3,6,10) where the values of factor loadings are higher than 0.3.

The fourth component explains 12.1% of the variations between experts' opinions, including the following opinions (1,7,13), where the values of factor loadings are higher than 0.3.

4.3 Correlation Analysis

Table 7: The Correlation between Experts' Opinions.

Experts	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Exp.1	1.0	0.0	0.1	0.1	0.2	-0.3	0.3	0.0	0.1	0.0	-0.1	-0.3	-0.2	-0.1
Exp.2	0.0	1.0	0.2	-0.1	-0.1	0.2	0.2	.568**	0.4	-0.1	0.4	0.2	0.1	0.2
Exp.3	0.1	0.2	1.0	0.0	0.2	0.3	0.2	-0.3	-0.2	0.3	0.2	-0.3	0.0	-0.1
Exp.4	0.1	-0.1	0.0	1.0	0.2	-0.1	0.1	0.0	-0.1	0.2	-0.1	0.2	0.0	-0.1
Exp.5	0.2	-0.1	0.2	0.2	1.0	0.0	0.1	0.1	-0.1	.418*	.521*	.464*	0.0	-0.1
Exp.6	-0.3	0.2	0.3	-0.1	0.0	1.0	0.1	-0.1	0.0	0.0	-0.2	0.1	0.0	0.1
Exp.7	0.3	0.2	0.2	0.1	0.1	0.1	1.0	0.2	0.0	0.1	0.1	0.1	-.42*	-0.1
Exp.8	0.0	.568**	-0.3	0.0	0.1	-0.1	0.2	1.0	0.1	-0.1	0.3	0.4	0.1	-0.1
Exp.9	0.1	0.4	-0.2	-0.1	-0.1	0.0	0.0	0.1	1.0	0.0	0.0	0.1	0.3	.784**
Exp.10	0.0	-0.1	0.3	0.2	.418*	0.0	0.1	-0.1	0.0	1.0	0.4	-0.2	0.0	0.0
Exp.11	-0.1	0.4	0.2	-0.1	.521*	-0.2	0.1	0.3	0.0	0.4	1.0	.472*	-0.1	-0.1
Exp.12	-0.3	0.2	-0.3	0.2	.464*	0.1	0.1	0.4	0.1	-0.2	.472*	1.0	0.0	0.1
Exp.13	-0.2	0.1	0.0	0.0	0.0	0.0	-.42*	0.1	0.3	0.0	-0.1	0.0	1.0	0.1
Exp.14	-0.1	0.2	-0.1	-0.1	-0.1	0.1	-0.1	-0.1	.784**	0.0	-0.1	0.1	0.1	1.0

** . Correlation is Significant at the 0.01 Level (2-tailed).

* . Correlation is Significant at the 0.05 Level (2-tailed).

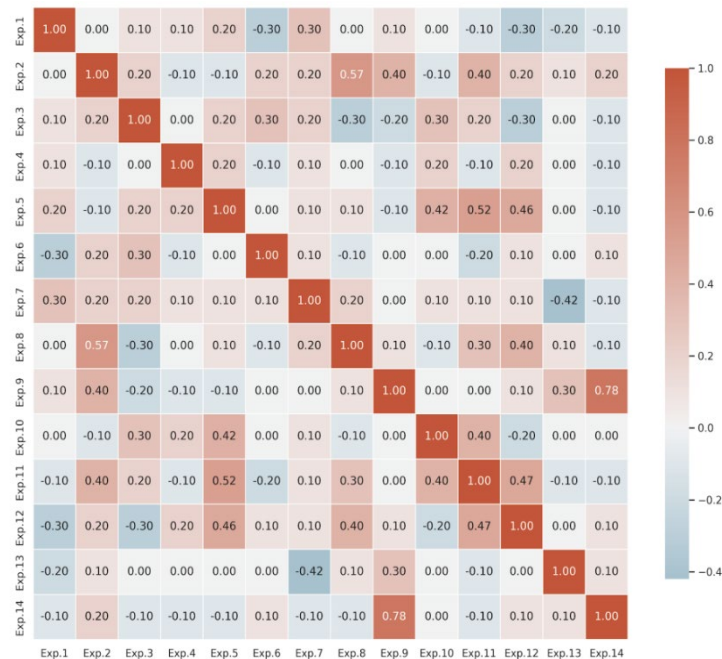


Figure 2: Correlation Matrix between Experts' Opinions.

From Table (7) and Figure (2), it is clear that:

There is no correlation between expert (1) and all other experts.

There is no correlation between expert (2) and all other experts, except for expert (8).

There is no correlation between expert (3) and all other experts.

There is no correlation between expert (4) and all other experts.
 There is no correlation between expert (5) and all other experts, except for experts (10,11,12).
 There is no correlation between expert (6) and all other experts.
 There is no correlation between expert (7) and all other experts, except for expert (13).
 There is no correlation between expert (8) and all other experts, except for expert (2).
 There is no correlation between expert (9) and all other experts, except for expert (14).
 There is no correlation between expert (10) and all other experts, except for expert (5).
 There is no correlation between expert (11) and all other experts, except for experts (5,12).
 There is no correlation between expert (12) and all other experts, except for experts (5,11).
 There is no correlation between expert (13) and all other experts, except for expert (7).
 There is no correlation between expert (14) and all other experts, except for expert (9).

4.4 Kruskal-Wallis Test

The research used the Kruskal-Wallis test to compare means of experts' opinions, as depicted in Table (8)

Table 8: The Kruskal-Wallis Test Results to Compare Means of Experts.

Experts	Mean	Std. Deviation	Kruskal Wallis Test	df	p-Value
1	3.6522	0.98205	16.18	13	0.24
2	3.1304	0.96786			
3	3.5652	1.16096			
4	3.3043	1.29456			
5	3.7391	0.91539			
6	3.3913	0.72232			
7	3.6522	1.11227			
8	3.1739	1.11405			
9	3.3478	1.33514			
10	3.2609	1.13688			
11	3.9565	0.92826			
12	3.7391	1.00983			
13	3.2174	1.08530			
14	3.5652	1.23679			
Total	3.4783	1.08852			

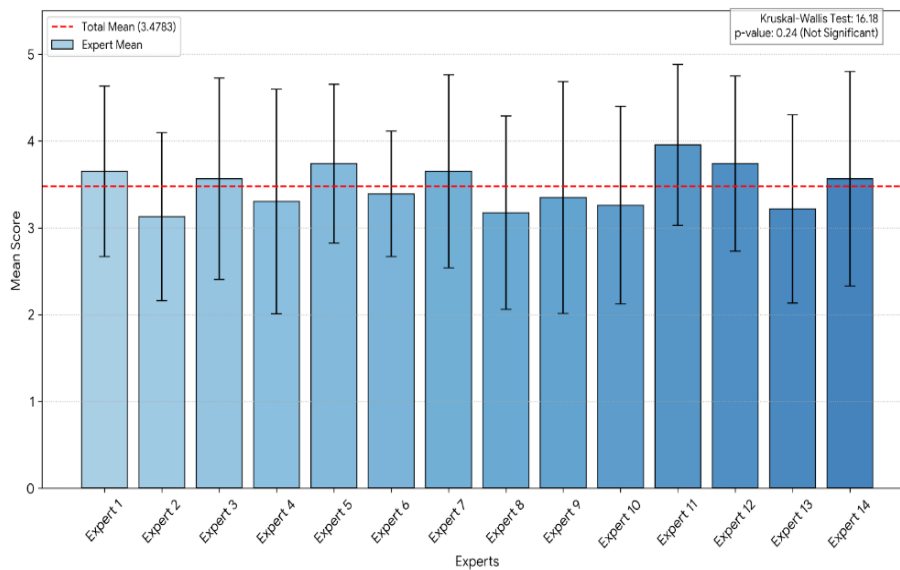


Figure 3: Experts' Opinions: Mean Scores and Standard Deviation.

According to Table (8) and Figure (3), it can be concluded that:

There is no significant difference in means among all experts' opinions where the p -value = 0.24, which is greater than ($\alpha=0.05$), indicating a similarity in opinions among experts.

5. Discussion

In the above-mentioned survey, respondents rated a number of factors in terms of their impact on construction waste in the construction life cycle CLC of industrial projects (design, construction, maintenance, demolition). The research tried to identify construction waste generation factors in all different stages of construction. Starting with, the most critical 35 factors mentioned in (table1) were identified as per the literature review also according to experts and the surveys. Eventually, the experts participating in the survey determined the degree of importance of the factors through a Likert scale that consists of 23 factors (table2) that are of major importance in generating construction waste at all stages of construction in industrial projects.

Accordingly, inferential statistical tests were carried out for the opinions of the selected experts. The sample size was designed according to Equation (1), which consists of 12 experts. The experts' opinions were increased to 20 experts to increase the accuracy of the results.

When the reliability test was conducted, the opinions of 6 experts gave weak reliability according to Table (3), so they were ignored. 14 experts gave a value of 0.65 which is an acceptable value according to Table (4).

An explanatory factor analysis test was conducted to validate expert opinions. The four common factors managed to absorb 58% ($> 50\%$) of the variations between experts' opinions; so there is factor validity according to Table (5).

Then, the research calculated the Pearson correlation coefficient for measuring validity. Pearson correlation test has two hypotheses, the null hypothesis "there is no correlation" while the alternative hypothesis "there is correlation". Based on P - the value the researcher can decide to accept or reject the null hypothesis. P -value > 0.05 mean accepting the null hypothesis, while p -value < 0.05 means rejecting the null hypothesis. Pearson correlation coefficient ranges from -1 to 1, values with sign (-) mean negative correlation, and Values with sign (+) mean positive correlation. Values between 0.1 and 0.4 mean weak correlation, 0.4-0.7 mean moderate correlation and 0.7-1 mean strong correlation according to Table (7) 0.4-0.7 mean moderate correlation.

The research has conducted Kruskal - Wallis test for comparing the results of experts' opinions. Kruskal - Wallis test has two hypotheses, the null hypothesis "there is no difference in means" while the alternative hypothesis "there is a difference in means". Based on P -value the researcher can decide accepting or reject the null hypothesis. P -value > 0.05 means accepting the null hypothesis, while p -value < 0.05 means rejecting the null hypothesis according to a table (8) There is no significant difference in means among all expert's opinions where the p -value = 0.24 which is greater than ($\alpha=0.05$); this indicates a similarity in opinions among experts.

It could be concluded that the Statistical Package for Social Science (SPSS) was used where the respondents' scores assigned to each factor were entered. Then, the response questionnaires have been further verified by a statistical analysis to give accuracy. According to the current research, the contribution of each factor to construction waste generation was precisely determined during the construction phases of the industrial projects (design, construction, maintenance, and demolition).

6. Conclusion

Achieving significant waste reduction throughout the construction lifecycle is a critical imperative for industrial projects, given their inherent structural complexity and the massive scale of their components, both of which necessitate advanced operational management. This research established a comprehensive conceptual framework designed to mitigate both quantitative and qualitative waste drivers by integrating Building Information Modeling (BIM) and Lean Construction principles across the design, construction, maintenance, and demolition phases. A central finding of the study highlights that proactive, early-stage interventions during the design phase guided by BIM serve as a primary mechanism for curbing qualitative waste factors, which subsequently streamlines maintenance and diminishes demolition at the end of the facility's service life. Simultaneously, the application of Lean methodologies focused on the quantitative factors prevalent during the construction phase, identifying this period as the peak interval for waste generation. The study is developing a BIM and lean decision framework to decrease material waste in mechanical system interfaces of industrial facilities, based on experts' knowledge. It covers the fact that material waste can arise from substandard workmanship or poor estimate of quantities, but it could be due to lack of coordination of interface issues with mechanical equipment, another part of the structure, a service route, another piece of plumbing equipment, another piece of electrical equipment, a sequence of the work, access for service items, or dismantling needs. Combining BIM and lean construction concepts for eliminating waste can provide a systematic approach to dealing with waste-producing situations before they occur to impact procurement, fabrication and installation onsite.

The framework demonstrates that BIM can be most successful if it is used as a decision support tool or as a clash detection tool. BIM can allow project teams to visualize mechanical systems within other disciplines, highlight hard clashes and clearance issues, review quantities, evaluate constructability and visualize installing mechanical systems before materials are even manufactured or deployed to the field. These capabilities help ensure better and more timely decisions to avoid rework, unnecessary materials procurement, off cut and late design changes. Lean principles are not just used alongside BIM, but are embedded within the process, with a clear prioritization of risk, assigning responsibility, pulling in plans to address risk and a process of continuous improvement. The advantages of this research are the structure formed according to the input of experts. As context-based problems, like access to maintenance, feasibility of fabrication, operability of equipment or waste during dismantling, can only be identified using context, automated BIM checks may be able to detect them. However, it is important that the mechanical engineers, BIM coordinator, construction managers, procurement experts, fabricators and site supervisors have a sound understanding and perspective on interface risks and the selection of a suitable solution. The framework takes the expert judgment into a structured decision-making process, which connects individual waste drivers (late design change, incorrect measure, asynchrony in coordination, wrong sequencing, lack of clearance) to targeted waste interventions based on BIM and lean principles. The proposed model can help in material planning stage with more accuracy, in the factory readiness stage in material preparation of the pieces, with a lower rework/recycling and/or with a lower rate of material scrap, and with better collaboration between different departments in industrial projects. It also enables project teams to document waste risk, give ownership of the management of the waste risk, and evaluate the maturity of the interface between the mechanical system, before taking procurement and/or installation. This allows BIM to enable visualization and coordination through data to be set to BIM's value creation and waste reduction aspects as promoted by lean. The framework should be extended with further studies on a multiple industrial case-studies to validate the framework, quantify the effects of material waste, rework, cost and schedule, and extend the framework with digital tools such as 4D BIM, digital twin, machine learning-based clash prioritization, real-time material tracking, etc. Further efforts may also lead to an industry standard interface-risk checklists and decision rules for mechanical systems, including HVAC, process piping, fire protection and utility networks. When considering overall sustainability, it concludes that a BIM–lean decision process using the team expertise could increase the efficiency, effectiveness and coordination of the mechanical systems delivered in industrial facilities.

7. Research Contributions

This research deals with the problem of construction waste in the construction life cycle of industrial projects based on the literature review reviewed in this research. This study tried to improve the literature review to a more boarder view and comprehensive way of thinking to address the problem of construction waste. This research proposed a framework for the construction life cycle of industrial projects using BIM and Lean concepts.

7.1 Limitations and Implications.

Inferential statistical analysis test results of the factors causing construction waste need more clarification towards the appropriate solution or advice needed by decisionmakers to reduce construction waste in the construction life cycle of industrial projects. There is a need to identify different alternatives to reduce construction waste for each stage of the construction life cycle of industrial projects.

7.2 Recommendations & Future Works.

Based on the above-mentioned results and interviews with experts, they have determined the qualitative and quantitative factors mentioned in this research for the construction life cycle of industrial projects causing construction waste. This raises the need for further research regarding the possible alternatives that can reduce construction waste for all stages of construction and further determine the best alternatives for all these phases.

7.3 Authorship Contributions

Construction waste; construction life cycle (CLC) construction waste factors; building information modeling; lean concepts and statistical analysis (Cronbach's Alpha, explanatory factor analysis, Pearson correlation, Kruskal wallis test) to check the validity of the experts' opinions using SPSS 24.

7.4 Funding

This research was conducted independently and did not receive any specific grants, commercial sponsorships, or external financial assistance from public or private funding agencies, The authors formally declare that there are no financial, personal, or professional affiliations that could be perceived as having influenced the objectivity, integrity,

or results of the research presented in this manuscript.

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