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ADVANCING THE CIRCULAR ECONOMY: A BIM AND LEAN CONSTRUCTION DYNAMIC FRAMEWORK FOR PRE-CONSTRUCTION PHASES

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Abstract. The execution of construction technology projects generates substantial construction waste, both site-based and non-site-based, posing significant environmental and economic challenges worldwide. This paper explores a proactive approach to minimizing construction waste by controlling its causes during the pre-construction phase by integrating Building Information Modeling (BIM) and Lean Construction principles. Key pre-construction activities such as cost estimation, scheduling, constructability reviews, value engineering, procurement, and contracting are analyzed for their potential to reduce waste. Two scenarios - Existing Waste Management Strategies and Waste-Effective Site Management Practices are assessed using quantitative metrics and system dynamics modeling. The proposed technique employs eight causal loop diagrams, reflecting expert insights into waste reduction strategies, and is implemented using AnyLogic software with a stock-flow system dynamics model. Validation is achieved through a real-world case study, demonstrating the technique's applicability and effectiveness in minimizing construction waste during the pre-construction phase. The findings highlight the dynamic buildup of critical variables influencing waste generation and provide a framework for evaluating and implementing optimal waste reduction strategies. This research underscores the potential of BIM and Lean Construction to drive sustainable waste management practices in construction technology projects, contributing to enhanced efficiency and environmental stewardship.

Keywords: sustainable pre-construction phase, construction waste, lean construction and BIM, system dynamics, sustainability.

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1. Introduction

The construction industry significantly impacts sustainability, consuming vast natural resources and contributing 44% of landfill waste in the UK (Anderson et al., 2002; Department for Environment, Food and Rural Affairs, 2013). Industrial construction projects, often complex and hazardous, require improved efficiency and management to address waste generation and enhance sustainable practices during the construction phase (Meshref et al., 2022; Hu & Mohamed, 2014; Horman & Kenley, 2005). At the beginning in construction practices, design phase and documentation are essential to be reviewed during construction practices, which are the more significant processes, since the most recognized causes of waste arise during this period. It has been claimed that the waste of construction 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 preconstruction phase that include (cost estimating – scheduling – constructability reviews – value engineering – procurement – contracting) of the industrial projects to alleviate construction waste such as (non-site based and site based) waste as much as possible.

Construction waste is defined as "any material that must be transported away from construction site or utilized on site itself for landfilling, reusing, or recycling other than the intended specific aim of the project due to material damage, non-use, excess, or non-compliance with the specifications, or because it is a by-product of the construction process" (Ekanayake & Ofori, 2000). Waste generated through construction, refurbishment, and demolition projects, such as site clearing, road construction, building, land excavation, remodeling, and demolition, is known as (C&D) waste (Shen et al., 2004).

There are two primary types of construction waste; the first is physical waste such as material waste, which includes excess ordering, improper handling, excess output, improper storage, and manufacturing flaws. The second is non-physical such as waste time overrun, which includes waiting times, clarification requests, interruptions, changes in information, information rework, inefficient work, delays in scheduled operations, and anomalous equipment wear (Anis et al., 2001). Additionally, it has been anticipated that cost overrun results from various types of both time overrun and material waste on construction projects. In the Dutch construction industry, solid waste accounts for between 1% and 10% of all incoming construction materials, or about 9% of the total quantity of materials purchased (Bossink & Brouwers, 1996). Since materials contribute more than half of the cost of a building project, at least 20% of the material purchased will often remain unused after every project (Yuan, 2012). In this regard, it is notable to review cost overrun that will affect the competitive edge of contractors, making their survival more difficult in such a competitive environment (Macozoma, 2002). It could be concluded that a broader view of waste management is needed to minimize both material waste and resource waste such as equipment and labor (Formoso et al., 2002). Construction waste stems from site-based and non-site-based factors during the construction phase. Addressing these in preconstruction – via cost estimating, scheduling, constructability reviews, value engineering, procurement, and contracting – is crucial. This study leverages BIM and Lean construction to identify key factors and propose scenarios for minimizing waste in the preconstruction stage.

BIM is defined as the process of developing, preserving, transferring, and disseminating building information that is operable, reusable (Vanlande et al., 2008). It involves creating and implementing a computer-generated model to reproduce a project's construction life cycle (Azhar et al., 2008). BIM is the practical of creating and using a computer-generated model to duplicate construction life cycle of a building facility. BIM can be respected as a store of data, intelligent, object-oriented, and parametric digital presentation of building facilities (Associated General Contractors of America, 2005). It is spatial and data transmission technology that would be integrated efficiently and systematically with identification and data collection technologies in architectural, engineering, and construction (AEC) industry. In this regard, BIM represents both physical, functional characteristics of a specific building (NIST, 2012).

The lean construction (LC) concept has been derived from lean manufacturing concept and refers to Toyota production system (Bajjou et al., 2017). The implementation of lean thinking has been regarded as a basic feature in the building industry and has been termed as "the new production philosophy" in construction industry (Koskela, 1992). This term was created by the global set for LC during a conference held in Finland in its first implementation in 1993 (Alarcón, 1997). In this respect, LC is "a strategy of structuring manufacturing processes so as to maximize value while minimizing resources waste, time and labor" (Koskela et al., 2002). The term LC has a variety of definitions, ranging from a broad definition that incorporates all design and building processes to definitions focusing on specific production tasks and tool applications by contractors (Emmitt, 2007; Nouh et al., 2022b).

Industrial construction projects have many phases, complex disciplines that must be considered through many components frame. In this respect, dynamics are procedures to control and analyze sophisticated feedback systems that were decided specifically to cooperate with complex systems (Yuan, 2012). Dynamic technique is a group of components that react with another elements to nature of reaction (Cheng, 2012).

The study suggests utilizing dynamics technique for all major variables to evaluate both scenarios – Existing waste management strategies and Waste effective site management practice – to minimize construction waste such as (non-site based and site based) waste during preconstruction phase in industrial projects. To manage the optimal preconstruction phase, Stakeholders would be capable of estimate objective functions' effect, prior putting into implementation, utilizing the proposed model. The model is able to, firstly: maximizing quality concepts in pre-construction phase, construction technology projects, secondly: Improving material productivity through pre-construction phase and construction technology projects, thirdly: Minimizing cost overrun, time overrun, LICC, material waste through construction technology projects, fourth: maximizing (LEAED) impacts and (LICA) in pre-construction phase (Meshref et al., 2023). The novelty of this research arrive for utilizing a dynamics technique for all major variables to assess two scenarios to minimize construction waste during preconstruction phase in industrial construction projects, taking into dynamic for variables' interaction, objective functions and different scenarios to minimize construction waste. The real case study, in this paper, highlighted more efficient causes of waste minimization that extend together national, international Stakeholders' better scenarios for minimizing construction waste during preconstruction phase that include (cost estimating – scheduling – constructability reviews – value engineering – procurement – contracting).

2. Literature review

2.1. The 3R Principle (Reuse, Recycle, Reduce)

The 3R Principle, which advocates reducing, reusing, and recycling waste, 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 economy and the environment (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, minmizing the utilize of raw materials, extending the live of natural resources, and lowering environmental pollution that is harmful human health. Increasing business prospects, cutting project costs, lowering the risk of litigation involving construction waste, and commitment to minimising the environmental effect of construction are just a few of the features from an economic standpoint (Addis, 2006; Dajadian & Koch, 2014; Nouh et al., 2022a). In this respect, research studies suggested several method to reduce construction and demolition waste with reducing, reusing, recycling construction waste (Porwal & Hewage, 2012).

2.2. Factors affecting construction waste such as (non-site based and site based) waste during pre-construction phase

Regarding the construction practices, construction form and its purpose, implementation process itself, project timetable, scale of the project, site circumstances, and the surrounding environment, all these causes 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 needed resources and planning, as well as methods and methodologies, is being determined based on the score of complexity. Environmentally, it could be noted that each building project is unique and difficult, requiring a significant quantity of processes and thus has a direct effect on the amount of waste created by construction operations (Karim & Marosszeky, 1999). In this regard, pre-construction preparations were the primary cause of construction waste during the building phase, and there are several additional elements contributing to construction waste through construction practices. Moreover, waste can be created throughout the building process because of poor coordination and control (Alwi et al., 2002; Khanh & Kim, 2014), poor construction technique selection (Bossink & Brouwers, 1996; Wan et al., 2009), and reworks (John & Itodo, 2013; Bekr, 2014). It could be inferred that more common issues mentioned during the building phase are order errors and poor workmanship, indicating that each element has a substantial role in waste generation throughout construction process because ordering errors increase in an overabundance or scarcity of orders. And as a result, over-ordering can increase in an overabundance of supplies and waste (Agyekum et al., 2012). Contrarily, a shortfall of orders may be found in insufficient material availability, halting building operations on the job site, and thus the material must be reordered, which will extend the time it takes to receive items from the supplier and by far extend the project deadlines (Nagapan et al., 2012). Regarding labor, the chosen of poor craftsmanship is considered a significant contributor to construction waste throughout the period of construction time. Moreover, unskilled labor, insufficient equipment, and tools, and/or a bad working environment can all contribute to poor craftsmanship (Gavilan & Bernold, 1995). It is like that important to note that poor craftsmanship may be caused, in some situations, by aggressive inspector supervisors and project managers (Nagapan et al., 2012). And by a result, poor craftsmanship will result in worker conflict due to deviations from the major goal (Wan et al., 2009). And finally, it may result in abandoned work, especially during the construction/renovation stage (Tam et al., 2007).

2.3. Categories for construction waste during the construction phase

The concepts of Construction and demolition (C&D) of construction waste generation includes several different waste sources that arises throughout the project construction from start to completion. There are six distinctive sources of construction waste including procurement, design, materials handling, residual, operation, and other aspects (Bossink & Brouwers, 1996). In that respect, a broader view for classification of construction 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) Practices and Site Management (Gavilan & Bernold, 1995). Accordingly, an evaluation for waste of construction according to the following sources: (1) design (i.e., detail error, blueprint error, 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., unreclaimable non-consumables and leftover scrap); and other factors (Gavilan & Bernold, 1995). In another perspective, conceptual planning and feasibility studies, design and engineering, construction, operation, and maintenance are few aspects that include a project's life cycle (Wang et al., 2009; Kartam, 1996). 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 (Liu et al., 2011; Alshubbak et al., 2009).

2.4. Scenarios for minimizing construction waste through preconstruction phase

Effective site management enhances construction performance and minimizes waste through adherence to project drawings, avoiding design changes, material logistic management, maximizing material reuse, and segregating waste, supported by contractual provisions (Figure 1 and Table 1) (Ajayi et al., 2015). Despite various waste management strategies, diverting construction waste from landfills remains challenging, contributing significantly to environmental pollution. The study examines Existing waste management strategies and Waste-effective site management practices (Figure 2 and Table 2) (Ajayi et al., 2015), simulating both scenarios during the pre-construction phase (e.g., cost estimating, scheduling, value engineering) to identify the most effective method for minimizing site-based and non-site-based waste. There are scenario requisites for effective waste management, this suggest scenario in the future to reduce construction waste during design and pre-construction phases (Figure 3 and Table 3).

The paper now clearly defines and differentiates the two compared approaches, Existing Waste Management Strategies (EWMS) and Waste-Effective Site Management Practices (WESMP), within the pre-construction phase of industrial projects. The EWMS approach includes conventional measures such as waste sorting and recycling, use of waste prediction tools, site waste management plans (SWMP), design for flexibility and deconstruction, just-in-time (JIT) procurement, offsite or modular construction, and compliance with environmental legislation or taxation incentives. In contrast, the WESMP approach focuses on proactive site-level management actions that prevent waste generation at its source, including contract management that embeds waste control clauses, segregation and reuse of materials, materials logistics management, and improved communication and supervision practices. Both methods were modeled as fixed quantitative variables influencing dependent factors such as design change, poor workmanship, waiting time, and unstructured site layout. Through system dynamics simulation, the study demonstrates how WESMP offers a more integrated, preventive, and efficient-driven approach compared to the reactive nature of EWMS, resulting in significantly lower waste outputs and higher productivity and quality indices.

Figure 1. Waste effective site management practice

Table 1. Waste effective site management components

S. No.	Extracted and rotated components	Eigen value	% of Variance	Factor loading	% Weighting within group
COMP-1	**Contract management**	9.474	35.174		
M-2	Waste target set for sub-trades			0.734	19.3
M-3	Recycling target to be set for every project			0.538	14.2
M-13	Follow the project drawings/designs			0.885	23.3
M-18	Ensure fewer design changes during construction			0.898	23.7
M-27	Making sub-contractors responsible for waste disposal			0.742	19.5
COMP-2	**Waste segregation**	8.096	29.985		
M-15	Preventing waste mixture with soil			0.729	19.6
M-16	Providing bins for collecting waste for each sub-contractor			0.564	15.2
M-17	Dedicated space for sorting of waste			0.777	20.9
M-19	Setting up temporary bins for each building zone			0.812	21.8
M-23	Provision of waste skips for specific materials (waste segregation)			0.837	22.5
COMP-3	**Materials reuse**	4.975	18.427		
M-1	Detect the construction activities that can admit reusable materials from the construction			0.582	13.3
M-7	Use of reclaimed materials			0.778	17.8
M-10	Reuse of off-cuts materials (such as wood)			0.661	15.1
M-11	Use of demolition and excavation materials for landscape			0.748	17
M-25	Soil remains to be used on the same site			0.701	16
M-28	Maximisation of on-site reuse of materials			0.91	20.8
COMP-4	**Materials logistic management**	3.377	12.507		
M-4	Use of safe materials storage facilities			0.662	17.6
M-5	Prevention of over ordering			0.651	17.4
M-6	Prevention of double handling of materials/Logistic management to prevent double handling			0.783	20.9
M-20	Adequate site access for materials delivery and movement			0.92	24.5
M-22	Central areas for cutting and storage			0.736	19.6

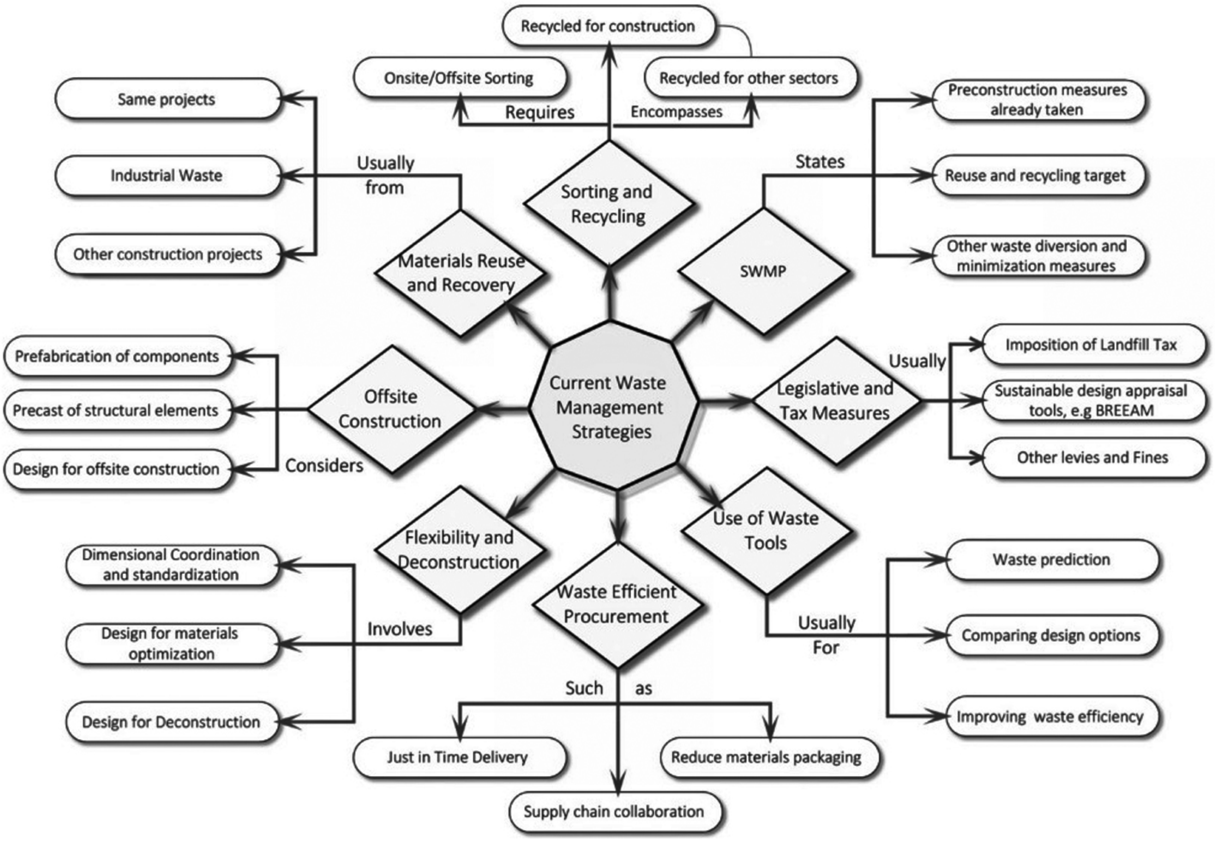


Figure 2. Existing waste management strategies

Table 2. Existing waste management strategies and impediments to their effectiveness

#	Waste management strategies	Limitations	Focus groups (1–4)	Category A–E*
1	Sorting and recycling	▪ Extra labour/man-hours is needed for successful sorting exercise	1, 3	D
		▪ Substantial site space is required, and it cannot be done in confined sites	3	C
		▪ Recycling consumes substantial energy for transportation and recycling	4	D
		▪ It is an end of pipe treatment rather than waste preventive measure	1, 2, 3, 4	A
		▪ It costs time, money and interferes with other site operations	3, 4	D
		▪ It cannot even tackle all waste categories as some are not recyclable	1, 2, 4	C
2	Materials reuse	▪ It is not adaptable for all waste streams	2	C
		▪ It is an end of pipe treatment	1, 2, 3, 4	A
		▪ Uncertainty about lifecycle quality of reused materials prevents its use	1, 4	E
3	Use of waste prediction tools	▪ Most prediction tools lack provision for actual waste reduction/minimization	1	C
		▪ Building information are input manually, and this discourages its use	1, 4	B
		▪ Incompatibility with drawing tools discourages their wider acceptability	1, 3	B
		▪ Extra man-hours/efforts are required as they are external to drawing tools	1, 2, 4	D
		▪ Not realistic in complex design with irregular shapes	1	C
4	Site waste management plan (SWMP)	▪ Only being used as a means of fulfilling legal requirements or BREEAM points	3, 4	E
		▪ No standard benchmark as it is done based on individuals' instinct	1, 4	C
		▪ It requires additional man-hours/specialist	3	D
		▪ No solid follow up on original plan	4	E
5	Design for flexibility and deconstruction	▪ It requires added expertise as well as dedicated planning which are unpaid for	1, 2, 3	D
		▪ Deconstruction is more expensive than demolition	3, 4	D
		▪ It does not offer immediate benefits to project teams	1, 2	E

End of Table 2

#	Waste management strategies	Limitations	Focus groups (1–4)	Category A–E*
6	Waste efficient procurement, e.g., JIT	■ Measures such as JIT increases transportation cost	3, 4	D
		■ It sometimes delays projects	3	D
7	Offsite construction and other MMC	■ More expensive than in-situ mode of construction	3, 4	D
		■ It requires more careful planning which counts on project cost	1, 3	D
8	Legislation and tax measures	■ It gives little attention to design stages which is key to waste reduction	1, 4	C

Notes: *A – End of pipe treatment; B – Externality/incompatibility of waste management tools with design tools; C – Failure of waste management strategies to offer holistic solutions; D – Perceived or unexpected high cost of waste management; E – Waste behavioural culture.

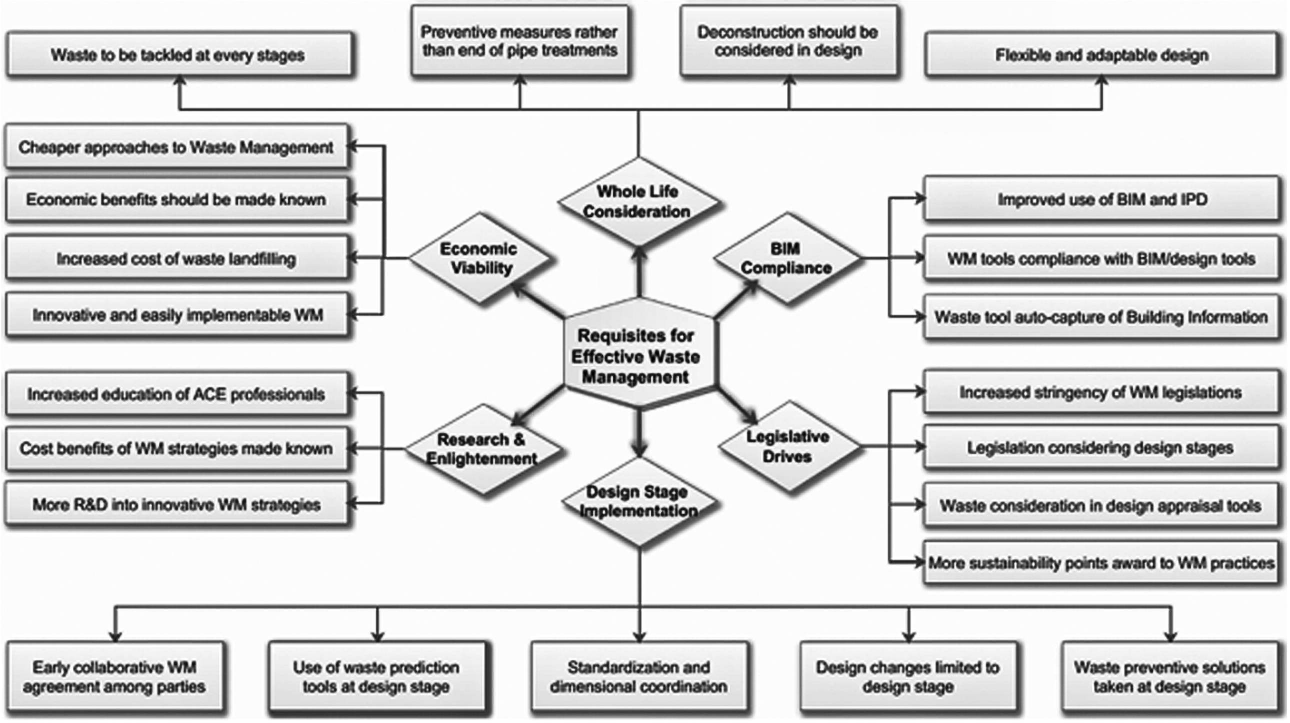


Figure 3. Requisites for minimizing waste intensiveness of the construction industry

Table 3. Requisite for reducing waste intensiveness of construction industry

#	Major categories of the strategies	Identified measures for improving effectiveness of waste management strategies	Focus groups (1–4)
1	Design stage implementation	■ Increasing implementation of waste management solutions right from design stage	3, 4
		■ Optimization/standardization of designs to achieve waste effective solutions	1, 2
		■ Early collaborative waste management arrangement among project teams	3, 4
		■ Design changes should be limited to the design stages	2, 4
		■ Waste management software solutions should be implementable within design platform	1, 4
2	Whole life consideration	■ Waste management solutions should cover all stages of project lifecycle than construction stage	2
		■ Waste prevention should be given adequate consideration as much as end of pipe treatment options	1, 4
		■ Flexibility should be considered while planning/specifying design and construction techniques	2, 3, 4
		■ Deconstruction should be planned at design/construction stage to reduce end of life waste	2, 3, 4

End of Table 3

#	Major categories of the strategies	Identified measures for improving effectiveness of waste management strategies	Focus groups (1–4)
3	Building information modelling (BIM) compliance	■ Improve use of BIM and integrated project delivery (IPD) will enhance project's waste effectiveness	1, 2, 3, 4
		■ As the industry shifts towards BIM, waste management tools should be made BIM compatible	1, 4
		■ Capability of waste prediction/management tools to automatically capture building information	1
4	Economic viability	■ Waste preventive/management measures should be made cheaper than allowing waste to occur	2, 3
		■ Economic benefits of adopting waste management strategies should be more pronounced	3
		■ Increasing cost of waste landfilling could make waste prevention more economical and accepted	1
		■ Easily implementable strategies devoid of causing project delay should be encouraged	3, 4
5	Legislation drives	■ Increased stringency of waste management regulations	2, 4
		■ Consideration of design stage in future waste management regulations	1, 3, 4
		■ Inclusion of waste management in project sustainability appraisal tools and building control process	1, 4
		■ Award of more points to waste effectiveness of construction projects	1, 3, 4
6	Research and enlightenment	■ More research into impacts of different design and construction practices on waste output	2, 4
		■ Cost benefits analysis of various low waste building techniques should be illuminated	3, 4
		■ Increased education of design and construction professionals about waste preventive measures	1, 2, 3, 4

The paper integrates an optimization process within its system dynamics framework to enhance the accuracy and performance of waste-reduction simulations. Specifically, the Anylogic application's built-in optimization engine was used to run 500 simulation iterations, identifying the optimal combination of parameters that minimize waste while maximizing key performance metrics such as material productivity, quality, life cycle assessment (LICA), and LEED performance. The optimization procedure functions by adjusting variable constraints to achieve ideal maximum and minimum values, minimizing negative outcomes like material waste, time and cost overruns, and life cycle cost (LICC), while maximizing desired outputs. This approach can be extended by using metaheuristic optimization techniques, such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), or Simulated Annealing (SA), which are compatible with the system dynamics framework to further refine results. These methods could provide improved convergence on global optima across multiple conflicting objectives, thereby enhancing the model's decision-support capacity for sustainable waste reduction in industrial construction projects.

2.5. System dynamics impacts in waste of construction

Much research has appeared for construction waste and demolition waste (CDW) management. In these regards, quantitative research is to evaluate social effect on construction waste minimization utilizing system dynamics. Several indices have been utilized to evaluate social effects of (CDW) (Yuan, 2012). Their research on managing (CDW). The research appeared that system dynamics has ability to control sub-systems and give best intelligence of impacts for (CDW) management and the dynamic interactions (Hao et al., 2007). Rong (2004) utilized system dynamics methodology and (AHP) to manage prospective construction waste scenarios. Hsiao et al. (2002) presented research to simulate materials inflow of concrete waste (CDW). Accordingly, this research utilizes the system dynamics technique to minimize waste of construction in industrial projects, and in special to minimize waste of construction technology projects such as (non-site based and site based) waste through preconstruction phase whether material waste, cost overrun or time overrun, labor waste, equipment waste.

3. Research methodology

This paper suggests to improve a dynamic build up by forthright an experimental realization utilizing system dynamics technique for evaluating both scenarios – Existing waste management strategies and Waste effective site management practice – for minimizing construction waste such as (non-site based and site based) waste in industrial construction technology projects through pre-construction phase that include (cost estimating – scheduling – constructability reviews – value engineering – procurement – contracting). The proposed model may imitate any technique's long-range behavior in stock objective functions, including time and cost overrun, material waste, material productivity, quality, LICA, LICC, LEAED impacts (Meshref

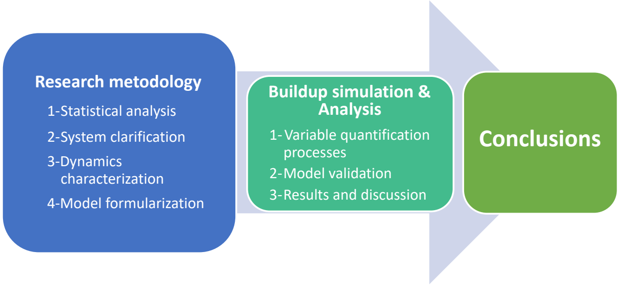


Figure 4. System dynamics method for construction phase

et al., 2023). The operation illustrated in Figure 4 is utilized to make simulation techniques to achieve that aim. The suggested model is completely illustrated in the subsequent sections.

Computer support is wanted to implement dynamics build up technique. A lot of applications previously used, including Anylogic, STELLA, IThink, Vensim, Matlab, Powersim and DYNAMO (High Performance Systems, Inc., 1997). Numeral solvers to algebraic, differential, different equations are inclusive in Anylogic application motor (Meshref et al., 2023).

The paper now clearly defines and differentiates the two compared approaches, Existing Waste Management Strategies (EWMS) and Waste-Effective Site Management Practices (WESMP), within the pre-construction phase of industrial projects. The EWMS approach includes conventional measures such as waste sorting and recycling, use of waste prediction tools, site waste management plans (SWMP), design for flexibility and deconstruction, just-in-time (JIT) procurement, offsite or modular construction, and compliance with environmental legislation or taxation incentives. In contrast, the WESMP approach focuses on proactive site-level management actions that prevent waste generation at its source, including contract management that embeds waste control clauses, segregation and reuse of materials, materials logistics management, and improved communication and supervision practices. Both methods were modeled as fixed quantitative variables influencing dependent factors such as design change, poor workmanship, waiting time, and unstructured site layout. Through system dynamics simulation, the study demonstrates how WESMP offers a more integrated, preventive, and efficiency-driven approach compared to the reactive nature of EWMS, resulting in significantly lower waste outputs and higher productivity and quality indices.

3.1. Statistical analysis

The study has conducted advanced statistical technique to get weighs for each cluster and criteria in the model using SPSS v 24. In the beginning the study reliability analysis was conducted (Cronbach's alpha) for measuring reliability of the clusters. In the second stage, the researchers conducted factor analysis (principal components analysis method) for calculating weights of each cluster and criteria. In the third part the researchers have conducted cluster analysis to make sure that criteria are classified in the same cluster (as the study proposed in the theoretical part) for each cluster. In the fourth part, the study has conducted correlation analysis to get correlation between clusters. In the fifth part, the researcher has calculated consistency ratio (*CR*) and consistency index (*CI*).

There are four phases, namely, design, pre-construction, maintenance, and demolition. These phases influence one another; therefore, the Analytic Network Process (ANP) method was used to calculate the weights of the criteria and alternatives.

This study focusses on pre-construction phase only to reduce construction waste before it occurs in construction phase.

3.1.1. Reliability analysis

In this part, the study will check the reliability of each cluster using Cronbach's alpha coefficient. Cronbach's alpha coefficient ranges from 0 to 1 and it is preferred to be higher than 0.7. Table 4 shows the reliability coefficients of phases.

Table 4. The reliability coefficients of phases

Reliability Statistics		
Phases	Cronbach's Alpha	N of Items
Design phase (Cluster 1)	0.928	7
Pre-construction phase (Cluster 2)	0.881	7
Maintenance phase (Cluster 3)	0.849	4
Demolition phase (Cluster 4)	0.912	5
The whole phases	0.872	23

From Table 4 we can see that:

- Cluster 1 is reliable where the value of Cronbach's alpha = 0.928 which is greater than 0.7;
- Cluster 2 is reliable where the value of Cronbach's alpha = 0.881 which is greater than 0.7;
- Cluster 3 is reliable where the value of Cronbach's alpha = 0.849 which is greater than 0.7;
- Cluster 4 is reliable where the value of Cronbach's alpha = 0.912 which is greater than 0.7;
- The whole clusters is reliable where the value of Cronbach's alpha = 0.872 which is greater than 0.7.

3.1.2. Calculating weights

In this part, the researchers will conduct factor analysis (principal components analysis method) to calculate weights for pre-construction phase and criteria and alternatives (see Tables 5–7).

a. Calculating weights for overall phases

From Table 5 we can see that:

- Cluster 1 has the largest weight with 29%, while in the second rank comes cluster 4 with 26%, while in the third rank comes cluster 3 with 23%, finally in the fourth rank comes cluster 2 with 22%;
- The Eigenvalue = 2.448.

Table 5. Weights for clusters

Cluster	Weight	Eigenvalue
cluster 1	29%	2.448
cluster 4	26%	
cluster 3	23%	
cluster 2	22%	

Figure 5 shows weights for overall phases.

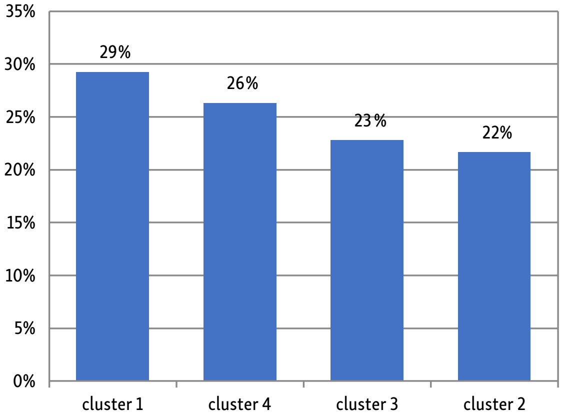


Figure 5. Weights for overall phases

b. Calculating weights criteria for pre-construction phase

Table 6. Weights for pre-construction phase criteria

criteria	weight	Eigenvalue
Waiting time (M)	4.8%	6.842
Complex design (J)	4.5%	
Poor work man ship (L)	3.7%	
Design errors (I)	3.5%	
Unstructured movement and non-productive site plan (N)	3.4%	
Design change (H)	3.2%	
Wrong material storage (K)	3.0%	

From Table 6 we can see that:

- Criterion M in the first rank with 4.8%, followed by criterion J with 4.5%, followed by criterion L with 3.7%, followed by criterion I with 3.5%, followed by criterion N with 3.4%, followed by criterion H with 3.2%, followed by criterion K with 3%;
- Eigenvalue = 6.842.

Figure 6 shows weights for pre-construction phase criteria.

c. Calculating weights alternatives for pre-construction phase

Table 7. Weights for pre-construction phase alternatives

Alternative	Weight
alternative 4	56.7%
alternative 3	43.3%

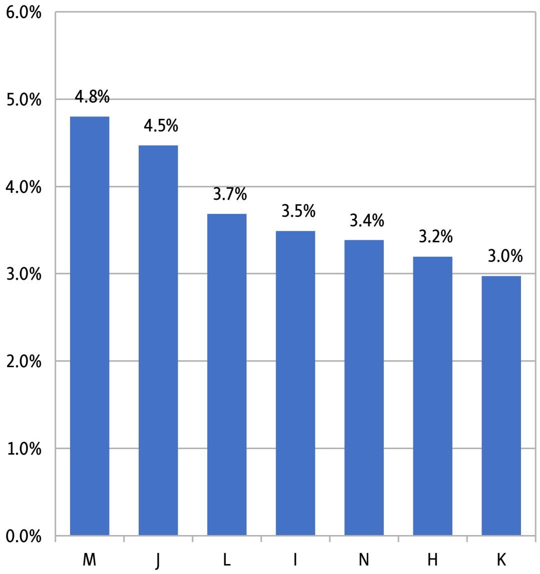


Figure 6. Weights for pre-construction phase criteria

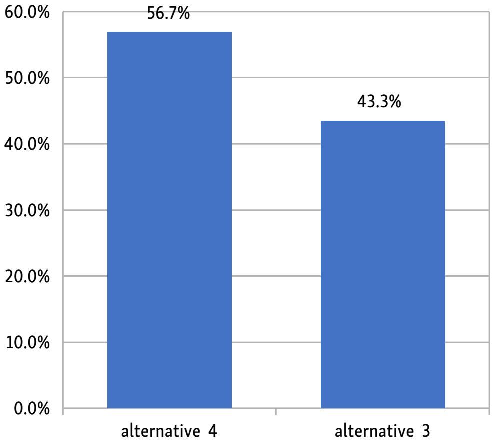


Figure 7. Weights for pre-construction phase alternatives

From Table 7 we can see that Alternative 4 in the first rank with 56.7%, followed by alternative 3 with 43.3% (see Figure 7).

Figure 7 shows weights for pre-construction phase alternatives.

3.1.3. Cluster analysis

In this part the study has conducted K-means cluster technique to make sure that criteria are distributed well in their clusters (see Table 8).

From Table 8 we can see that:

- Criteria (A, B, C, D, E, F, G) were grouped together in cluster 1;
- Criteria (H, I, J, K, L, M, N) were grouped together in cluster 2;
- Criteria (O, P, Q, R) were grouped together in cluster 3;
- Criteria (S, T, U, V, W) were grouped together in cluster.

Table 8. K-means cluster results

Criteria	Cluster
A	1
B	1
C	1
D	1
E	1
F	1
G	1
Design change (H)	2 pre-construction phase
Design errors (I)	2 pre-construction phase
Complex design (J)	2 pre-construction phase
Wrong material storage (K)	2 pre-construction phase
Poor work man ship (L)	2 pre-construction phase
Waiting time (M)	2 pre-construction phase
Unstructured movement and non-productive site plan (N)	2 pre-construction phase
O	3
P	3
Q	3
R	3
S	4
T	4
U	4
V	4
W	4

3.1.4. Correlation between clusters

The study has conducted correlation analysis through calculating Pearson correlation coefficient. Pearson correlation coefficient ranges from –1 to 1; – means negative relation while + means positive relation. Values less than 0.35 are considered to be weak correlation, while 0.35 to 0.7 moderate, while greater than 0.7 strong.

Table 9 shows Pearson correlation coefficient between clusters.

From Table 9 we can see that:

- There is significant correlation between cluster 1 and cluster 2 where the sig. (2-tailed) = 0.014 is less than α = 0.05. This correlation is moderate positive where the value of Pearson correlation = 0.616.
- There is no significant correlation between cluster 1 and cluster 3 where the sig. (2-tailed) = 0.143 is greater than α = 0.05.
- There is significant correlation between cluster 1 and cluster 4 where the sig. (2-tailed) = 0.0001 is less than α = 0.05. This correlation is strong positive where the value of Pearson correlation = 0.85.
- There is significant correlation between cluster 2 and cluster 3 where the sig. (2-tailed) = 0.014 is less than α = 0.05. This correlation is strong positive where the value of Pearson correlation = 0.788.
- There is significant correlation between cluster 2 and cluster 4 where the sig. (2-tailed) = 0.015 is less than α = 0.05. This correlation is moderate positive where the value of Pearson correlation = 0.611.
- There is significant correlation between cluster 3 and cluster 4 where the sig. (2-tailed) = 0.015 is less than α = 0.05. This correlation is moderate positive where the value of Pearson correlation = 0.524.

3.1.5. Consistency ratio/index

Consistency ratio is a measure of consistency, and it is preferred to be less than or equal 0.1, it can be written in the form of:

$$CR = \frac{CI}{RI}, \tag{1}$$

where *RI* is random consistency and its values are given in Table 10.

Table 9. Pearson correlation coefficient between clusters

Correlations					
		Cluster 1	Cluster 2	Cluster 3	Cluster 4
Cluster 1	Pearson Correlation	1	$.616^{*}$	0.396	$.850^{**}$
	Sig. (2-tailed)		0.014	0.143	0.000
	N	15	15	15	15
Cluster 2	Pearson Correlation	$.616^{*}$	1	$.788^{**}$	$.611^{*}$
	Sig. (2-tailed)	0.014		0.000	0.015
	N	15	15	15	15
Cluster 3	Pearson Correlation	0.396	$.788^{**}$	1	$.524^{*}$
	Sig. (2-tailed)	0.143	0.000		0.045
	N	15	15	15	15
Cluster 4	Pearson Correlation	$.850^{**}$	$.611^{*}$	$.524^{*}$	1
	Sig. (2-tailed)	0.000	0.015	0.045	
	N	15	15	15	15

Notes: * Correlation is significant at the 0.05 level (2-tailed); ** Correlation is significant at the 0.01 level (2-tailed).

Table 10. Random consistency table given by Saati

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.6	0.9	1.1	1.2	1.3	1.4	1.5

CI is consistency ratio which can be written in the form of:

$$CI = \frac{\lambda_{\max} - n}{n-1}. \tag{2}$$

According to the following formulas we can formulate Table 11.

From Table 11 we can see that:

- Cluster 1 is inconsistence where consistency ratio = 0.26 > 0.1;
- Cluster 2 is consistent where consistency ratio = 0.02 < 0.1;
- Cluster 3 is inconsistence where consistency ratio = 0.18 > 0.1;
- Cluster 4 is inconsistence where consistency ratio = 0.21 > 0.1.

3.2. System clarification

Main causes that an effect on system build up were considered while simulating long-range impacts of minimizing construction waste such as (non-site based and site based) waste in industrial projects during pre-construction phase that include (cost estimating – scheduling – constructability reviews – value engineering – procurement – contracting) for both scenarios (Existing waste management strategies and Waste effective site management practice) in eight major stock aspects of time overrun, cost overrun, material productivity, material waste, quality, LICA, LICC, LEAED effects. The model's build up variable values were collected from diversity of general research and comprehensive field studies in Arab Republic of Egypt (Meshref et al., 2023). The interval framework necessarily to be extended sufficient to explain impacts of both scenarios. It must therefore cover a long-range of time in the following to regard for late, indirect impacts of suggested procedures (Sterman, 2000). Accordingly, the outcome, 24 months is selected as common period framework in suggested dynamics technique.

3.3. Dynamics characterization utilizing causal loop diagram

Testing the effect of major variables on simulation results is substantial for estimating the stock objective functions of long-range effect of both scenarios. This is achieved by using a tool that visions the relation between the system's feedback impacts and variables. Anylogic application established (CLD), as depicted in Figure 4, appears the framework of the system dynamics technique. Accordingly, there are four (R1, R2, R3, R4) reinforcing loops, while the four (B1, B2, B3, B4) balancing loops (Meshref et al., 2023). The effort for minimizing construction waste such as (non-site based and site based) waste variable is estimated in the end inflow whose is (WG) and finally the end stock whose is (Waste generating during construction practices) (WGDCP) (Meshref et al., 2023). Accordingly, there are two major parameters linked to (Existing waste management strategies) and (Waste effective site management practice).

The dynamic variables are design change, design errors, complex design, wrong storage to material, poor work man ship, waiting time and unstructured movement and nonproductive site plan. The equation of all variables should only contain factors which related to that variable (Meshref et al., 2023). Dynamic variables in after stage are design change, waiting time because they are affected to any flows.

Every inflow has it possesses, single equation and rate of variables and stocks inside this equation as shown:

$$\text{change of cost overrun} = -\left(\frac{\text{waiting time}}{\text{time overrun}}\right) - \left(\frac{\text{waiting time}}{\text{material waste}}\right) - \left(\frac{\text{waiting time}}{\text{quality}}\right) - \left(\frac{\text{waiting time}}{\text{material productivity}}\right) - \left(\frac{\text{design change}}{\text{time overrun}}\right) - \left(\frac{\text{design change}}{\text{material waste}}\right) - \left(\frac{\text{design change}}{\text{quality}}\right) - \left(\frac{\text{design change}}{\text{material productivity}}\right); \tag{3}$$

$$\text{change of time overrun} = -\left(\frac{\text{waiting time}}{\text{quality}}\right) - \left(\frac{\text{design change}}{\text{quality}}\right); \tag{4}$$

$$\text{change of quality} = \left(\frac{\text{waiting time}}{\text{material waste}}\right) + \left(\frac{\text{waiting time}}{\text{material productivity}}\right) + \left(\frac{\text{waiting time}}{\text{LICA}}\right) + \left(\frac{\text{design change}}{\text{material waste}}\right) + \left(\frac{\text{design change}}{\text{material productivity}}\right) + \left(\frac{\text{design change}}{\text{LICA}}\right); \tag{5}$$

$$\text{change of material waste} = -\left(\frac{\text{waiting time}}{\text{quality}}\right) - \left(\frac{\text{waiting time}}{\text{material productivity}}\right) - \left(\frac{\text{design change}}{\text{quality}}\right) - \left(\frac{\text{design change}}{\text{material productivity}}\right); \tag{6}$$

Table 11. Consistency Ratio (*CR*) & Consistency Index (*CI*)

Cluster	*n*	$\lambda_{\max}$	Consistency index (*CI*)	Random consistency (*RI*)	Consistency ratio (*CR*)
Cluster 1	7	9.04	0.3405	1.3	0.261923
Cluster 2	7	6.842	–0.02633	1.3	–0.02026
Cluster 3	4	3.505	–0.165	0.9	–0.18333
Cluster 4	5	5.951	0.23775	1.1	0.216136

$$\text{change of material productivity} = \left(\frac{\text{waiting time}}{\text{material waste}}\right) + \left(\frac{\text{waiting time}}{\text{LICA}}\right) + \left(\frac{\text{design change}}{\text{material waste}}\right) + \left(\frac{\text{design change}}{\text{LICA}}\right); \tag{7}$$

$$\text{change of LICA} = \left(\frac{\text{waiting time}}{\text{material waste}}\right) + \left(\frac{\text{waiting time}}{\text{material productivity}}\right) + \left(\frac{\text{waiting time}}{\text{LEAED}}\right) + \left(\frac{\text{design change}}{\text{material waste}}\right) + \left(\frac{\text{design change}}{\text{material productivity}}\right) + \left(\frac{\text{design change}}{\text{LEAED}}\right); \tag{8}$$

$$\text{change of LICC} = -\left(\frac{\text{waiting time}}{\text{material waste}}\right) - \left(\frac{\text{waiting time}}{\text{material productivity}}\right) - \left(\frac{\text{waiting time}}{\text{LEAED}}\right) - \left(\frac{\text{waiting time}}{\text{quality}}\right) - \left(\frac{\text{waiting time}}{\text{time waste}}\right) - \left(\frac{\text{design change}}{\text{material waste}}\right) - \left(\frac{\text{design change}}{\text{material productivity}}\right) - \left(\frac{\text{design change}}{\text{quality}}\right) - \left(\frac{\text{design change}}{\text{LEAED}}\right) - \left(\frac{\text{design change}}{\text{timewaste}}\right); \tag{9}$$

$$\text{change of LEAED} = \left(\frac{\text{waiting time}}{\text{LICA}}\right) + \left(\frac{\text{design change}}{\text{LICA}}\right); \tag{10}$$

$$\text{ETRCW} = \text{ICOR} + \text{ITOR} + \text{IMAW} + \text{IMP} + \text{IQU} + \text{ILICA} + \text{ILEAED} + \text{ILICC} + \text{ICO}. \tag{11}$$

According to the previous equations, simulation needs a small duration to build up the model. Figure 8 shows dynamic build-up variables and stocks' values alteration with period to 24-month time selected (Meshref et al., 2023).

3.4. Model formularization as diagram

Each of important variables that build up impact chosen of several operations are highlights utilizing (CLD) as shown in Figure 8. The technique could be easily operated while (CLD) is converted to a quantitative build up (Meshref et al., 2023). In this direction (Anylogic) application has been utilized to convert (CLD) to stock – flow-diagram as illustrated in Figure 8, and technique variables build up are mentioned in Tables 12 and 13.

4. Build up simulation and analysis

4.1. Variable build up quantification processes

It is important for assuring that information inputs to all variables in this technique are appropriate prior operation simulation. Variables often find inside single of three groups: dependent, quantitative, or qualitative and any of them requires separate information (Meshref et al., 2023).

Quantitative variable is definite variable (fixed factor), their amount will be constant through simulation (Meshref et al., 2023). Instance of fixed parameters are "Existing waste management strategies" and "Waste effective site management practice". It might influence variables such as design change, design errors, complex design, wrong storage to material, poor work man ship, waiting time and unstructured movement and nonproductive site plan as illustrate in Figure 9, Table 14, also it will not be affected by all of variables. Fixed factors, like (Existing waste management strategies) and (Waste effective site management practice).

Dependent variable is many groups of variables. Amount of single or further of other variables in a function impact value for dependent variable. Thus, it is substantial to characterize dependent variable's link with other variables to simulate them neatly (Meshref et al., 2023). For instance, one illustration of a dependent variables is (Method for quantification M2) design change, waiting time where (Waste effective site management practice) impacts the chosen of design change and waiting time are being a variable, means that (Waste effective site management practice) will influence the rate of design change and waiting time within this technique.

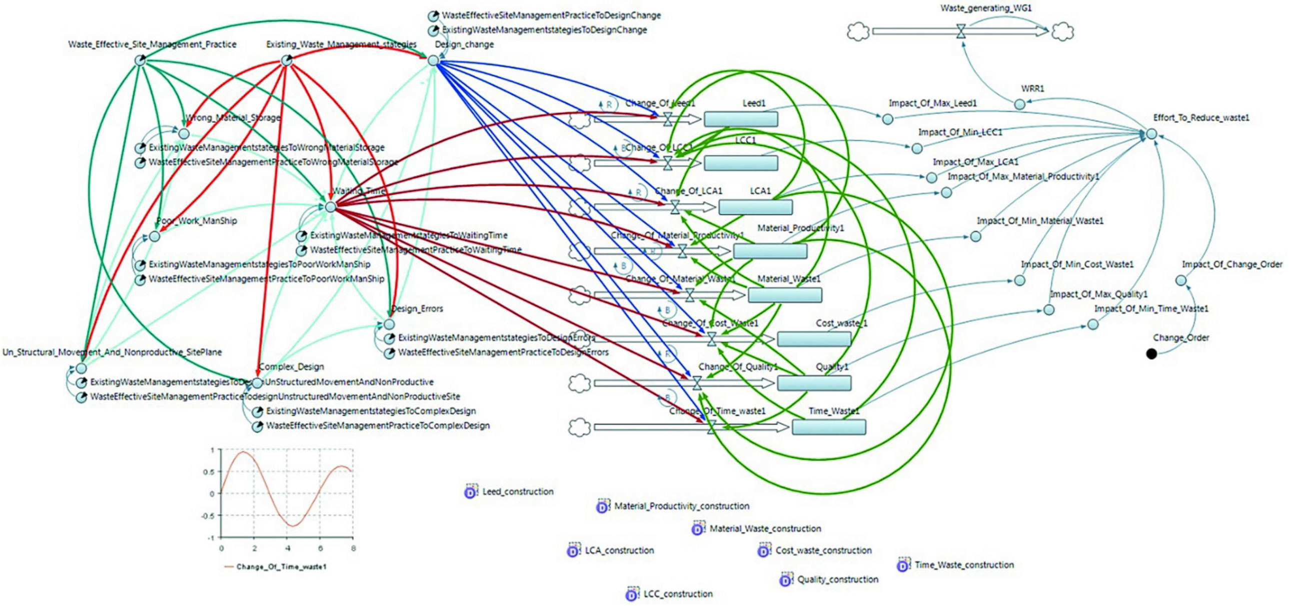


Figure 8. Build up diagram for minimizing construction waste in preconstruction phase

Table 12. Build up variable's description for the simulation

Acronyms	Definition	Unit	Quantification build-up	Case study
DC	DESIGN CHANGE	1	M2	0.35
DE	DESIGN ERRORS	1	M2	0.15
CD	COMPLEX DESIGN	1	M2	0.1
WMS	WRONG MATERIAL STORAGE	1	M2	0.12
PWM	POOR WORK MANSHIP	1	M2	0.1
WT	WAITING TIME	1	M2	0.15
USMN	UNSTRUCTURED MOVEMENT AND NON-PRODUCTIVE SITE PLAN	1	M2	0.15
COV	COST OVERRUN	EURO		
TOV	TIME OVERRUN	MONTH		
MAW	MATERIAL WASTE	TON		
MPR	MATERIAL PRODUCTIVITY	TON		
QU	QUALITY	%		
LICA	LIFE CYCLE ASSESSMENT	1		
LICC	LIFE CYCLE COST	EURO		
LEAED	LEADER ENERGY ENVIROMENTAL DESIGN	1		
ICOV	IMPACT COST OVERRUN	EURO	M2	
ITOV	IMPACT TIME OVERRUN	MONTH	M2	
IMAW	IMPACT MATERIAL WASTE	TON	M2	
IMPR	IMPACT MATERIAL PRODUCTIVITY	TON	M2	
IQU	IMPACT QUALITY	%	M2	
ILICA	IMPACT LCA	1	M2	
ILICC	IMPACT LCC	EURO	M2	
ILEAED	IMPACT LEED	1	M2	
COR	CHANGE ORDER	1	M3	0.07
ICOR	IMPACT OF CHANGE ORDER	1	M2	
ETRCW	EFFORT TO REDUCE CONSTRUCTION WASTE	1		
WRR	WASTE REDUCTION RATE	1	M2	
EWMS	EXISTING WASTE MANAGEMENT STRATEGIES	1	M1	0.433
WESMP	WASTE EFFECTIVE MANAGEMENT PRACTICE	1	M1	0.567
CCOV	CHANGE OF COST OVERRUN	EURO	M2	
CTOV	CHANGE OF TIME OVERRUN	MONTH	M2	
CMAW	CHANGE OF MATERIAL WASTE	TON	M2	
CMP	CHANGE OF MATERIAL PRODUCTIVITY	TON	M2	
CQU	CHANGE OF QUALITY	%	M2	
CLICA	CHANGE OF LICA	1	M2	
CLICC	CHANGE OF LICC	EURO	M2	
CLEAED	CHANGE OF LEAED	1	M2	
WG	WASTE GENERATING	1	M2	
WGDCP	WASTE GENERATING DURING CONSTRUCTION PRACTICES	1		

Table 13. Equations

IMPACT COST OVERRUN =	GRAPH (COST OVERRUN)
IMPACT TIME OVERRUN =	GRAPH (TIME OVERRUN)
IMPACT MATERIAL WASTE =	GRAPH (MATERIAL WASTE)
IMPACT MATERIAL PRODUCTIVITY=	GRAPH (MATERIAL PRODUCTIVITY)
IMPACT QUALITY =	GRAPH (QUALITY)
IMPACT LICA =	GRAPH (LICA)
IMPACT LICC =	GRAPH (LICC)
IMPACT LEAED =	GRAPH (LEAED)
IMPACT CHANGR ORDER =	GRAPH (CHANGE ORDER)
WRR =	GRAPH (ETRCW)
WG =	WRR
FACTORS FOR SCENARIOS (INPUT)	
EXISTING WASTE MANAGEMENT STRATEGIES TO DESIGN CHANGE	0.053
EXISTING WASTE MANAGEMENT STRATEGIES TO DESIGN ERROS	0.058
EXISTING WASTE MANAGEMENT STRATEGIES TO COMPLEX DESIGN	0.074
EXISTING WASTE MANAGEMENT STRATEGIES TO WRONG MATERIAL STORAGE	0.049
EXISTING WASTE MANAGEMENT STRATEGIES TO POOR WORK MAN SHIP	0.061
EXISTING WASTE MANAGEMENT STRATEGIES WAITING TIME	0.08
EXISTING WASTE MANAGEMENT STRATEGIES TO DESIGN UNSTRUCTURED MOVEMENT AND NON-PRODUCTIVE SITE PLAN	0.056
WASTE EFFECTIVE MANAGEMENT PRACTICE TO DESIGN CHANGE	0.07
WASTE EFFECTIVE MANAGEMENT PRACTICE TO DESIGN ERRORS	0.076
WASTE EFFECTIVE MANAGEMENT PRACTICE TO COMPLEX DESIGN	0.098
WASTE EFFECTIVE MANAGEMENT PRACTICE TO WRONG MATERIAL STORAGE	0.065
WASTE EFFECTIVE MANAGEMENT PRACTICE TO POOR WORK MAN SHIP	0.081
WASTE EFFECTIVE MANAGEMENT PRACTICE TO WATING TIME	0.105
WASTE EFFECTIVE MANAGEMENT PRACTICE TO UNSTRUCTURED MOVEMENT AND NON-PRODUCTIVE SITE PLAN	0.074
FACTOR TO REAL CONSTRUCTION PROJECT (INPUT)	
ESTIMATION COST FOR REAL CONSTRUCTION PROJECT	230 MILLION EURO
DURATION FOR REAL CONSTRUCTION PROJECT	24 MONTH
RATE OF MATERIAL WASTE FOR REAL CONSTRUCTION PROJECT	15%
RATE OF MATERIAL PRODUVTIVITY FOR REAL CONSTRUCTION PROJECT	85%
RATE OF QUALITY FOR REAL CONSTRUCTION PROJECT	85%
RATE OF LIFE CYCLE ASSESSMENT FOR REAL CONSTRUCTION PROJECT	95%
RATE OF LIFE CYCLE COST FOR REAL CONSTRUCTION PROJECT	20%
RATE OF LEADERSHIP IN ENERGY AND ENVIROMENTAL DESIGN FOR REAL CONSTRUCTION PROJECT	95%

Qualitative variable is final list of factors. The single method for collection quantity of qualitative variables is from survey processes such as questionnaires, interviews, site visit (Meshref et al., 2023). For example, Scale- Likert is utilized to evaluate performance of that qualitative variable (Quantification method M3) utilizing the variable such as (change order). Experts in the specialization will evaluate any qualitative variable degree from 0 to 100 (Meshref et al., 2023).

The paper already integrates Building Information Modeling (BIM) as a core analytical component to enhance the realism and applicability of the simulation. BIM was employed to model and test the benefits of waste reduction strategies during the pre-construction phase, specifically across activities such as cost estimation, scheduling, constructability reviews, procurement, and contracting. The model links BIM-generated data, such as quantities, materials, and design parameters-with the System Dynamics (SD) simulation in Anylogic software, enabling dynamic testing of how design changes, storage errors, and material handling affect waste generation. By coupling BIM's data-rich environment with SD causal loop and stock-flow modeling, the research demonstrates how digital design information can forecast waste outcomes before construction begins. This BIM-integrated approach allows stakeholders to visualize, quantify, and compare the benefits of both Existing Waste Management Strategies (EWMS) and Waste-Effective Site Management Practices (WESMP) under realistic project conditions, validating the model's predictive and decision-support capabilities.

4.2. Models build up validation

Simulation has emerged as a reliable technique when jobs and variables are well-defined, ensuring model accuracy and optimal outcomes (Sterman, 2000; Richardson & Pugh, 1981). This study uses simulation to evaluate and select the best scenario for minimizing construction waste in industrial projects during the pre- construction phase, based on a real-case application. The case selected in sokhna Fertilizer complex in Egypt is the Nasr Company to Intermediate Chemicals for the Phosphate Fertilizer Factory, by interview with project manager for Hany Mohei Eldeen in Hassan Allam Company. Furthermore, optimization was made for the outcomes of the better scenario by improving the system dynamics to arrive at the better outcomes. The main aims have been accurately considered through the simulation procedure, namely minimizing material waste, cost overrun, and time overrun, life cycle cost (LICC), maximizing material productivity and quality, life cycle assessment (LICA) and (LEAED). Anylogic application has an ability to optimization (Meshref et al., 2023).

Optimization is operation of finding ideal group of stipulations resulting in better available scenario. In this paper, certain factors are intended to be improved, while others are not. The former are treated as continuous variables, with defined maximum and minimum values for improvement, whereas the latter are considered constant. Accordingly, the simulation is conducted over 500 iterations. n the end, after obtaining improved values for each parameter related to construction practices, the simulation will be used to evaluate changes in these outcomes using the main simulation technique. Subsequently, the improved results will be validated using a system dynamics approach (Meshref et al., 2023).

4.3. Discussion and results

4.3.1 Comparative performance of waste management strategies

Accordingly, after the validation process, the technique is simulated over a 24-month period (Meshref et al., 2023). In the pre-construction phase, which includes cost estimating, scheduling, constructability reviews, value engineering, procurement, and contracting – two approaches are considered: existing waste management strategies and waste-effective site management practices. These approaches depend on quantitative factors identified in the pre-construction phase and are supported by BIM and lean construction concepts, which aim to minimize both off-site and on-site construction waste in industrial projects. The quantitative factors selected for the pre-construction phase are influenced by additional qualitative and quantitative factors arising in the design and construction phases. Their relative weights are determined using the Analytic Network Process (ANP), enabling the evaluation of both approaches in relation to BIM and lean construction principles for waste minimization. These factors are then integrated as variables within the system dynamics model.

Subsequently, both approaches are analyzed under different scenarios. In the first scenario, factors related to existing waste management strategies are disregarded, while those associated with waste-effective site management practices are retained. In the second scenario, the reverse is applied. The results are then compared through two diagrams (Figures 10a and 10b) to identify the more effective approach.

In those directions, system dynamic model was utilized for processing of simulation and evaluating outcomes (Meshref et al., 2023). In addition, the specific outcomes could be loaded on Anylogic application and the special cloud for them as illustrated in Figure 9.

An information group has been established to Waste generated during construction practice (WGDCP) as illustrated in Figure 9. The outcome of the experience detected that Waste effective site management practice has an important impact in minimizing construction waste during preconstruction phase.

The model build as follows: quantitative factors in pre-construction phase that include (cost estimating – scheduling – constructability reviews – value engineering – procurement – contracting) that cause construction waste such as (non-site based and site based) waste were described in the model as dependent variables that are reduced by quantitative variables that represent both alternatives (Existing waste management strategies and Waste effective site management practice) according to (BIM) and Lean construction concepts and work to reduce the effect of the quantitative factors to achieve the required goals that represent in the stock, which is stated as follows next.

The better outcome for the simulation during construction practices is Waste effective site management practice (49235.116) construction waste produced in construction practices, and the outcome for (Existing waste management strategies) (49244.511) occurred at the end of 24 months. The stock in the simulation represents eight objective functions, wherever quality in construction practices was (85%), by running simulation it was maximized for (152.14%). Also, material productivity was (85%), increased to (147.33%), likewise the LICA was (95%), became (163.21%), LEAED was (95%) and arrived to (99.30%), and the goal to minimize material waste, cost overrun, time overrun and LICC. Where material waste appeared (15%), and after twenty-four months, it became (5.476%), and cost overrun was minimized to (47%), as 230 million euros was the total cost, and time overrun was minimized to (53%),

The paper addresses this by translating the simulation outcomes into concrete, actionable strategies for reducing construction waste during the pre-construction phase. Based on the dynamic system results, six key waste factors were identified, waiting time, complex design, poor workmanship, wrong material storage, design errors, and unstructured site plans. For each of these factors, the study proposes practical applications under the Waste-Effective

Site Management Practice (WESMP) framework. For example, implementing lean scheduling tools and just-in-time delivery can reduce waiting time and improve workflow efficiency; early design coordination using BIM and modular construction methods can minimize design complexity and errors; workforce training and quality audits can mitigate poor workmanship; while material kitting, 5S site organization, and protected storage areas can prevent material losses. The simulation demonstrated that applying these targeted strategies can reduce total material waste from 15% to approximately 5.5%, while increasing productivity and quality by more than 60%. These results provide tangible guidance for project managers seeking to apply model-based insights to real-world waste minimization in industrial construction projects.

The study evaluated a 24-month construction phase using life cycle cost (LICC), revealing a 20% initial cost impact and a subsequent reduction to –92.33%. Comparing existing waste management strategies with waste-effective site management practices, the latter proved more effective. A dynamic system dynamics technique identified key loops influencing construction practices in industrial projects. Reinforcing loops (R1, R2) linked design changes, waiting times, construction quality, material waste, productivity, and life cycle assessment (LICA), demonstrating that minimizing design changes and waiting times enhances productivity and reduces waste and overruns.

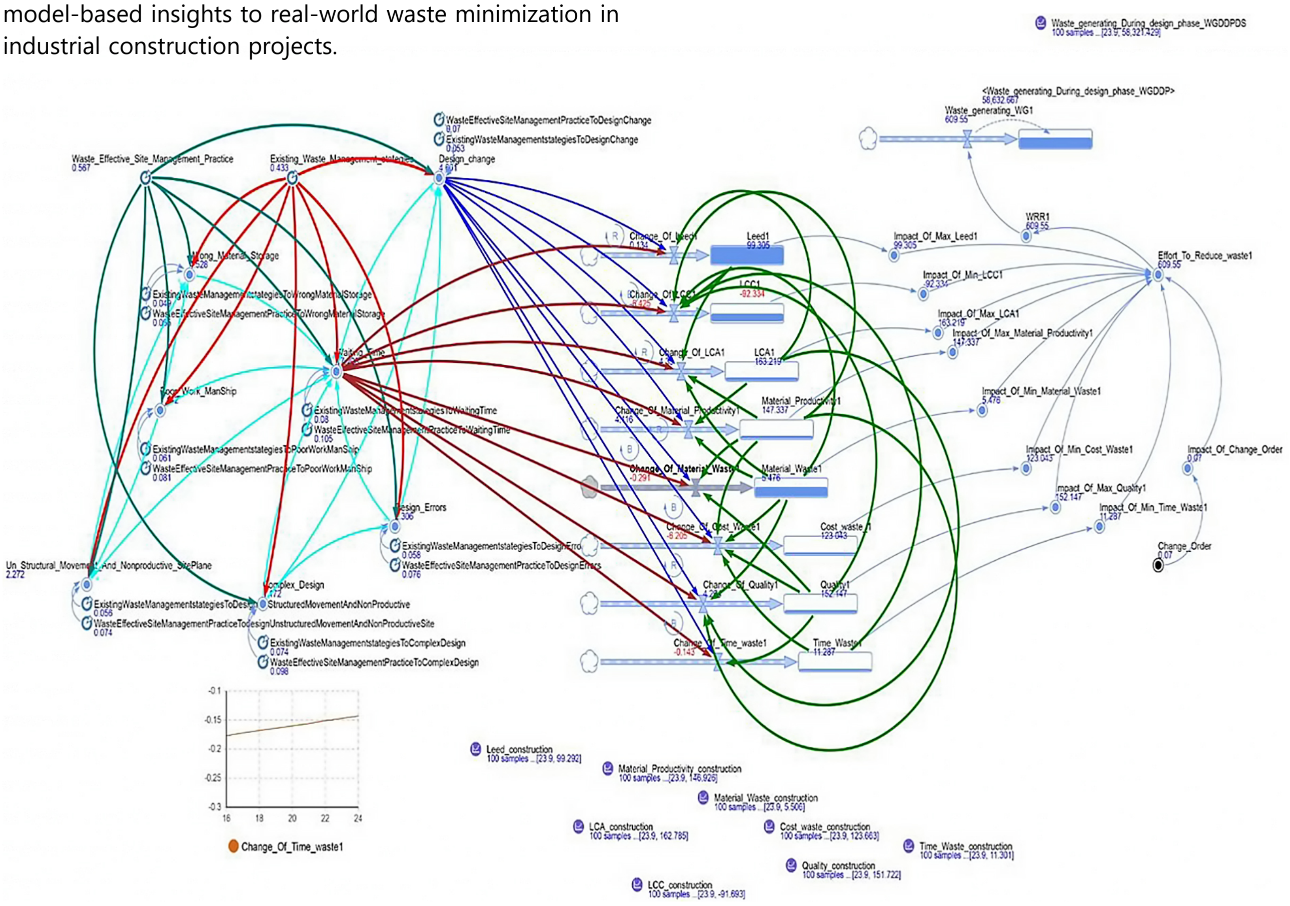
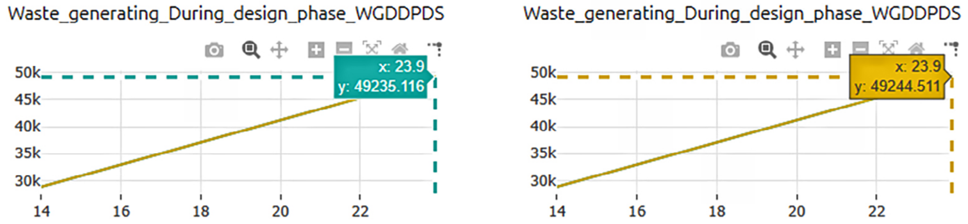


Figure 9. Operating the model by utilizing Anylogic software

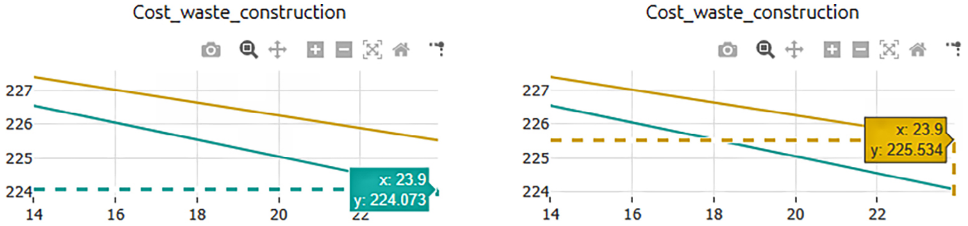
Table 14. Variables causing construction waste through pre-construction practices

Construction phase	
Design change	Lack of communication between contractors, designers, and clients through design phase
Design errors	Designers' lack of understanding of the nature and quality of the project leads to design errors
Complex design	Design to reduce the number of used materials was not optimized
Wrong material storage	Materials were not stored in a protected area on site to prevent premature damage and excessive inventories, which led to materials waste and monetary waste.
Poor workmanship	Poor qualifications in teamwork and unskilled workers, and poor labor productivity
Waiting time	The idle time is caused by the lack of synchronization, leveling of materials flows, and pace of work by different groups or equipment
Unstructured movement and non productive site plan	Poor planning and organization of work on the site



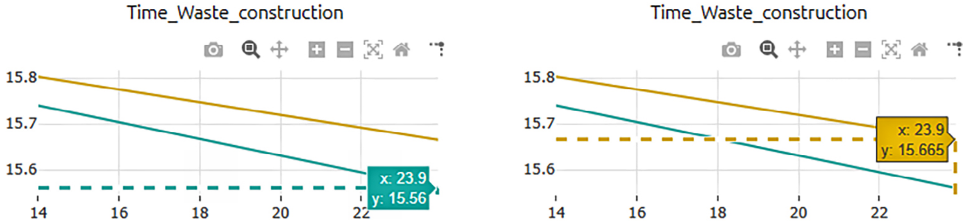
a) System dynamics outputs for (Waste effective site management practice)

b) System dynamics outputs for (Existing waste management strategies)



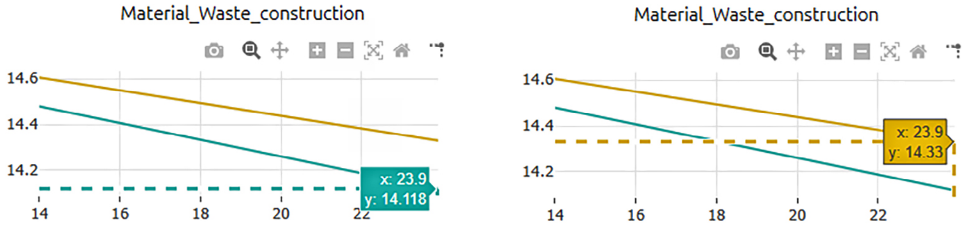
c) Reducing cost waste using (Waste effective site management practice)

d) Reducing cost waste using (Existing waste management strategies)



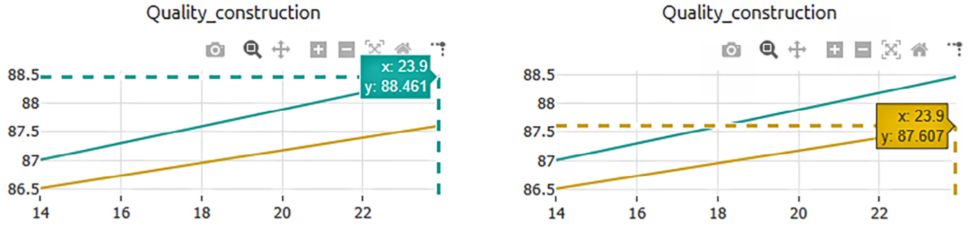
e) Reducing time waste using (Waste effective site management practice)

f) Reducing time waste using (Existing waste management strategies)



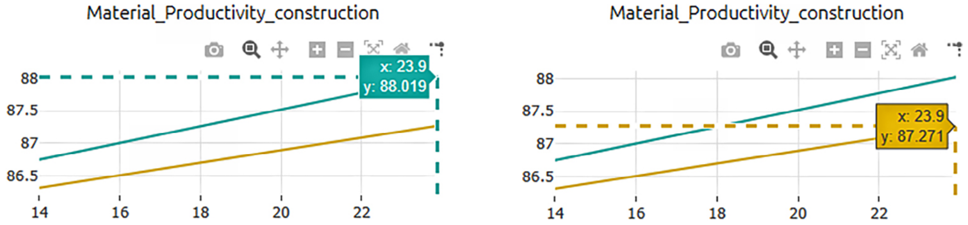
g) Reducing material waste using (Waste effective site management practice)

h) Reducing material waste using (Existing waste management strategies)



i) Increasing quality using (Waste effective site management practice)

j) Increasing quality using (Existing waste management strategies)



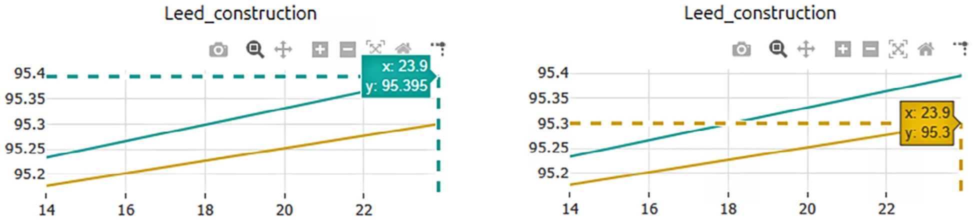
k) Increasing material productivity using (Waste effective site management practice)

l) Increasing material productivity using (Existing waste management strategies)

Figure 10. *Continued on next page*

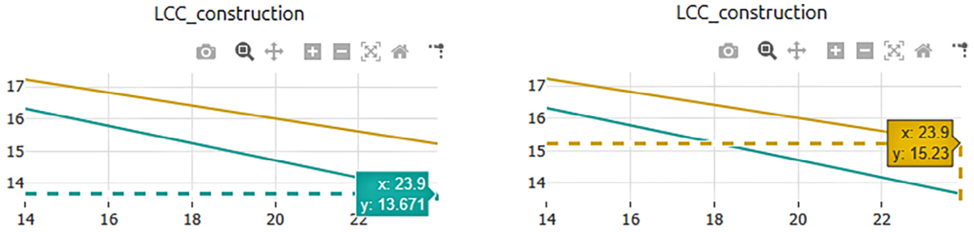
m) Increasing LEED using (Waste effective site management practice)

n) Increasing LEED using (Existing waste management strategies)



o) Reducing LCC using (Waste effective site management practice)

p) Reducing LCC using (Existing waste management strategies)



q) Increasing LCA using (Waste effective site management practice)

r) Increasing LCA using (Existing waste management strategies)

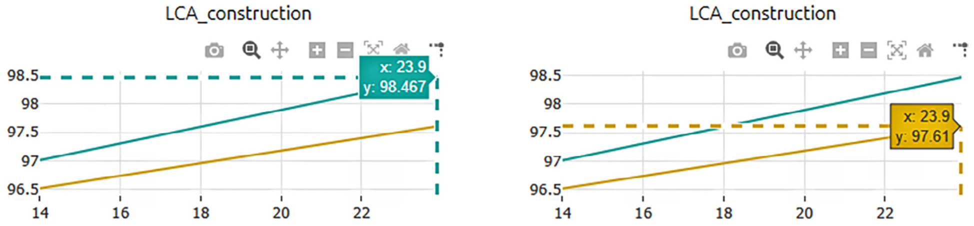


Figure 10. System dynamics build up for Existing waste management strategies and Waste effective site management practice

Similarly, loops (R3, R4) highlighted the role of LICA and LEAED impacts in achieving sustainability. Balancing loops (B1-B4) emphasized minimizing waste, cost, time overruns, and LICC through improved productivity and sustainable practices. The findings confirmed that waste-effective site management practices outperform existing strategies in reducing site-based and non-site-based waste during the preconstruction phase of industrial projects.

The paper already incorporates real project data to make the system dynamic (SD) scenarios more realistic, and evidence based. Specifically, it uses empirical data from an industrial construction case study (Sokhna Fertilizer Complex in Egypt) to calibrate and validate the simulation model. The model inputs, such as project cost (230 million EUR), project duration (24 months), and baseline waste generation rate (15%), were derived from actual construction project records and expert interviews. These real-world values form the initial conditions for variables including material productivity (85%), quality (85%), life cycle assessment (95%), life cycle cost (20%), and LEED performance (95%) within the simulation. By integrating these practical parameters, the study ensures that both the Existing Waste Management Strategies (EWMS) and Waste-Effective Site Management Practices (WESMP) scenarios reflect realistic site conditions, improving the credibility and applicability of the results in minimizing both site-based and non–site-based waste during the pre-construction phase.

4.3.2. Contribution to circular economy

This paper contributes to advancing the principles of the circular economy within the construction industry by developing a dynamic framework that integrates Building Information Modeling (BIM) and Lean Construction methodologies for waste reduction during the pre-construction phase. The circular economy emphasizes minimizing resource consumption, maximizing material reuse, and closing the loop on waste generation throughout a project's life cycle. In this study, the proposed framework employs system dynamics modeling to simulate and optimize strategies that prevent waste at its source, aligning construction processes with circular economy goals. By combining BIM's data-driven design and visualization capabilities with Lean Construction's process efficiency and waste minimization principles, the research provides a scientific model for comparing existing and effective waste management practices. The results demonstrate how early-stage decision-making and digital integration can significantly reduce material waste, improve productivity, and enhance sustainability performance, thereby supporting the transition from a traditional linear "take-make-dispose" model to a regenerative, circular approach in industrial construction projects.

The economic dimension of recycled construction materials plays a critical role in determining their feasibility and adoption within industrial projects. Recent studies highlight that recycled materials, such as recycled aggregates, reclaimed asphalt pavement, and secondary metals, can contribute to substantial cost savings through reduced raw material consumption, lower disposal fees, and decreased environmental compliance costs. Incorporating these findings, the revised manuscript now expands on the financial implications of integrating recycled materials by presenting comparative analyses between virgin and recycled alternatives. These economic insights reinforce the broader circular economy framework by demonstrating how resource efficiency can simultaneously enhance affordability and sustainability.

In addition to material value, the economic dynamics of construction and demolition waste have been explored through updated desk research. Evidence from international case studies shows that waste generation is closely influenced by market incentives, regulatory requirements, and the maturity of recycling infrastructure. However, despite the potential economic benefits, demand for recycled construction materials remains limited in many regions due to factors such as inconsistent material quality, insufficient standards, and low contractor awareness. By integrating these economic challenges and opportunities, the revised manuscript provides a more realistic representation of the current market conditions that govern the utilization of recycled materials.

To support a more comprehensive understanding of recycled material feasibility, furthermore, the manuscript has been enhanced with a technical analysis of characterization methods for recycled materials such as recycled concrete aggregates and asphalt. Techniques including compressive strength testing, gradation analysis, microstructural evaluation, and performance durability assessments are now discussed to illustrate how material properties can be reliably quantified. These characterization methods are essential for ensuring structural performance, building confidence among stakeholders, and overcoming barriers to market acceptance. Enhancing this section strengthens the manuscript's contribution to sustainable construction planning during the pre-construction phase by linking material properties, economic viability, and waste reduction strategies within a holistic decision-making framework.

4.4. Research limitations and future work

This study, while providing valuable insights into minimizing construction waste during the pre-construction phase, is subject to several limitations. First, the system dynamics model relies heavily on expert input and predefined causal relationships, which may introduce bias or oversimplification of complex interactions. The accuracy and generalizability of the model depend on the quality and comprehensiveness of the data provided by experts, which might not fully represent the diversity of industrial projects or regional variations. Additionally, the application of the Anylogic software for system dynamics modeling requires significant computational resources and technical expertise, potentially limiting the accessibility and adoption of the proposed methodology in smaller or less technologically advanced organizations.

Another key limitation is the focus on the pre-construction phase, which excludes the potential impacts of on-site construction activities and post-construction waste management strategies. While this phase is critical for proactive waste minimization, the study does not address waste generated during unexpected construction changes or external factors such as market fluctuations and regulatory challenges. Furthermore, the validation process, although supported by a real-world case study, is restricted to a single project, limiting the scope for broader applicability. Future research could expand the framework to include additional phases of construction and a wider range of case studies to enhance the robustness and scalability of the findings.

Future research could expand the scope of this study by incorporating additional phases of the construction lifecycle, including on-site construction and post-construction waste management. Exploring the integration of advanced technologies, such as digital twins (DTs), artificial intelligence (AI), and Internet of Things (IoT) systems, could enhance the dynamic modeling framework by providing real-time waste generation and management data. This would enable the development of predictive analytics and automated decision-making systems to optimize waste minimization efforts throughout the project lifecycle. Moreover, extending the system dynamics model to account for external variables such as regulatory changes, market conditions, and supply chain disruptions could improve the model's applicability to diverse and dynamic industrial project environments.

Another promising direction is the application of this framework across multiple projects and regions to validate its generalizability and adaptability. Comparative studies that analyze the effectiveness of the proposed techniques in different geographic and industrial contexts could offer valuable insights into region-specific challenges and opportunities for waste management. Additionally, integrating life-cycle assessment (LCA) techniques into the system dynamics model could provide a holistic understanding of the environmental impacts of construction waste, further aligning the research with sustainability goals. Future efforts can also explore collaboration with stakeholders across the construction industry to refine and implement the proposed framework on a larger scale as in Figure 11.

5. Conclusions

Minimizing construction waste, encompassing both site-based and non-site-based waste, during the pre-construction phase is pivotal, particularly for industrial construction projects characterized by their vast scale and intricate processes. This phase, which includes critical activities such as cost estimating, scheduling, constructability reviews, value engineering, procurement, and contracting, plays a decisive role in mitigating waste generation. The study leverages Building Information Modeling (BIM) and Lean

Figure 11. The future research directions

construction techniques to address waste factors classified as dependent variables. These variables include design changes, design errors, complex designs, inadequate material storage, subpar workmanship, waiting time, and unstructured site plans. Using system dynamics and causal loop diagrams (CLD), the research compares two scenarios: existing waste management strategies and waste-effective site management practices. Through this evaluation, eight dynamic loops were identified, comprising reinforcing loops to maximize material productivity, quality, and lifecycle assessment (LICA), and balancing loops to mitigate costs, delays, waste, and lifecycle costs (LICC). The findings underscore that waste-effective site management practices deliver superior outcomes in reducing preconstruction waste.

The study contributes significantly to the body of knowledge on construction waste minimization by offering three critical insights. First, it provides actionable recommendations for effective waste minimization scenarios specific to the preconstruction phase, highlighting the enhanced efficiency of waste-effective site management practices through dynamic modeling and real-case simulations. This approach equips stakeholders with a clear understanding of the most effective strategies to minimize waste. Second, the research empowers decision-makers with tools to evaluate the impact of their preconstruction planning decisions, preventing errors that could escalate costs and delays. The dynamic model also fosters a deeper understanding of the interplay between various waste factors, aiding project managers in making informed, strategic choices for industrial construction projects. Lastly, the integration of system dynamics within the study offers a robust framework for testing different scenarios, ensuring the scalability and adaptability of waste minimization strategies across projects of varying sizes and complexities.

Building upon these findings, the study sets a strong foundation for future research aimed at further refining waste minimization strategies in industrial construction. One key avenue for future work involves addressing maintenance waste during the operational phase, an area often overlooked in traditional waste management approaches. By developing and analyzing dynamic loops specific to operational waste, researchers can extend the applicability of the system dynamics model, ensuring comprehensive lifecycle waste management. Additionally, the study calls for more real-case project analyses to validate the proposed model's effectiveness and adapt it to diverse industrial contexts. These additional studies would enhance the model's credibility and utility in guiding stakeholders toward sustainable construction practices. Ultimately, this research emphasizes the importance of holistic approaches that integrate innovative methodologies such as BIM, Lean construction, and system dynamics, paving the way for significant advancements in waste reduction across all phases of industrial construction technology projects.

Data availability statement

The data presented in this research are available on request from the corresponding author.

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Conflicts of Interests

The authors declare no conflict of interest.

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