






An integrated framework to improve waste management practices and environmental awareness in the Saudi construction industry

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ABSTRACT

There are concerns that the rapid expansion of the Saudi construction industry is contributing to substantial waste production, resulting in significant environmental impacts. Despite global efforts to improve sustainability, the Saudi construction industry faces challenges due to the high levels of construction waste, a limited focus on managing environmental impacts beyond physical waste (i.e., solid or hazardous waste), and the lack of comprehensive waste management strategies. This research introduces a novel integrated framework that combines lean construction principles with environmental management systems to support efficient waste management in Saudi construction projects. The framework integrates the Define, Measure, Analyse, Improve, Control (DMAIC) model from Lean Six Sigma with the Aspect and Impact Analysis (AIA) from environmental management to simultaneously manage both production and environmental wastes. To develop this framework, the current state of waste management practices in Saudi Arabia was investigated through semi-structured interviews with industry practitioners, revealing 44 factors contributing to waste generation. Poor planning emerged as the most frequently cited factor, followed by poor coordination among stakeholders, leftover materials on-site and frequent design changes. These findings underscore the need for a comprehensive and structured approach to address waste management. The proposed framework guides practitioners through defining and measuring waste, analysing root causes, prioritising waste-generating activities based on their impact, and implementing improvement strategies across strategic, tactical, and operational levels. The framework's application is demonstrated through a case example of piling operations and is validated through expert interviews. The integrated framework contributes to knowledge by offering a holistic approach to addressing both production and environmental waste, which aligns with Saudi Arabia's sustainability goals. It equips organisations with a practical tool to optimize resources, reduce environmental impacts, and enhance overall project efficiency.

1. Introduction

The rapid expansion of the Saudi construction industry has led to significant waste production, resulting in considerable environmental impacts both regionally and globally (Blaisi, 2019; Haider et al., 2022; Ouda et al., 2018). In response, the Saudi government launched Vision 2030, a strategy aimed at enhancing sustainability and economic

diversification, with a strategic focus on improving sector-wide performance, particularly in infrastructure and construction industries. The vision emphasises developing more efficient and environmentally conscious approaches to national development (Amran et al., 2020). In line with Vision 2030, Saudi Arabia has set ambitious targets for waste management. The Kingdom aims to recycle up to 95 % of its waste by 2040, potentially contributing SAR 120 billion to the GDP and creating

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over 100,000 jobs (Saudi Gazette, 2024). This initiative aligns with the broader National Environment Strategy and addresses the challenges posed by rapid urbanisation and population growth (MEWA, 2017). As a key sector, the construction industry plays a pivotal role in shaping economic, social, and environmental outcomes. Saudi Arabia's challenges and large-scale projects reflect broader trends in rapidly developing regions, making its experience relevant for understanding and managing construction waste globally.

Despite the global efforts to promote sustainability within the construction industry over the past decade (Gibbin et al., 2023; Moshood et al., 2024), Saudi Arabia continues to face challenges (Aljarallah et al., 2024; AlMunifi and Almutairi, 2021; Ouda et al., 2018). The industry's poor sustainability performance can be attributed to several key factors, including the high level of waste generated by construction activities, a lack of comprehensive awareness among practitioners regarding effective waste management practices, and the limited adoption of formal waste management plans on-site (Ali et al., 2013; Aljarallah et al., 2024; Blaisi, 2019; Ouda et al., 2018). The growing number of large-scale construction projects further intensifies these issues, increasing the demand for natural resources and escalating the environmental impact. Therefore, the Saudi construction industry must address the dual challenge of reducing waste and conserving natural resources. Traditional waste management approaches have struggled to deliver comprehensive solutions, particularly when it comes to integrating sustainability into construction processes. Lean construction emerges as a key approach that has the potential to support efficient waste management and maximise value by applying Lean principles, originally developed in the automobile production industry to minimise waste and enhance project performance (Koskela, 2020). Extensive evidence suggests that the application of Lean principles improves construction sustainability performance (Francis and Thomas, 2020; Sarhan et al., 2019; Xing et al., 2024), yet awareness and implementation remain limited in the Saudi construction industry (Ali et al., 2013; Ouda et al., 2018).

The main aim of this paper is to introduce an integrated framework for managing both production and environmental wastes in the Saudi Arabian construction industry. In the context of this research, production waste refers to waste generated during the construction process, including excess materials, defective products, and inefficiencies in resource utilisation. Environmental waste encompasses waste that negatively impacts the environment, including physical waste (such as construction debris) and non-physical waste like emissions and pollution associated with construction activities. The proposed framework incorporates the Define, Measure, Analyse, Improve, Control (DMAIC) model from Lean Six Sigma and the Aspect and Impact Analysis (AIA) from environmental management systems. Initial observations of inefficiencies in waste management and limited Lean construction adoption have highlighted the need for improvement. To refine and inform this framework, the research first assesses the current state of waste management practices and the extent of Lean construction application in Saudi Arabia. This assessment helps establish a detailed baseline and identify gaps in existing practices, ensuring that the framework is both relevant and effective. The resulting framework aims to simultaneously address production and environmental wastes, improving sustainability and efficiency within the industry.

2. Background

The construction industry is widely recognised as a major contributor to waste production, with significant environmental impacts (Islam et al., 2019; Mahamid, 2020). Globally, the production of construction waste exceeds 10 billion tons annually (Wu et al., 2019), with the major contributors including the United States (US Environmental Protection Agency, 2020a), the European Union (Menegaki and Damigos, 2018), China (Zheng et al., 2017), and the Gulf Cooperation Countries (GCC). Within the GCC, Saudi Arabia faces particular challenges, with more than 120 million tons of construction and demolition waste generated

annually (Blaisi, 2019; Ouda et al., 2018). As construction waste accounts for up to 50 % of solid waste in some regions, addressing this issue is crucial for sustainable development (Amran, 2024; Contreras et al., 2016).

Despite growing awareness of the need to reduce construction waste, traditional waste management practices have struggled to provide comprehensive solutions, particularly when it comes to integrating sustainability into construction processes. Lean construction emerges as a promising approach that focuses on eliminating waste through the reduction of non-value-adding (NVA) activities. Originally developed within the manufacturing industry, lean construction has expanded lean principles to include categories such as Making-do (Koskela, 2004), Unfinished work (Fireman and Formoso, 2013), Waste of human potential (Macomber and Howell, 2004), and Institutional waste (Sarhan et al., 2014), all of which can adversely impact environmental performance (Banawi and Bilec, 2014; Belayutham et al., 2016). Therefore, the elimination or minimisation of waste, particularly NVA activities, has been proposed as a mechanism to enhance both process flow and the environmental performance of construction projects (Formoso et al., 2020; Sarhan et al., 2019).

Current waste management practices in the Saudi construction industry often lack practical applicability (Ajayi et al., 2017; Sarhan and Pretlove, 2021). This limited adoption can be attributed to the industry's reactive nature, with practitioners typically addressing waste only after it occurs. Additionally, these practices frequently treat production and environmental waste as separate entities (Kabirifar et al., 2020), neglecting their interconnectedness.

To address the growing challenges in waste management, Saudi Arabia has recently implemented several initiatives and regulations. The Ministry of Municipal and Rural Affairs and Housing has recently issued a guide for construction, demolition, and renovation waste disposal. This guide includes regulations that aim to establish uniform criteria for waste management, preserve public property, and improve urban landscapes (MOMRAH, 2024). The National Centre for Waste Management (MWAN) plays a crucial role in consolidating regulatory frameworks and spearheading public-sector initiatives. In 2021, Saudi Arabia published a new Waste Management Law to regulate various aspects of waste management, including transport, segregation, storage, and safe disposal (MWAN, 2021).

While Saudi Arabia is developing its approach to construction waste management, it's important to consider and learn from global frameworks and initiatives that have been successful in addressing similar challenges. The European Union's Waste Framework Directive (WFD) provides a comprehensive model for sustainable waste management, which emphasises a 'waste hierarchy' approach and sets targets for recycling and material recovery (European Commission, 2023). The EU's Construction & Demolition Waste Management Protocol and Guidelines aim to increase confidence in the waste management process and promote more efficient use of resources (European Commission, 2018). In the United States, the Environmental Protection Agency (EPA) has developed guidelines for construction and demolition materials management that emphasise reduction, reuse, and recycling (US Environmental Protection Agency, 2020b). China has implemented policies to promote construction waste recycling and utilisation, given its rapid urbanisation (Huang, et al., 2018). The ISO 14001 standard provides guidelines for organisations to improve their environmental performance, including waste management practices (ISO 14001, 2015). These global frameworks and standards offer valuable insights for developing comprehensive waste management strategies. They emphasise the importance of a circular economy approach, which aligns with recent initiatives in Saudi Arabia, such as Vision 2030's sustainability goals.

A limited number of studies have recently focused on waste management in Saudi Arabia's construction sector. Issa and Alqurashi (2020) introduced a two-tier model using fuzzy logic to evaluate the causes of waste and lean implementation, testing it with data from Egypt

and Saudi Arabia. Kabirifar et al. (2020) examined legislative and policy challenges in managing construction and demolition waste to offer a roadmap for effective waste management. AlMunifi and Almutairi (2021) investigated lifecycle practices to develop an integrated strategic construction project management framework to enhance efficiency and effectiveness. Haider et al. (2022) emphasised recycling materials to align with Vision 2030 by highlighting the benefits of recycling construction and demolition waste. Aljarallah et al. (2024) explored the implementation of Lean principles in the construction of housing infrastructure in Saudi Arabia, emphasising the identification and reduction of waste to enhance the reliability, stability, and profitability of construction operations.

While these studies contribute valuable insights, many remain limited in scope, focusing on specific project types or aspects of waste management. For instance, Issa and Alqurashi (2020) study focused primarily on lean principles without fully addressing Saudi Arabia's specific cultural, regulatory, and technological factors. Kabirifar et al. (2020) work was based on a literature review, lacking empirical data. AlMunifi and Almutairi (2021) research, while comprehensive, focused on higher education facilities and did not specifically address waste management practices. Haider et al. (2022) study used European context data due to the lack of region-specific data for Saudi Arabia. Aljarallah et al. (2024) research was limited to housing projects and did not cover the full spectrum of construction types in Saudi Arabia.

In contrast, our proposed integrated framework builds upon these studies by combining lean construction principles with environmental management systems to offer a more comprehensive approach that addresses both production and environmental wastes simultaneously. This holistic approach distinguishes our framework from existing models and aligns with global best practices in construction waste management while specifically tailoring solutions to the Saudi Arabian context.

3. Research design

This research employs a constructive research methodology to address the identified objectives. The constructive research approach facilitates the development of innovative solutions to practical problems while maintaining a strong connection to both theory and practice (Aken, 2004; Koskela, 2008). Accordingly, this research followed the five-stage constructive approach proposed by Kasanen et al. (1993). The following is a description of the five stages and how they are implemented in this research.

3.1. Stage 1: identification of a practical problem

The research begins by pinpointing a practical problem within the Saudi construction industry, specifically addressing the challenges associated with waste management practices and environmental awareness. This involves understanding the current state of waste management, identifying key issues, and recognising opportunities for improvement in alignment with sustainability goals and industry standards.

3.2. Stage 2: understanding of the problem

Building upon the practical issues identified in Stage 1, semi-structured interviews were designed to obtain an understanding of the dimensions of waste management issues within the Saudi construction industry based on input from industry practitioners. This understanding entails exploring the root causes of inefficient waste management practices and assessing the level of environmental awareness within the construction sector. By gaining a deeper understanding of these challenges, the outcomes of this stage lay the foundation for the subsequent stages of solution development.

3.3. Stage 3: innovation of solution idea

Based on the insights derived from the previous steps for problem analysis, an integrated framework tailored to address the specific challenges of waste management and environmental awareness in the Saudi construction industry is proposed. This framework integrates lean construction principles with environmental management systems, aiming to optimise resource utilisation and minimise environmental impact throughout the construction phase.

3.4. Stage 4: implementation and testing of the solution

The proposed framework was implemented and tested within a retrospective real-world construction case study to evaluate its effectiveness and practical applicability. Subject matter experts in Lean construction and sustainability were engaged to evaluate the framework based on criteria such as feasibility, scalability, and its ability to minimise waste. The evaluation aimed to validate both the practical and theoretical applicability of the framework.

3.5. Stage 5: identification of theoretical contribution and scope of application

The research concludes by identifying the theoretical contributions of the proposed solutions to the body of knowledge in lean construction, particularly in bridging the gap between production and environmental waste management. The scope of application within the Saudi construction industry was validated through evaluation sessions with experts, confirming the framework's practical implications for enhancing both sustainability and operational efficiency.

4. The current state of waste management and lean construction in the Saudi construction industry

4.1. Data collection

This section addresses the foundational step of assessing the current state of waste management practices and the extent of Lean construction application in the Saudi construction industry, providing the necessary baseline to inform the development of the proposed framework. Semi-structured interviews were chosen as the data collection method to gain a deep understanding of the current issues of waste management within the Saudi construction sector.

The semi-structured interview sessions comprised eight questions designed to explore the understanding of waste among Saudi construction practitioners, identify waste generation factors, examine the focus of current waste management practices, and assess the dimensions of production and environmental waste generation and management. Additionally, the interviews evaluated the status of Lean construction implementation. The interview questions were designed to explore both production and environmental waste challenges, providing a dual focus that informs the framework's development.

Eighteen participants from Saudi companies of various sizes were interviewed, using a purposive sampling strategy. Participants were chosen based on specific criteria, including their roles (managerial, technical, and strategic positions), years of experience, and involvement in different project types (residential, commercial, and infrastructure). This purposive approach ensured diverse perspectives from stakeholders directly involved in construction waste management practices. Table 1 provides information about the participants' profiles.

While the sample size of 18 participants is not statistically representative of the entire Saudi construction industry, it provides diverse perspectives from key stakeholders. This sample size aligns with similar qualitative studies in construction waste management research. For instance, Udawatta et al. (2015) conducted 16 semi-structured interviews with construction practitioners to explore waste management

Table 1
Participants profile.

Participant	Position	Years of experience	Organisation/Sector
P1	Assistant Manager	4	Local Civil Engineering Contractor
P2	Civil Engineer	7	International Infrastructure Contractor
P3	Construction Engineer	7	International Infrastructure Contractor
P4	Electrical Engineer	9	International networking and telecommunications company
P5	Engagement Manager for Services	13	International Infrastructure Contractor
P6	General Manager	23	Local Civil Engineering Contractor
P7	Installation Manager	8	International networking and telecommunications company
P8	MEP Manager	9	International Infrastructure Contractor
P9	Owner of a company	31	Local Civil Engineering Contractor
P10	Procurement Manager	18	Local networking and telecommunications company
P11	Program Director for Site Acquisition Civil Work	24	International Manufacturer of Rail Transport Solutions
P12	Project Coordinator	6	International Infrastructure Contractor
P13	Project Manager	9	Local Civil Engineering Contractor
P14	Project Manager	12	Local Civil Engineering Contractor
P15	Quality Inspector	14	International Manufacturer of Rail Transport Solutions
P16	Site Engineer	6	Local Civil Engineering Contractor
P17	Site Engineer	5	International Manufacturer of Rail Transport Solutions
P18	Technical Coordinator	7	International Manufacturer of Rail Transport Solutions

practices in the Australian construction industry. Similarly, [Lu and Yuan \(2010\)](#) carried out 14 semi-structured interviews with construction stakeholders to study construction waste management policies in Shenzhen, China. Importantly, several of the interviewed companies in this study are part of a consortium working with public sector entities such as Riyadh Region Municipality and the Royal Commission for Riyadh City on major projects like the Riyadh Metro. This connection ensures that although the participants are from private companies, their insights are closely relevant to public sector construction activities.

Data from the interview sessions were transcribed and analysed using the content analysis technique, a research technique that enabled the researcher to make valid inferences by interpreting and coding written, verbal, or visual communication messages ([Bauer, 2000](#)). Content analysis also allows the conversion of qualitative insights into quantifiable data ([Srnlka and Koeszegi, 2007](#)), providing a structured approach to identifying the root causes of waste generation and environmental challenges, directly supporting the development of the proposed framework. The analysis followed three steps, as suggested by [Elo and Kyngäs \(2008\)](#): Open coding, creating categories, and abstraction. Data was analysed regardless of participants' experience levels to ensure objectivity and capture a broad range of perspectives. The sample was deliberately selected to include varying years of experience, allowing us to incorporate both traditional and modern views on waste management practices. This approach provided a comprehensive understanding of the current state of waste management in the Saudi construction industry across different career stages.

4.2. Construction waste management practices in Saudi Arabia

This sub-section addresses the first objective of this study by presenting the findings related to the status of construction waste management in Saudi Arabia. It starts by reporting the definition of waste in the industry, followed by a thorough identification of waste generation factors. It then provides a critical discussion of the main current practices for waste management in SA as well as any training initiatives to promote waste management in the industry.

4.2.1. Definition of waste in Saudi industry

Participants in the semi-structured interviews were asked to describe their understanding of the term "waste" in the context of the construction industry in Saudi Arabia. Approximately 60 % of participants identified waste as either physical-related (material-related waste) or non-physical-related (time and cost overrun). The remainder described waste as either solely physical or non-physical. The common understanding among the participants is that waste is anything that directly or indirectly affects the consumption of materials, time, and project costs. This encompasses factors such as inefficiencies in resource utilisation, delays, and rework.

Participant 3 stated that "waste is anything that causes us to spend more time and money". Participant 8 referred to waste as "any human activity or procedure that may lead to rework". Additionally, several participants provided insights specifically on physical waste, with Participant 9 noting that "Physical waste includes leftover materials that could have been reused or recycled, which not only affects costs but also impacts our environmental performance". Moreover, Participant 11 emphasised that "Improper handling of materials on-site leads to significant physical waste, which we need to address to improve our overall efficiency."

While participants demonstrated a general understanding of waste, particularly its physical aspects, there was limited awareness of the concept of non-value-adding (NVA) activities beyond immediate time and cost implications. This gap in understanding highlights the need for a deeper comprehension of lean principles and their application in the construction industry. The limited awareness of NVA activities is central to our discussion because it underscores a critical gap in the application of Lean principles in Saudi construction practices. This gap directly impacts both production efficiency and environmental sustainability, which emphasises the need for our integrated framework that addresses both aspects simultaneously.

4.2.2. Factors contributing to the generation of waste

The factors contributing to waste generation in the Saudi construction industry were identified through a comprehensive analysis of the interview transcripts. This process involved extracting waste causes mentioned by participants, determining the frequency of mention for each cause, and analysing interviewees' statements to establish links between causes and impacts. The resulting data, presented in [Table 2](#), reflects the perspectives and experiences of the interviewees.

Data analysis revealed 44 factors that generate waste in the Saudi construction industry. Poor planning emerged as the most frequently mentioned waste factor among participants, followed by poor coordination among stakeholders, leftover materials on-site/packaging, poor attitudes of workers, frequent design changes, and lack of waste management practices.

The participants were asked to discuss the possible impact that the identified waste factors could have on a project based on their practical experience. They were also asked to provide a probability of the impact in percentage. The data collected from the discussion was coded and analysed to define the most influential factors on the project management elements. Poor planning and unsuitable management tools emerged as the most critical waste factors, significantly impacting time, cost, and material consumption across all project management elements. Environmental factors were reported less frequently, with only seven out of the 44 factors directly impacting environmental sustainability.

Table 2
Waste factors in Saudi Arabia.

WASTE ORIGIN	CAUSES OF WASTE	Frequency	Waste Impact						
			Time	Cost	Material	Quality	Machine	Labour	Environment
Design	Frequent design changes	5	**		****			*	
	Design errors	1			****				
	Poor design quality	2			****				
Information, Communication and Coordination	Poor coordination among parties	7	****	*	*				
	Poor Communication	4	**	*	***		*		
Materials	Wrong interpretation of information or instructions	1	****			****			
	Leftover materials on-site	7	*	*	****				
	Lost material or items during construction	1	****	****					
	Items not in compliance with specification	1			****				
	Materials supplied in a standard size	3	**	**	****				
Labour	Inaccurate quantity survey	1			****				
	Poor attitudes of workers	6	***	**	**	***	*		**
	Lack of experience	5	*	**	****	***		*	
	Lack of training	1	****	****	****	****	****		****
	Interference of other crew members	1	****	****	****	****			****
	Poor human resource utilisation	1	****	****					
Technical, Management, and Administration	Poor Planning	9	****	**	****	*	*	*	*
	Inadequate controlling	2	**		****	****	**		
	Inappropriate construction methods	4	**	*	***			*	
	Unsuitable management tools	2	**	**	****	****	****	**	**
	Poor supervision	1	****	****					
	Lack of waste management practices	5	**	**	***	**	*		
	Issues in contract document	1	****		****				
	Lack of awareness about waste generating factors in construction	2			****	****	**		
	Ignorance of government rules/Lack of legal enforcement	1	****	****	****	****		****	
	Physical paperwork	1	****		****				
	Late approvals	4	****		**		*	*	*
	Unimplemented waste management measures	1			****	****	****		
	Wrong sequence of activities	3	***	**	****	***		**	
	Prioritising cost and schedule	1			****	****			
	Uninformed decision making	1	****	****	****	****		****	
Improper task allocation	2	****	**	****	****		**		
Lack of quality management system in small size companies and subcontractors	1			****	****	****			
Space	Inadequate on-site maintenance of equipment	1	****		****		****	****	****
	Improper storage of materials	3	**	**	****				
	Storage location	1	****	****	****				
	Inefficient use of site space	1			****		****		
	Poor Material handling	1	****		****				
Procurement	Damage during transportation	1	****		****				
	Ordering errors	2	****		**				
	Delay in material supply	1	****						
External	Shortage of materials in market	1	****						
	Unforeseen site/ground conditions	2	****	****					
	Accidents	2	****		**			**	

Key: Significance level of the identified factors on the construction process’s resources. It was calculated (using R), based on the number of mentions and probability that each waste cause could have on the construction process’s resources (Time, Cost, Material, Quality, Machine, Labour, Environment). The meaning of the stars for the probability percentage is shown below.

- * = 0–25 %
- ** = 25–50 %
- *** = 50–75 %
- **** = 75–100 %

These findings highlight the need for a framework that not only addresses production waste but also integrates environmental considerations, reinforcing the importance of Lean principles in minimizing both forms of waste. This is also consistent with the findings in the literature (Ali et al., 2013; Aljarallah et al., 2024; Blaisi, 2019; Haider et al., 2022; Ouda et al., 2018).

4.2.3. Current practices for waste management

The findings of the interviews indicate that construction practitioners in Saudi Arabia primarily deal with waste reactively, addressing it once encountered on-site. Participant 10 stated that “I didn’t encounter before any manager in the top management, who gave too much attention to waste generation”. Participant 13 supported the

previous statement by stating that, “I have never encountered a plan to manage waste while the construction process is in progress”. More than one participant highlighted that the industry culture in Saudi Arabia is more concerned with time and cost performance, neglecting the quality standard or physical waste impacts on the environment. Even when waste is of concern, the attention is mostly limited to the amount (and cost) of material waste generated, which needs to be moved off-site.

It was also found that waste monitoring and measurement methods in the Saudi construction industry are limited to the materials used during the construction phase, e.g., daily checklists of ordered and used materials, overlooking other types of non-material wastes. Most participants pointed out that waste management practices typically involve collecting waste in on-site containers for disposal by local waste

management companies. The participants were asked to explain how they measure waste. Half of the participants indicated no specific method to measure waste on-site. 38 % stated that waste is measured by the size of containers and bins placed on site. The remaining indicated that waste management is considered as part of other management plans such as risk and resource management. This confirms that prevailing on-site waste management practices in Saudi Arabia are mainly focused on material-related waste.

Environmental waste management practices are largely inadequate, with minimal attention given to recycling or reusing materials. The prevailing industry culture prioritises time and cost performance over environmental sustainability. Participant 12 stated that “honestly, we don’t, or mostly here in Saudi Arabia, they don’t care about the environment, it’s the very least; we have never had someone who cares about the environment”. Participant 4 supported it by saying, “We focus on waste reduction to save money, not the environment”. Additionally, Participant 6 stated that “for the environment it is only related to sort and throw”. Participant 10 further emphasised that “we do not have the mentality for sorting and recycling to protect the environment in Saudi”.

The reactive approach to waste management, as indicated by the participants, underscores the need for a more proactive, structured framework that integrates Lean principles and environmental sustainability. Such a framework would prioritise waste prevention rather than merely addressing it after it occurs. The lack of structured waste management practices is further compounded by the absence of formal training and awareness programs, as discussed in the following section.

4.2.4. Waste management training

Despite the critical role of waste management in construction projects, there is a notable lack of training and awareness among construction practitioners in Saudi Arabia. Challenges such as the absence of dedicated training courses, limited knowledge about waste generation factors and impacts, and cultural attitudes toward waste indicate this gap. The findings of the interviews show that only a minority of participants had received any form of waste management training, typically as part of broader health and safety courses.

Participants emphasised the need for mandatory waste management training as part of project induction processes to enhance awareness and improve waste management practices. Participant 11 stated that “Without proper training, we often overlook the amount of waste we generate and its implications”. Similarly, Participant 6 indicated that “Training should focus not just on disposal but on prevention and resource optimisation”.

The findings of the interviews confirm that waste management training programmes for construction practitioners should encompass several key components to enhance awareness and practices. These include understanding the types of waste generated, both physical (materials) and non-physical (time and costs), as well as strategies for waste prevention at the source to emphasise efficient resource utilisation. Training should also cover recycling and reuse practices, supported by successful case studies, and ensure compliance with local regulations regarding waste management and environment sustainability.

Incorporating comprehensive training programmes into the proposed framework would ensure that practitioners are equipped with the knowledge and skills necessary to address both production and environmental waste proactively. By integrating training, the framework will align waste management practices with both operational efficiency and sustainability goals.

4.3. Lean construction application in Saudi Arabia

We assessed the understanding and implementation of Lean Construction (LC) for waste minimisation in Saudi Arabia next. This section defines construction activities that utilise resources without creating value for the customer, i.e., non-value-adding (NVA) activities and

examines their impact on environmental waste generation. It also reviews the current status of managing production and environmental waste from an LC perspective.

4.3.1. NVA activities in the Saudi construction industry

Results from the semi-structured interviews identified seven NVA activities prevalent in the Saudi Arabian construction industry. These activities and their respective frequencies of mention are summarised in Table 3. Among these, ‘Waiting’ emerged as the most frequent NVA activities mentioned by participants, followed by ‘Unnecessary

Table 3
NVA activities in Saudi Arabia.

Waste categories/ frequency of mention	Description	Reasons for occurrence
Waiting (66.67 %)	Time spent for approval, use of equipment, space, or materials delivery.	<ul style="list-style-type: none"> – Waiting for replacement of wrong material delivered – Waiting due to too many inspections – Waiting for repair (Stopping time for redesigning or rework) – Waiting for approval – Delay in operation due to stoppage or suspension of the project – Late delivery of material to the site
Unnecessary-Ordering (38.89 %)	Ordering more than what is required	<ul style="list-style-type: none"> – Over-ordering due to mistakes in quantity or delivery – Ordering more resources than necessary due to rework or to catch up on planned time – Ordering extra materials to mitigate risks related to material shortage – Hiring more labour than what is required
Overproduction (33.33 %)	Producing more than what is required.	<ul style="list-style-type: none"> – Producing more than what is required to satisfy the client – Producing wrong work due to poor guidance on site – Poor planning – Mistakes/faults during the execution process
Transportation (33.33 %)	Unnecessary transportation to the site and excessive use of transportation on-site.	<ul style="list-style-type: none"> – Unnecessary movement of heavy vehicles – Too many site visits – Travel time to deliver physical paperwork
Over-Processing (22.22 %)	Invaluable, wrong or overuse of resources like materials, labour, equipment, or site space.	<ul style="list-style-type: none"> – Unnecessary/over-use of machinery – Over-utilisation of labours – Over-use of materials
Motion (16.67 %)	Unnecessary or over movement of machines, equipment or workers while the construction process is in progress	<ul style="list-style-type: none"> – Several unauthorised breaks for lunch or social activities – Unnecessary movement of heavy vehicles
Other (33.33 %)	Any activity, action, behaviour, or attitude associated with the project but does not add value	<ul style="list-style-type: none"> – Early kick-off (starting before having the final design approved) – Eating onsite – Rushing to complete work without proper procedures – Unnecessary cleaning of equipment (e.g., repeatedly washing cars and trucks)

Ordering’ and ‘Overproduction’. Each NVA category is associated with specific reasons for occurrence, ranging from inefficient resource utilisation to delays in project execution.

Understanding these NVA activities is crucial for recognising their broader impact, both on project efficiency and on environmental waste generation, as will be explored in the next section.

4.3.2. Relationship between NVA activities and environmental waste

To identify the relationship between production and environmental waste, participants in this study were asked to state their level of agreement about the impact that NVA activities could have on the environment. Then, they were asked to provide examples that support their answers. Content analysis was conducted to detect, in a wider scope, the impact of NVA activities on the sustainability pillars. Table 4 highlights the effects of these activities on environmental, economic, and social sustainability.

The majority of participants (13 participants) agreed that NVA activities significantly contribute to environmental waste generation. Only four participants believed that there is little or no impact on the environment, as they thought that NVA activities affect only the production process. Content analysis revealed that all NVA activities contribute to energy consumption, while Overproduction notably affects multiple sustainability elements. Lastly, one participant had no clear understanding of the impact of NVA activities on the environment.

The relationship between NVA activities and environmental waste is significant, particularly in terms of excessive energy consumption and emissions. Overproduction, in particular, was identified as having a substantial impact across multiple sustainability elements, further emphasising the need to integrate environmental considerations into waste minimisation strategies. The findings from this analysis underscore the importance of developing a Lean-based framework that not only addresses production waste but also integrates environmental sustainability.

4.3.3. Production and environmental waste management in Saudi Arabia

Despite the recognised impact of NVA activities on the generation of environmental waste, current waste management practices in Saudi Arabia predominantly focus on productivity performance, neglecting environmental considerations. Participant 15 stated, “We mostly look at these types of waste from the productivity perspective and to manage the project time and cost, and honestly, the environment is of minor concern in our management practice, as it is in most Middle Eastern countries”. This indicates a lack of integration between production and environmental waste management, which highlight a key problem of short-term thinking and lack of sufficient understanding of long-term consequences. Similarly, Participant 1 noted “I didn’t face any special waste management practices dealing with these two waste types, for environment and production together”. Moreover, Participant 14 stated that “they are managed separately; for productivity we deal with waste once found, but for the environment, we just sort waste and ask someone to remove it out of the site”.

The management of environmental waste is often limited to physical waste, such as solid or hazardous materials, and does not extend to the environmental impacts of production processes. This separation reflects a broader issue of fragmented management practices, which fail to recognise the interconnectedness of production inefficiencies and their environmental consequences, as highlighted by the Lean approach. This short-term focus on productivity at the expense of environmental considerations undermines long-term sustainability goals, particularly those outlined in Saudi Arabia’s Vision 2030.

Despite the current lack of integration, participants expressed strong support for implementing a management framework that simultaneously manages production and environmental waste. Specifically, 17 participants (90 %) agreed with the idea, while one participant justified their disagreement by saying, “because we are not dealing with material which causes environmental effect.” This response indicates a limited

Table 4 Impact of production waste on sustainability.

NVA category	Environmental waste										Economic Impact				Social			
	Excessive Consumption					Excessive Emission					Productivity		Human Health					
	Material	Energy	Water	Land		Air pollution	Solid Waste	Hazardous Waste	Water pollution	Soil Pollution	Others (Rubbish and deforestation)	Time	Cost	Quality	Labour	Noise	Stress	Accident
Motion												**						
Over- Processing	**	****				**	**	**		**		**					**	****
Over- Production	*	**	**	**		**	**	**	**	**		****	***	*				
Transportation		****				****				**		**	**			**		
Unnecessary ordering	***	**				**	***		**			***	***					
Waiting		**				*	*		*			****	**	*			*	*
Other	***						**		*	*		**		*		*		*

Significance level of the production waste on sustainability. It was calculated (using R), based on the number of mentions and probability that each waste cause could have on sustainability element. The meaning of the stars for the probability percentage is shown below.

* = 0–25 %
 ** = 25–50 %
 *** = 50–75 %
 **** = 75–100 %

understanding of the broader concept of waste management.

5. An integrated framework for waste management in the Saudi construction industry

This section outlines processes linked to the development and verification of a novel and integrated framework for improving waste management practices and environmental awareness in the Saudi construction industry. As discussed in Section 4, current waste management practices in Saudi Arabia lack integration between production and environmental waste, which results in inefficiencies and missed opportunities for sustainability. To address these gaps, this framework aims to manage both types of wastes concurrently.

5.1. Development of the framework

In the construction industry, waste management practices usually deal with production and environmental waste as separate issues. This separation often leads to inefficiencies and missed opportunities to improve sustainability. In this paper, a novel framework is proposed that integrates principles from both lean production and environmental sustainability research. The framework integrates the DMAIC (Define, Measure, Analyse, Improve, and Control) model from Lean Six Sigma with the Aspect and Impact Analysis (AIA) from environmental management systems. The integration of these two approaches allows for a holistic approach to waste management, where production waste and environmental impacts are treated not as isolated issues but as interconnected challenges that can be managed more effectively through data-driven and environmentally focused solutions.

DMAIC is a structured data-driven method to optimise existing production processes or develop new ones. (Banawi and Bilec, 2014). Relying on data-driven decision-making, DMAIC helps to define and

measure waste, analyse the root causes of the problems, and enhance overall process performance. Additionally, it assists in controlling the proposed actions and establishing procedures for future improvements. AIA, on the other hand, is an environmental management system that focuses on improving environmental performance (International Organization for Standardization, 2015). AIA is used to identify NVA activities that contribute to environmental waste, find their root causes, prioritise them based on the level of impact, and suggest suitable actions to address these causes and impacts.

The integration of these two approaches enabled this study to develop a novel framework that consists of six stages. Fig. 1 illustrates the framework, which is used to define, measure, analyse, and improve processes, as well as to identify waste and suggest ways to reduce environmental impact.

The framework flow is designed to provide clear guidance to industry practitioners on production and environmental waste management in construction projects. It follows a straightforward approach aiming to capture NVA activities and recognise their impact across three production levels: strategic, tactical, and operational. The framework’s practical implementation is critical to its success. It provides industry practitioners with actionable steps for managing waste at different production levels.

However, it is important to understand that some NVA activities are unavoidable in construction, and completely eliminating them is unrealistic. While Lean principles strive for waste minimisation, it is acknowledged that some NVA activities are inevitable in construction. Therefore, the framework is designed not for complete elimination but for continuous improvement by minimising their impact over time. The framework should be implemented iteratively to ensure that all NVA activities are identified and managed effectively. A detailed explanation of the framework and its components is provided in the description of the case example in the next section.

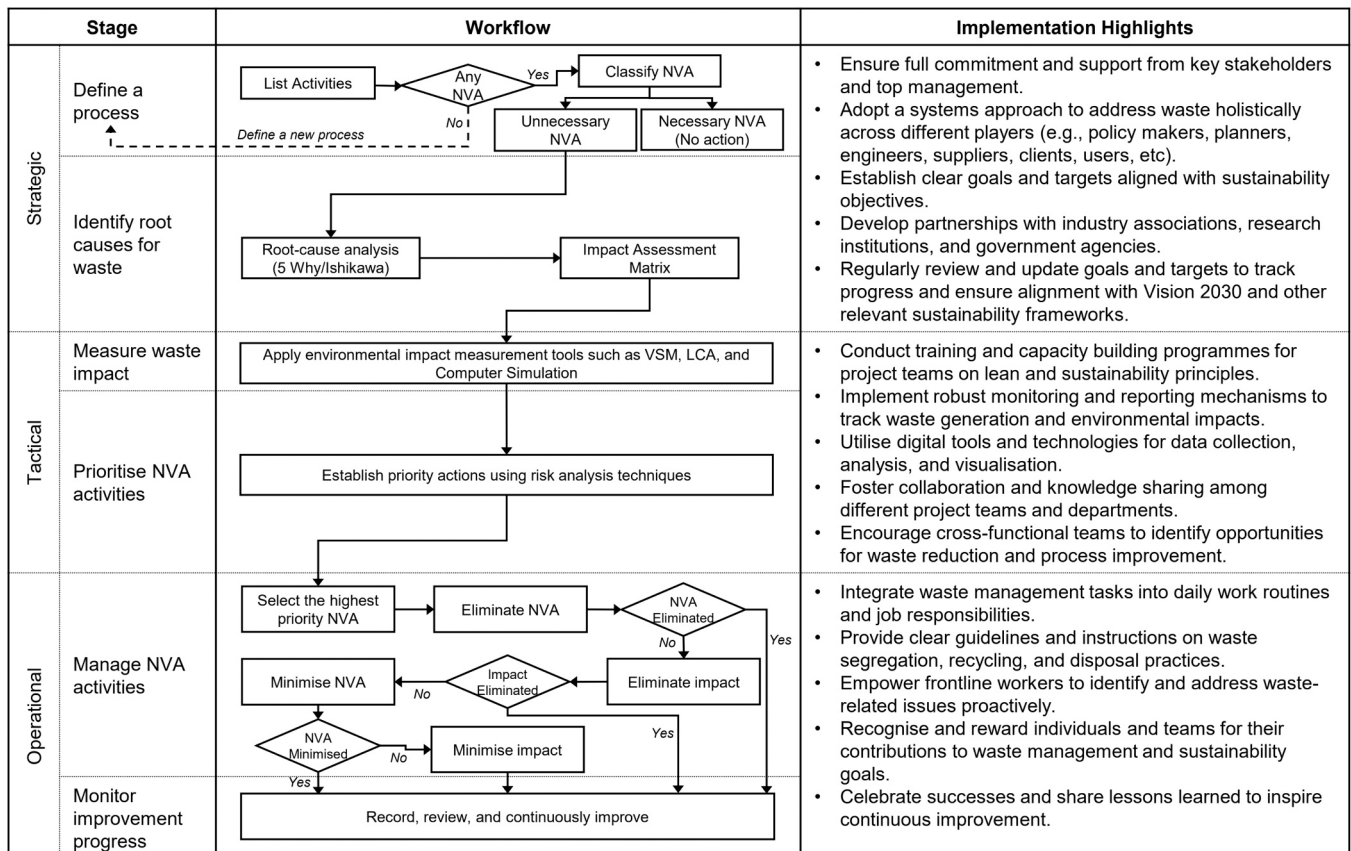


Fig. 1. The proposed framework stages and workflow.

5.2. Case example: the construction of case-in-place reinforced concrete piles

To demonstrate the implementation of the novel and comprehensive waste management framework, this paper provides a case example of constructing cast-in-place reinforced concrete piles. Piles form a key structural element in several types of buildings. Piling operations are inherently complex due to the fact that they involve interrelated activities that require different materials and machinery. Furthermore, external factors such as groundwater level, space constraints, and soil profile can all contribute to the complexity of operations.

This example aligns with the study conducted by Banawi and Bilec (2014), which demonstrated the use of a Lean, Green, and Six Sigma (LG6) model on pile cap operations. Their research shows that implementing lean practices in piling cap construction can lead to a 1 % reduction in costs and a 9 % reduction in environmental waste.

The case example presented here, based on a construction project of an educational building, demonstrates how the framework addresses both production and environmental wastes concurrently within a complex piling operation. The project was located in a busy area with proximity to a hospital and residential buildings, posing several challenges. One significant challenge was complying with the restrictions on machinery types and numbers. Careful planning was required to ensure uninterrupted production while still meeting these constraints.

The piling process involved seven main activities, each requiring careful planning and coordination. The first activity was site preparation, followed by land surveying, pile drilling, dewatering, steel cage insertion, concrete pouring, and the removal of excavated soil. In addition to the seven main activities, two other activities were essential: ensuring a consistent supply of steel cages and fresh concrete. A detailed overview of each of the six stages of the framework’s implementation is provided in the following subsections.

5.2.1. Stage 1: define a process

The objective of this stage of the framework is to identify the sources of waste generated during construction. Initially, a production process or sub-process within a construction operation is chosen to investigate the reasons for waste production. It is crucial to evaluate the current state of the selected process by identifying all activities and sorting them into Value-Adding (VA) or Non-Value-Adding (NVA) categories. NVA activities should be further classified into necessary and unnecessary subcategories.

Necessary NVAs are inherent and indispensable to the production process, while unnecessary ones use up resources without adding value to the final product. The framework concentrates on dealing primarily with unnecessary NVA activities (i.e., waste). This aligns with the Lean construction principles of reducing inefficiencies, which were discussed earlier in the paper, emphasising the minimisation of both production and environmental waste.

It is important to note that activities such as necessary NVA and VA can also have environmental impacts; however, addressing them requires distinct approaches and falls beyond the scope of the proposed framework. The classification in Table 5 are determined through the framework’s process of identifying VA and NVA activities, as outlined in the Define stage of the framework. As demonstrated, three activities are classified as VA activities, three as necessary NVA activities, and one as unnecessary NVA activity. It is crucial to highlight that this analysis depends on the project requirements, complexity, and circumstances. Therefore, these activities may be classified differently in other settings.

This classification helps inform the subsequent stages of the framework, where unnecessary NVAs can be targeted for elimination or mitigation, improving both productivity and environmental outcomes.

5.2.2. Stage 2: identify the root causes of the identified wastes

In order to effectively address waste, it is imperative to identify its root causes. This stage aims to accomplish this end by utilising the 5-

Table 5

VA and NVA activities for the construction of cast-in-place concrete piles.

Piling activities	VA	Necessary NVA	Unnecessary NVA	Explanation
Site preparation		✓		Although this process does not directly contribute to pile production, it is necessary to allow piling machinery to operate within the pile location. Land survey is classified as VA as any mistakes in pile locations might diminish the operational value of the pile to support the building structure.
Land survey	✓			Piles cannot be constructed without displacing the soil in the pile location to allow for the steel and concrete to be inserted. Dewatering is a necessary NVA due to the negative effect of water on the quality of the pile materials. It is not VA as the pile can still be produced underwater using special tools and materials if necessary. Steel is a critical structural component of reinforced concrete piles, so it has to be inserted into the piling location. Concrete is a critical structural component of reinforced concrete piles, so it has to be poured into the piling location. The process of drilling produces soil from the pile location. The removal of this soil does not add value to the production of piles. This soil type was found to be suitable for recycling in any future construction operations and thus was unnecessary to be removed from the site.
Drilling		✓		
Dewatering			✓	
Steel cage insertion		✓		
Concrete pouring		✓		
Excavated soil removal			✓	

Whys technique developed by Sakichi Toyoda (Ohno, 1988) and the Ishikawa diagram, also known as the fishbone diagram (Ishikawa, 1990), to identify the root causes of NVA activities and their impacts. This stage considers both production and environmental waste, aligning with the dual focus of the framework on improving efficiency and sustainability. The 5-Whys technique is a powerful tool for uncovering the origins of waste in the process, while the Ishikawa diagram effectively illustrates the cause-and-effect relationships between the different causes of waste and their impacts.

The outcome of this stage can be presented in a matrix that outlines the connections between identified root causes and their potential impacts. This is critical to ensure that the root causes and impacts of each identified NVA activity are transparent, thereby enabling actionable waste management strategies in the following stages. By uncovering the root causes of both production and environmental waste, these tools help lay the foundation for targeted strategies to minimise inefficiencies and environmental impacts, supporting the overarching goals of the framework.

To illustrate the application of this stage, the Ishikawa diagram method was employed to identify the root causes for the soil removal activity in the case example. The identified root causes are presented in Fig. 2.

Table 6 demonstrates the relationship and impact that the identified NVA activities could have on production and environmental waste generation during the construction process. Soil removal may generate both production and environmental waste due to the use of transportation within the construction site and outside to the dumping site. The removal of soil necessitates excessive movement of excavators to shift the soil to a stocking area, as well as haul trucks to transport the soil from the construction site to the dumping station. These machines consume energy, generate pollutants, and create dust. Additionally, the use of heavy machinery increases the risk of hazardous material leakage and soil pollution.

5.2.3. Stage 3: measure waste impact

Building on the root cause analysis conducted in Stage 2, this stage focuses on quantifying the environmental impact of the identified NVA activities. While conventional lean practice prioritises productivity, time, and cost efficiency, it often overlooks environmental impacts (Teixeira et al., 2021; Wu et al., 2013). However, research suggests that incorporating environmental considerations into lean principles is both useful and feasible (Aljarallah et al., 2024; Arroyo and Gonzalez, 2016; Issa and Alqurashi, 2020). By extending Lean principles to include environmental waste, this stage contributes to a more holistic waste management strategy, addressing both productivity and sustainability goals.

To reinforce the environmental aspect of lean, the framework proposes process analysis techniques, such as Value Stream Mapping (VSM) (Weinheimer et al., 2017), Life Cycle Assessment (LCA) (Farias et al., 2019), and Simulation modelling (Golzarpoor et al., 2017), to gauge the environmental impact of targeted NVA activities. The selection of analysis techniques may vary depending on the waste types and available data and is at the framework user’s discretion.

Since the case study was retrospective, the impact of soil removal activities was not measured. It is expected that incorporating a simulation model can prove to be a highly efficient approach in aiding impact measurement. This is primarily because simulation modelling possesses advanced analytical capabilities that enable it to capture intricate systems and assess project performance against various criteria. Simulation modelling offers a sophisticated means of evaluating complex systems, which can be beneficial in accurately gauging impact (Abdelmegid et al., 2022; Hao et al., 2019; Züst et al., 2021). This approach ensures that

future projects can utilise advanced tools to quantify the environmental impact of NVA activities, enabling more informed decision-making and continuous improvement.

5.2.4. Stage 4: prioritise NVA activities

This stage of the framework is part of the tactical level. The first step is to assess the identified NVA activities using a risk assessment rating system. This system considers both the probability and impact of each activity to enable determining which ones pose a low, medium, or high risk in terms of both production and environmental waste. This prioritisation process is crucial, as it helps to focus attention and resources on addressing the riskiest NVA activities. This, in turn, aids in defining a strategic and efficient approach to waste management in the following stages.

To illustrate this process, Table 7 shows the results of the risk assessment for three NVA activities. Based on this assessment, soil removal the highest priority for management intervention due to its classification as an unnecessary NVA activity. However, it is also important to assess the other NVA activities, even if they are deemed necessary for the process. Such activities will be analysed in the next stage to establish if it is possible to reduce the need for these activities or minimise their impact on production and environmental waste.

5.2.5. Stage 5: manage NVA activities

Building on the prioritisation of NVA activities in Stage 4, this stage focuses on managing those activities by developing actionable strategies to reduce or eliminate waste. The ultimate goal is to prevent the creation of unnecessary waste by eliminating NVA activities altogether. If complete elimination is not feasible, alternative measures should be implemented to minimise their impact on production and the environment.

The proposed framework outlines a strategic and structured approach to manage NVA activities in a specific order, enhancing the effectiveness of minimising their impacts. These steps include:

1. focusing on immediate measures to prevent waste generation,
2. redesigning production operations to avoid unnecessary NVA activities, and
3. utilising approaches to control waste generation in the process.

In the case example, it was discovered that the NVA activity of soil removal during construction operations could be partially eliminated. Some of the excavated soil was not suitable for other construction activities, leading to unnecessary removal. To prevent the generation of such waste in piling operations, a mitigation strategy was developed,

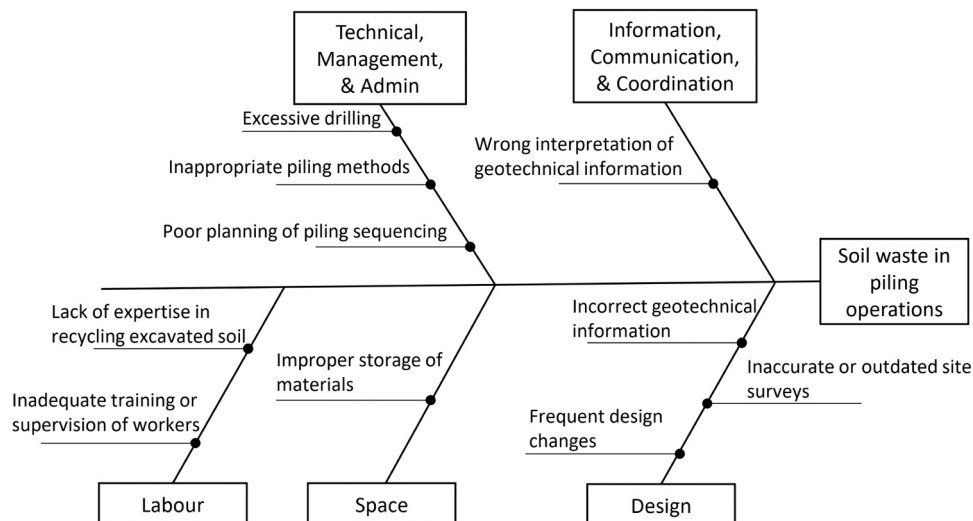


Fig. 2. Ishikawa diagram for the root causes of soil removal in the case example.

Table 6
Impacts of NVA activities.

Piling activities	VA	Necessary NVA	Unnecessary NVA	Explanation
Site preparation		✓		Although this process does not directly contribute to pile production, it is necessary to allow piling machinery to operate within the pile location.
Land survey	✓			Land survey is classified as VA as any mistakes in pile locations might diminish the operational value of the pile to support the building structure.
Drilling	✓			Piles cannot be constructed without displacing the soil in the pile location to allow for the steel and concrete to be inserted.
Dewatering		✓		Dewatering is a necessary NVA due to the negative effect of water on the quality of the pile materials. It is not VA as the pile can still be produced underwater using special tools and materials if necessary.
Steel cage insertion	✓			Steel is a critical structural component of reinforced concrete piles, so it has to be inserted into the piling location.
Concrete pouring	✓			Concrete is a critical structural component of reinforced concrete piles, so it has to be poured into the piling location.
Excavated soil removal			✓	The process of drilling produces soil from the pile location. The removal of this soil does not add value to the production of piles. This soil type was found to be suitable for recycling in any future construction operations and thus was unnecessary to be removed from the site.

which involved a thorough review of the geotechnical report and regular updates based on accurate site information gathered during operations.

Moreover, it was found that any excess soil excavated from piling operations could be utilised as a temporary protective layer under heavy machinery, preventing physical damage to the site and minimizing environmental impact. Later, the foundation contractor could remove the soil during their site excavation activities, eliminating the need for dedicated soil removal operations and thus improving resource utilisation and boosting productivity. These align with the framework’s goal of reducing environmental impact, ensuring environmental sustainability, and enhancing process efficiency, consistent with Lean principles.

5.2.6. Stage 6: monitor improvement progress

The final stage of the framework is centred around monitoring the performance of implemented waste reduction strategies and identifying any new forms of waste that may arise as a result of the strategies implemented in the previous stage. This stage is a key distinguishing feature of the proposed framework, as it emphasises the need for continuous evaluation and adaptation to address evolving waste

Table 7
VA and NVA activities for the construction of cast-in-place concrete piles.

Piling activities	VA	Necessary NVA	Unnecessary NVA	Explanation
Site preparation		✓		Although this process does not directly contribute to pile production, it is necessary to allow piling machinery to operate within the pile location.
Land survey	✓			Land survey is classified as VA as any mistakes in pile locations might diminish the operational value of the pile to support the building structure.
Drilling	✓			Piles can not be constructed without displacing the soil in the pile location to allow for the steel and concrete to be inserted.
Dewatering		✓		Dewatering is a necessary NVA due to the negative effect of water on the quality of the pile materials. It is not VA as the pile can still be produced underwater using special tools and materials if necessary.
Steel cage insertion	✓			Steel is a critical structural component of reinforced concrete piles, so it has to be inserted into the piling location.
Concrete pouring	✓			Concrete is a critical structural component of reinforced concrete piles, so it has to be poured into the piling location.
Excavated soil removal			✓	The process of drilling produces soil from the pile location. The removal of this soil does not add value to the production of piles. This soil type was found to be suitable for recycling in any future construction operations and thus was unnecessary to be removed from the site.

management challenges. This addresses the limitation of waste management frameworks that focus solely on the initial implementation of improvement strategies, and thereby overlook the dynamic nature of construction projects and the potential for new waste streams to emerge (Ajayi et al., 2015; Osmani, 2012). By incorporating a dedicated stage for performance monitoring and waste identification, this framework ensures that organisations remain vigilant and proactive to changing conditions. This stage allows for the early detection of new waste streams and the timely adaptation of strategies to address them.

It is crucial to maintain a record of the current challenges and the decisions or solutions that have been implemented to ensure continuous improvement. These records can be used as valuable lessons learned to enhance knowledge retention and transfer. The documentation of lessons learned is a common practice in project management, as it facilitates organisational learning and continuous improvement (Aerts et al., 2017; Kiomjian et al., 2020; Langlely, 2015). By applying this principle to waste management, the framework promotes a culture of continuous learning and adaptation, enabling organisations to stay ahead of emerging waste challenges and maintain their competitive edge in the industry. This focus on continuous monitoring and adaptation aligns

with the core principles of Lean construction, where ongoing improvement and waste minimisation are central to enhancing both productivity and sustainability.

5.3. Framework evaluation

5.3.1. Expert evaluation

The evaluation of the proposed framework was conducted by experts from both academic and industry backgrounds in the fields of lean construction and sustainability. Expert evaluation is a commonly used qualitative method for the evaluation of conceptual models and frameworks, as established by (Hancock et al., 2001). Initially, a sample of 10 participants was selected based on their extensive experience in both lean construction and sustainability. Six experts agreed to participate in the study. The demographic details of the participants are presented in Table 8. These experts were chosen for their extensive experience in Lean construction and sustainability, providing a balanced perspective from both academic and industry viewpoints.

This evaluation study employed semi-structured interviews conducted online via Zoom. The interviews focused on ensuring the alignment of the developed framework with state-of-the-art research and industrial best practices. The interviews were based on four key categories, which were identified based on the research objectives and the framework components. The expert evaluation process yielded results that are detailed in the following subsections. Based on the outcomes of these interviews, the framework underwent refinement to incorporate feedback and recommended modifications.

5.3.2. General overview of the framework

After familiarising themselves with the framework, the experts shared their general impressions, which were critical in assessing its clarity and potential effectiveness. Several experts agreed that the framework is well-organised and easy to follow, with Expert 2 noting, "The flow of the framework is clear, easy to follow" and Expert 5 emphasising its holistic approach to waste management and sustainability. Expert 3 added, "I found your framework very useful, and it's a good idea to combine lean and sustainable concepts every time, in my opinion". This feedback reinforces the core objective of the framework: to bridge Lean construction and sustainability practices in a cohesive and actionable manner.

In assessing the effectiveness of the framework, experts provided valuable insights. Expert 1 emphasised that "it can eliminate the non-value adding activities... It has the potential to reduce schedule for sure, environmental impact in terms of emission from the construction phase". This feedback highlights the framework's ability to identify and eliminate non-value-adding activities, which can lead to significant improvements in project performance and environmental impact.

Expert 2 pointed out the framework's comprehensive approach, stating, "The framework consists of strategic, tactical, and operational levels... This will help in LEED accreditation... I notice that in your framework". This comment suggests that the framework's multi-level structure enhances its practical relevance and applicability.

Furthermore, Expert 4 noted, "This framework could definitely improve the efficiency of construction, provided the users could properly conduct and understand the impact measurement well." This statement underscores the importance of proper implementation and understanding of the framework for realising its full potential in improving construction efficiency.

5.3.3. Applicability of the framework

The subsequent interview question was designed to explore the practicality of the framework by identifying potential issues or constraints that could impede its implementation in construction projects. The participants expressed a high degree of confidence in the framework's applicability in real-world construction projects, highlighting its ease of practical application and reporting no significant impediments. This confidence was largely due to the framework's structured approach, which integrates Lean principles with sustainability practices in a way that is practical and adaptable to various construction projects.

Expert 3 stated, "Yes, in my opinion, you can apply it to a real construction project". This affirmation suggests that the framework is perceived as relevant and actionable within the context of actual construction scenarios. Similarly, Expert 5 emphasised, "Absolutely yes...I would apply it straight away as we are suffering from a lack of attention in waste management". This comment reflects a sense of urgency and a recognition of the framework's potential to address existing challenges in waste management practices.

5.3.4. Benefits and drawbacks of implementing the framework

To evaluate the feasibility of the framework, the next inquiry examined its advantages and disadvantages. The reported drawbacks primarily concerned the time and costs involved in implementing such a management intervention.

On a positive note, the experts identified potential benefits for the framework in construction projects, such as reducing production and environmental waste, boosting productivity, enhancing time and cost performance, and raising awareness about environmental waste. The experts also noted that the framework can improve comprehension of the interplay between lean and sustainability concepts, enhancing the overall efficiency of construction processes.

5.3.5. Challenges of implementation

Despite the numerous benefits, the experts also identified several challenges that must be addressed to ensure the framework's successful implementation. One of the major challenges identified was related to resistance to change. Additionally, construction practitioners' lack of knowledge about lean and sustainability concepts was another obstacle. Expert 1 highlighted that "Measuring NVA can be hard but depends on NVA types" pointing to the difficulty of assessing non-value-adding activities, which could hinder the framework's implementation.

The scope of implementation was also discussed, and the experts suggested starting with smaller pilot projects before tackling entire projects. In order to overcome these challenges, well-designed guidelines and clear demonstrations of the framework's benefits were deemed

Table 8
Demographic details of participant.

Interview Reference	Title of Interviewee	Education	Country	Years of experience in lean and/or sustainability	Type of Experience
Expert 1	Researcher/ Academic	Doctoral	USA	Over 15 years	Academic+ Practical
Expert 2	Researcher/ Academic	Doctoral	Chile	Over 15 years	Academic + Practical
Expert 3	Researcher/ Academic	Doctoral	Turkey	Over 15 years	Academic + Practical
Expert 4	Researcher/ Academic	Doctoral	Malaysia	five to ten years	Academic + Practical
Expert 5	Project Manager	Master	Saudi Arabia	five to ten years	Practical
Expert 6	Construction Manager	Bachelor	New Zealand	Five years	Practical

necessary by the experts. Successfully overcoming these challenges is essential to achieving the framework's aim of integrating Lean principles with sustainability, ensuring long-term waste reduction and project efficiency.

6. Conclusion

The construction industry in Saudi Arabia faces significant challenges in waste management and the preservation of natural resources, especially in light of the ambitious projects outlined in Vision 2030. This study aimed to contribute to addressing these challenges by developing an integrated framework that combines lean construction principles with environmental management systems. The proposed framework offers a structured approach to managing both production and environmental wastes, empowering construction organisations and professionals in Saudi Arabia to utilise resources effectively and reduce environmental impact throughout all stages of project execution.

The study employed a constructive research approach, beginning with semi-structured interviews to gain insights into the current state of waste management in the Saudi construction industry. These interviews identified several key factors contributing to waste generation, with poor planning and coordination among stakeholders being the most prominent issues. Additionally, the study found that current waste management efforts are primarily focused on material waste, often overlooking the broader environmental implications of construction activities. This highlights the need for a more integrated approach that addresses both production and environmental waste simultaneously.

Also, the study found that waste management practices in Saudi Arabia are mainly approached from a productivity perspective to manage time and cost; however, environmental sustainability consideration is relatively overlooked, or at least seen by many practitioners as a concept of minor concern in comparison to productivity.

The proposed framework provides this integration by enabling waste management at strategic, tactical, and operational levels. Its application in the case study demonstrated its effectiveness in identifying non-value-adding (NVA) activities, analysing their root causes, and prioritising them based on their potential impact on both production and environmental waste generation. This proactive approach fosters a culture of continuous improvement in construction organisations, allowing them to optimise resources and improve project outcomes.

The expert evaluation process affirmed the framework's clarity, effectiveness, and applicability in real-world construction projects. By incorporating lean and sustainability principles, the framework presents a practical solution to reduce production and environmental waste simultaneously. It equips construction organisations with tools to improve their operational efficiency while implementing environmentally friendly strategies. Through its use, industry professionals can identify inefficiencies and improve overall performance in terms of cost, time, and environmental sustainability.

However, the successful implementation of the framework may face challenges, such as resistance to change and a lack of knowledge among construction practitioners regarding lean and sustainability concepts. To overcome these obstacles, well-designed guidelines and clear demonstrations of the framework's benefits were presented. Previous studies have emphasised the importance of practical applicability and overcoming the industry's reactive nature to effectively address construction waste.

This study acknowledges certain limitations. The framework focuses on unnecessary NVA activities, but necessary NVA and VA activities can also generate waste during construction operations. Therefore, embedding sustainability into engineering methods and the design of construction operations is crucial to avoid waste generation. By doing so, it is possible to avoid waste generation during both the construction and operation of the asset. Moreover, the use of a retrospective case study may not fully represent the complexities of real-life implementation. Future research should refine the framework by applying it in live

construction projects in Saudi Arabia to validate its effectiveness in practical settings and expand it to cover the entire lifecycle of construction projects. Additionally, future research should explore how the proposed framework can inform and support the development of comprehensive waste management policies in the Saudi construction sector, particularly as new regulations emerge in line with Vision 2030 sustainability goals.

In conclusion, this research contributes to the body of knowledge in lean construction and sustainability by offering a holistic approach to waste management. By integrating production and environmental waste management, the framework addresses a critical gap in current practices and offers a pathway towards achieving the sustainability goals outlined in Vision 2030. As the construction industry in Saudi Arabia continues to expand, adopting this framework can play a pivotal role in promoting resource efficiency, reducing environmental impact, and fostering a more sustainable future for the built environment.

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CRediT authorship contribution statement

Saleh Alazmi: Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Mohammed Abdelmegid:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis. **Saad Sarhan:** Writing – review & editing, Validation. **Mani Poshdar:** Writing – review & editing, Validation. **Vicente Gonzalez:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization. **Ali Bidhendi:** Writing – review & editing, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix a. : interview questions

1. Waste generation during the construction phase of a project is a big concern nowadays and has different impacts on the projects, based on your experience and perspective, could you please talk about this?
 1. What is your perception/definition of waste?
 2. What would you consider as a waste?
1. As you know, during the construction phase, there are different types of waste generated. Could you please talk about waste types that are generated during the construction process of your current or last projects, and what are their reason/s of occurrence?
 11. What are the major areas of waste during the construction phase?
 12. What are the biggest contributors to waste in terms of project completion, time, quality, and Profit & Loss?
2. During the construction process, there are activities and aspects that affect the construction productivity and/or cause environmental waste or, rather, losses. Could you please think of any of these activities or aspects, and explain how?
3. Following up with the previous question, would you group the activities that you just mentioned in one category or into different categories? If so, on what basis?
4. Researchers argue that the activities that are not adding value to the project have negative impacts on the environment. To what extent do you agree? Please support your answer with examples.

5. Based on the types of waste that you have identified, how could you manage these wastes effectively?
 51. How do you usually monitor waste during the construction process?
 52. How do you usually measure waste? Based on which criteria?
 53. Have you ever undertaken training courses for waste management?
6. There are two types of waste: production and environmental waste. Do you think that the current waste management plan in your company manages both types simultaneously? Explain?
7. Based on your experience, can you think of a method, tool, technique or action that could be used on-site to manage production and environmental waste concurrently?
 - 8.1 If the answer is "YES".
 701. How do you think this new method will benefit and reflect on the project and the company as a whole?
 702. Would you like to adapt such a method to your current or next project instead of your current methods?
 - 8.2 If the answer is "NO".
 - 8.2.1 Why do you think that there is no need to modify the current method used on-site?

Data availability

The data that has been used is confidential.

References

- Abdelmegid, M.A., O'Sullivan, M., González, V.A., Walker, C.G., Poshdar, M., 2022. A case study on the use of a conceptual modeling framework for construction simulation. *Simulation* 98 (5), 433–460.
- Aerts, G., Dooms, M., Haezendonck, E., 2017. Knowledge transfers and project-based learning in large scale infrastructure development projects: an exploratory and comparative ex-post analysis. *Int. J. Proj. Manag.* 35 (3), 224–240.
- Ajayi, S.O., Oyedele, L.O., Bilal, M., Akinade, O.O., Alaka, H.A., Owolabi, H.A., Kadiri, K. O., 2015. Waste effectiveness of the construction industry: understanding the impediments and requisites for improvements. *Resour. Conserv. Recycl.* 102, 101–112.
- Ajayi, S.O., Oyedele, L.O., Bilal, M., Akinade, O.O., Alaka, H.A., Owolabi, H.A., 2017. Critical management practices influencing on-site waste minimization in construction projects. *Waste Manag.* 59, 330–339.
- Aken, J.E., 2004. Management research based on the paradigm of the design sciences: the quest for field-tested and grounded technological rules. *J. Manag. Stud.* 41 (2), 219–246.
- Ali, H.A.E.M., Al-Sulaihi, I.A., Al-Gahtani, K.S., 2013. Indicators for measuring performance of building construction companies in Kingdom of Saudi Arabia. *J. King Saud. Univ. Eng. Sci.* 25 (2), 125–134.
- Aljarallah, N., M. Alsugair, A., Almohsen, A., Al-Gahtani, K., 2024. Identifying the significant causes of waste of housing infrastructure projects in the Kingdom of Saudi Arabia. *Alex. Eng. J.* 86, 217–229.
- AlMunifi, A.A., Almutairi, S., 2021. Lessons learned framework for efficient delivery of construction projects in Saudi Arabia. *Constr. Econ. Build.* 21 (4).
- Amran, M., 2024. Innovative technology for converting automobile tire waste bead wires into recycled steel fibers for sustainable concrete composites: insights for the Al-Kharj Governorate construction industry. *Int. J. Build. Pathol. Adapt.*
- Amran, Y.H.A., Amran, Y.H.M., Alyousef, R., Alabduljabbar, H., 2020. Renewable and sustainable energy production in Saudi Arabia according to Saudi Vision 2030; current status and future prospects. *J. Clean. Prod.* 247, 119602.
- Arroyo, P., Gonzalez, V., 2016. Rethinking Waste Definition to Account for Environmental and Social Impacts, 24th Annual Conference of the International Group for Lean Construction. Boston, Massachusetts, USA.
- Banawi, A., Bilec, M.M., 2014. A framework to improve construction processes: integrating Lean, Green and Six Sigma. *Int. J. Constr. Manag.* 14 (1), 45–55.
- Bauer, M.W., 2000. Classical content analysis: a review. *Qual. Res. Text. Image Sound* 131–151.
- Belayutham, S., González, V.A., Yiu, T.W., 2016. Clean-lean administrative processes: a case study on sediment pollution during construction. *J. Clean. Prod.* 126, 134–147.
- Blaisi, N.I., 2019. Construction and demolition waste management in Saudi Arabia: current practice and roadmap for sustainable management. *J. Clean. Prod.* 221, 167–175.
- Conterras, M., Teixeira, S.R., Lucas, M.C., Lima, L.C.N., Cardoso, D.S.L., da Silva, G.A.C., Gregório, G.C., de Souza, A.E., dos Santos, A., 2016. Recycling of construction and demolition waste for producing new construction material (Brazil case-study). *Constr. Build. Mater.* 123, 594–600.
- Elo, S., Kyngäs, H., 2008. The qualitative content analysis process. *J. Adv. Nurs.* 62 (1), 107–115.
- European Commission, 2018. EU Construction and Demolition Waste Protocol and Guidelines. Available at: (https://ec.europa.eu/growth/content/eu-construction-and-demolition-waste-protocol-0_en) (Accessed: 01/12/2024).
- European Commission, 2023. Waste Framework Directive. Available at: (https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en) (Accessed: 01/12/2024).
- Farias, L.M.S., Santos, L.C., Gohr, C.F., Oliveira, L.Cd, Amorim, M.Hd.S., 2019. Criteria and practices for lean and green performance assessment: systematic review and conceptual framework. *J. Clean. Prod.* 218, 746–762.
- Fireman, M.C.T., Formoso, C.T., 2013. Integrating Production and Quality Control: Monitoring Making-Do and Unfinished Work, in: Formoso, C.T., Tzortzopoulos, P. (Eds.), 21th Annual Conference of the International Group for Lean Construction. Fortaleza, Brazil, pp. 515–525.
- Formoso, C.T., Bølviken, T., Viana, D.D., 2020. *Understanding Waste in Construction*. Routledge.
- Francis, A., Thomas, A., 2020. Exploring the relationship between lean construction and environmental sustainability: a review of existing literature to decipher broader dimensions. *J. Clean. Prod.* 252, 119913.
- Gibbin, R.V., Sigahi, T.F.A.C., Pinto, Jd.S., Rampasso, I.S., Anholon, R., 2023. Thematic evolution and trends linking sustainability and project management: scientific mapping using SciMAT. *J. Clean. Prod.* 414, 137753.
- Golzarpour, H., González, V., Shahbazzpour, M., O'Sullivan, M., 2017. An input-output simulation model for assessing production and environmental waste in construction. *J. Clean. Prod.* 143, 1094–1104.
- Haider, H., AlMarshod, S.Y., AlSaleem, S.S., Ali, A.A.M., Alinizzi, M., Alresheedi, M.T., Shafiquzzaman, M., 2022. Life cycle assessment of construction and demolition waste management in Riyadh, Saudi Arabia. *Int. J. Environ. Res Public Health* 19 (12).
- Hancock, B., Ockleford, E., Windridge, K., 2001. *An Introduction to Qualitative Research*. Trent focus group London.
- Hao, J., Yuan, H., Liu, J., Chin, C.S., Lu, W., 2019. A model for assessing the economic performance of construction waste reduction. *J. Clean. Prod.* 232, 427–440.
- Huang, B., Wang, X., Kua, H., Geng, Y., Bleischwitz, R., Ren, J., 2018. Construction and demolition waste management in China through the 3R principle. *Resour. Conserv. Recycl.* 129, 36–44.
- International Organization for Standardization, 2015. ISO 14001:2015 Environmental Management Systems. International Organization for Standardization.
- Ishikawa, K., 1990. *Introduction to Quality Control*. Taylor & Francis.
- Islam, R., Nazifa, T.H., Yuniarto, A., Shanawaz Uddin, A.S.M., Salmiati, S., Shahid, S., 2019. An empirical study of construction and demolition waste generation and implication of recycling. *Waste Manag.* 95, 10–21.
- Issa, U.H., Alqurashi, M., 2020. A model for evaluating causes of wastes and lean implementation in construction projects. *J. Civ. Eng. Manag.* 26 (4), 331–342.
- Kabirifar, K., Mojtahedi, M., Wang, C., Tam, V.W.Y., 2020. Construction and demolition waste management contributing factors coupled with reduce, reuse, and recycle strategies for effective waste management: a review. *J. Clean. Prod.* 263, 121265.
- Kasanen, E., Lukka, K., Siitonen, A., 1993. The constructive approach in management accounting research. *J. Manag. Account. Res.* 5.
- Kiomjian, D., Srour, I., Srour, F.J., 2020. Knowledge sharing and productivity improvement: an agent-based modeling approach. *J. Constr. Eng. Manag.* 146 (7).
- Koskela, L., 2004. Making-do — the Eighth Category of Waste, in: Bertelsen, S., Formoso, C.T. (Eds.), 12th Annual Conference of the International Group for Lean Construction. Helsingør, Denmark.
- Koskela, L., 2008. Which Kind of Science Is Construction Management?, in: Tzortzopoulos, P., Kagioglou, M. (Eds.), 16th Annual Conference of the International Group for Lean Construction. Manchester, UK, pp. 51–60.
- Koskela, L., 2020. *Theory of Lean Construction*. Lean construction. Routledge, pp. 2–13.
- Langley, M.A., 2015. Capturing the Value of Project Management through Knowledge Transfer. Project Management Institute, Inc. Pmi.org/Pulse, 1–32.
- Lu, W., Yuan, H., 2010. Exploring critical success factors for waste management in construction projects of China. *Resour., Conserv. Recycl.* 55 (2), 201–208.
- Macomber, H., Howell, G., 2004. Two Great Wastes in Organizations, the Source of Untapped Inventiveness, Talents, and Wisdom: A Typology for Addressing the Concern for the Underutilization of Human Potential.
- Mahamid, I., 2020. Impact of rework on material waste in building construction projects. *Int. J. Constr. Manag.* 22 (8), 1500–1507.
- Menegaki, M., Damigos, D., 2018. A review on current situation and challenges of construction and demolition waste management. *Curr. Opin. Green Sustain. Chem.* 13, 8–15.
- Ministry of Environment, Water and Agriculture (MEWA), 2017. National Environment Strategy: Executive Summary for the Council of Economic and Development Affairs. Available at: (<https://www.mewa.gov.sa/en/Ministry/initiatives/SectorStrategy/Documents/6%20BAH-MEWA-KSA%20NES-CEDA%20Executive%20Summary%20v3%2020180221%20ENG.pdf>) (Accessed: 01/12/2024).
- Ministry of Municipal Rural Affairs and Housing (MOMRAH), 2024. MOMRAH Issues Guide Of "Requirements for the Disposal of Construction, Demolition, and Renovation Waste". Available at: (<https://momrah.gov.sa/en/news/momrah-issues-guide-requirements>) (Accessed: 01/12/2024).
- Moshood, T.D., Rotimi, J.O.B., Shahzad, W., 2024. Enhancing sustainability considerations in construction industry projects. *Environ., Dev. Sustain.*
- National Center for Waste Management (MWAN), 2021. Waste Management Law. Available at: (<https://mwan.gov.sa/web/content/6359000?unique=ed6d3abb-d0795c7383e82b0c93638af77f67f10d&>) (Accessed: 01/12/2024).
- Ohno, T., 1988. *Toyota Production System: Beyond Large-scale Production*. Productivity Press, Cambridge, Mass.

- Osmani, M., 2012. Construction waste minimization in the UK: current pressures for change and approaches. *Procedia Soc. Behav. Sci.* 40, 37–40.
- Ouda, O.K.M., Peterson, H.P., Rehan, M., Sadeq, Y., Alghazo, J.M., Nizami, A.S., 2018. A case study of sustainable construction waste management in Saudi Arabia. *Waste Biomass Valoriz.* 9 (12), 2541–2555.
- Sarhan, S., Pasquire, C., King, A., 2014. Institutional waste within the construction industry - an outline, in: Kalsaas, B.T., Koskela, L., Saurin, T.A. (Eds.), 22nd Annual Conference of the International Group for Lean Construction. Oslo, Norway, pp. 895–906.
- Sarhan, S., Pasquire, C., Elnokaly, A., Pretlove, S., 2019. Lean and sustainable construction: a systematic critical review of 25 years of IGLC research. *Lean Constr. J.*
- Sarhan, S., Pretlove, S., 2021. Lean and sustainable construction: state of the art and future directions. *Constr. Econ. Build.* 21 (3), 1–10.
- Saudi Gazette, 2024. Saudi Arabia Aims to Recycle 95% of Waste, Boosting GDP by SR120 Billion, 14 January. Available at: (<https://saudigazette.com.sa/article/639571/SAUDI-ARABIA/Saudi-Arabia-aims-to-recycle-95-of-waste-boosting-GDP-by-SR120-billion>) (Accessed: 01/12/2024).
- Srnka, K.J., Koeszegi, S.T., 2007. From words to numbers: how to transform qualitative data into meaningful quantitative results. *Schmalenbach Bus. Rev.* 59 (1), 29–57.
- Teixeira, P., Sá, J.C., Silva, F.J.G., Ferreira, L.P., Santos, G., Fontoura, P., 2021. Connecting lean and green with sustainability towards a conceptual model. *J. Clean. Prod.* 322, 129047.
- Udawatta, N., Zuo, J., Chiveralls, K., Zillante, G., 2015. Improving waste management in construction projects: an Australian study. *Resour., Conserv. Recycl.* 101, 73–83.
- US Environmental Protection Agency, 2020a. Advancing Sustainable Materials Management: Facts and Figures Report. US Environmental Protection Agency (EPA) Washington, DC, USA.
- US Environmental Protection Agency, 2020b. Construction and Demolition Debris Management in the United States. Available at: (https://www.epa.gov/sites/default/files/2020-03/documents/final_cd-eol-management_2015_508.pdf) (Accessed: 01/12/2024).
- Weinheimer, N., Schmalz, S., Müller, D., 2017. Green Building and Lean Management: Synergies and Conflicts, 25th Annual Conference of the International Group for Lean Construction. Heraklion, Greece, pp. 911–918.
- Wu, P., Low, S.P., Jin, X., 2013. Identification of non-value adding (NVA) activities in precast concrete installation sites to achieve low-carbon installation. *Resour. Conserv. Recycl.* 81, 60–70.
- Wu, H., Zuo, J., Zillante, G., Wang, J., Yuan, H., 2019. Status quo and future directions of construction and demolition waste research: a critical review. *J. Clean. Prod.* 240, 118163.
- Xing, Z., Zhang, Z., Wang, Y., Xu, P., Guo, Q., Zeng, C., Shi, R., 2024. SDC-DeepLabv3+ : lightweight and precise localization algorithm for safflower-harvesting robots. *Plant Phenomics* 6, 0194.
- Zheng, L., Wu, H., Zhang, H., Duan, H., Wang, J., Jiang, W., Dong, B., Liu, G., Zuo, J., Song, Q., 2017. Characterizing the generation and flows of construction and demolition waste in China. *Constr. Build. Mater.* 136, 405–413.
- Züst, S., Züst, R., Züst, V., West, S., Stoll, O., Minonne, C., 2021. A graph based Monte Carlo simulation supporting a digital twin for the curatorial management of excavation and demolition material flows. *J. Clean. Prod.* 310, 127453.