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AN INTEGRATED FRAMEWORK FOR PRODUCTION AND ENVIRONMENTAL WASTE MANAGEMENT IN CONSTRUCTION

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ABSTRACT

Lean construction has successfully developed and utilised several tools to minimise production waste generation in construction projects. In addition, sustainability research has contributed to improving the environmental performance of the construction industry by managing the impact of construction waste on the environment. Research on construction sustainability has been utilising some of the capabilities of lean construction tools to address environmental-related issues that are difficult to tackle using conventional approaches. Even though research in the Lean-Sustainability area has progressed over the last two decades, knowledge of Lean-Sustainability applications is still limited amongst industrial practitioners. A potential reason is the lack of an integrated approach combining lean principles and sustainability for construction applications. To address this limitation, this paper proposes a management framework that deals with both production and environmental wastes concurrently. The framework is developed by combining a lean process improvement method with an environmental management system approach. The framework is validated through interviews with experts in lean construction and sustainability to establish its theoretical contribution and practical applicability. Through this integrated waste management framework, this study contributes to the efforts of managing production and environmental wastes to deliver more efficient and environmentally friendly projects in the construction industry.

KEYWORDS

Sustainability, Lean Construction, Value Stream, Production waste, Environmental waste

INTRODUCTION

There have been growing concerns about the adverse environmental impact of the construction industry over recent decades (Li et al., 2022). Extensive research efforts have been dedicated to investigating the environmental issues associated with construction activities, including greenhouse gas emissions and the depletion of natural resources (Dräger

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& Letmathe, 2022; Farias et al., 2019; Kosasih et al., 2023). Many studies have been conducted to propose concepts and practices to enhance the environmental performance of construction projects, but there remains to be a gap in translating existing research recommendations into practical implementation. A potential explanation for this shortage in knowledge lies in the current industry focus on managing waste based on its consequences rather than addressing its root causes (Farias et al., 2019; Kosasih et al., 2023; Poshdar et al., 2022). Furthermore, prevailing sustainability practices tend to concentrate primarily on the design phase of construction projects, often neglecting process wastes and the interrelationship between design and construction (Rosenbaum et al., 2014).

To bridge these gaps, lean construction research has sought to address these limitations by emphasising the interrelationship between production and environmental waste in construction. This shift in focus can potentially overcome the constraints of managing production and environmental wastes separately (Arroyo & Gonzalez, 2016). Therefore, integrating lean and sustainability principles presents an opportunity to tackle different types of waste at different production levels (Khodeir & Othman, 2018).

In response to the existing gaps in construction waste management, this paper introduces a novel management framework that integrates lean and sustainability concepts. Adopting a constructive research methodology, this study identifies a practical problem within the existing body of knowledge and introduces a new construct to address it. By combining elements from lean and sustainability approaches and considering all production planning levels (strategic, tactical, and operational), the proposed framework ensures the visibility of all waste types, effectively addressing the challenge of invisible waste, as highlighted by Koskela (2004).

BACKGROUND

The environmental repercussions of construction activities rank among the key concerns within the industry (Araujo et al., 2020). The magnitude of construction-related waste generation remains alarmingly high in both developed and developing countries. For instance, in 2018, the United States produced over 600 million tons of construction-related waste, surpassing the municipal solid waste generated in the country (US Environmental Protection Agency, 2020). Similarly, the Gulf Cooperation Countries (GCC) produces a staggering 120 million tons of construction and demolition waste annually (Ouda et al., 2018). This surge in construction waste has substantial consequences, impacting production costs (Formoso et al., 2020) and depleting natural resources (Pradhan et al., 2017). Consequently, global awareness regarding the magnitude of construction waste and its environmental impact has grown, leading to an increased focus on waste minimisation in the construction domain (Ajayi et al., 2017).

Waste has been a central theme in the field of lean construction. From a lean perspective, production waste arises from non-value-adding (NVA) activities, which represent processes that consume resources without contributing value to the final product or end-user. Examples of NVA activities include over-production, waiting, and unnecessary motion (Ohno, 1988). Ohno initially defined seven categories of NVA within the manufacturing industry, a classification subsequently adopted by lean construction, which expanded to include additional categories (see Table 1).

Research has established that NVA activities can exert adverse effects on the environment (Banawi & 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). Despite the growing interest in advancing sustainability in construction through waste minimisation approaches, current waste management practices often lack practical applicability in the industry (Ajayi et al., 2017; Sarhan and Pretlove, 2021). This limited adoption of current practices can be attributed to their reactive nature, as they tend to address wasteful processes and their root causes after they have occurred. Additionally, these practices frequently treat production and environmental waste as separate entities (Kabirifar et al., 2020), indicating a lack of recognition of their interconnectedness within construction projects. Interested readers on the interrelated connections and trade-offs between Lean and Sustainability are referred to the systematic review by Sarhan et al., (2019).

Table 1: Construction Waste Categories

Waste Categories	Definition	Reference
Motion	Equipment or people moving more than necessary	(Ohno, 1988)
Waiting	Time lost in between steps in production	
Transportation	Moving products that do not need to be moved	
Inventory	Work and finished work not being processed	
Over-Processing	Poor use of tools and in the production of the goods that the customers do not need	
Overproduction	Production moves ahead of demand	
Defects	Extra effort involved in fixing problems	
Making- do	It refers to a situation where a task is started without all its standard inputs, or the execution of a task is continued although the availability of at least one standard input has ceased.	(Koskela, 2004)
Work in progress	Working on relatively small tasks left from the previous plan	(Hopp & Spearman, 2011)
Unfinished work	It includes rework and small finishing tasks that are left over after a crew leaves a workstation.	(Fireman & Formoso, 2013)
Waste of human potential	For example, not speaking and not listening. It also includes late or lack of involvement of contractors and specialist subcontractors in design and planning stages	(Macomber and Howell, 2004)
Institutional waste	Systems, norms, and routines, which are taken for granted and impede efficiency and improvement efforts in construction	Sarhan et al (2014)

RESEARCH METHODOLOGY

This research is conducted over five phases following the constructive research approach, which is centred around developing innovative solutions to practical problems that have research potential (Kasanen et al., 1993). The first phase included an examination of the body of knowledge to identify the gap related to the lack of a practical framework for the integrated management of production and environmental waste in construction. Subsequently, the second phase focused on obtaining a comprehensive understanding of the identified problem through a thorough literature review on the topics of lean construction and environmental waste management. In the third phase, a solution is proposed by integrating lean process improvement techniques with an environmental management system to develop a conceptual framework. The framework was validated in the fourth phase through expert interviews (refer to Table 4 for further details). Also, a case example is presented to demonstrate the framework's applicability in actual construction piling operations. Finally, insights for the successful implementation of the framework are presented based on the lessons learned from the validation exercise and the case-example demonstration. The final stage aims to establish the theoretical and practical contribution of the proposed solution as per the requirements of the constructive research approach.

PRODUCTION AND ENVIRONMENTAL WASTES IN CONSTRUCTION: A MANAGEMENT FRAMEWORK

DEVELOPMENT OF THE FRAMEWORK

Traditional practices for waste management in construction usually tackle production and environmental waste separately. This paper suggests a way to combine the two by integrating principles from lean and sustainability research. The proposed framework combines a lean-six Sigma improvement model and an environmental management system by integrating the DMAIC (Define, Measure, Analyse, Improve, and Control) with the Aspect and Impact Analysis (AIA).

DMAIC is a data-driven model that guides the process of gathering information and optimising production processes (Banawi & Bilec, 2014). In this context, DMAIC is employed in the framework to define and measure wastes, analyse and manage their root causes, and enhance overall process performance. It also helps control the proposed actions and establish procedures for future improvements. On the other hand, AIA is an environmental management system that focuses on improving environmental performance (International Organization for Standardization, 2015). In the scope of this research, AIA is utilised to identify NVA activities contributing to environmental waste, find their root causes, prioritise them based on impact level, and suggest suitable actions to address these causes and impacts. The integrated framework is structured into six stages as illustrated in Figure 1.

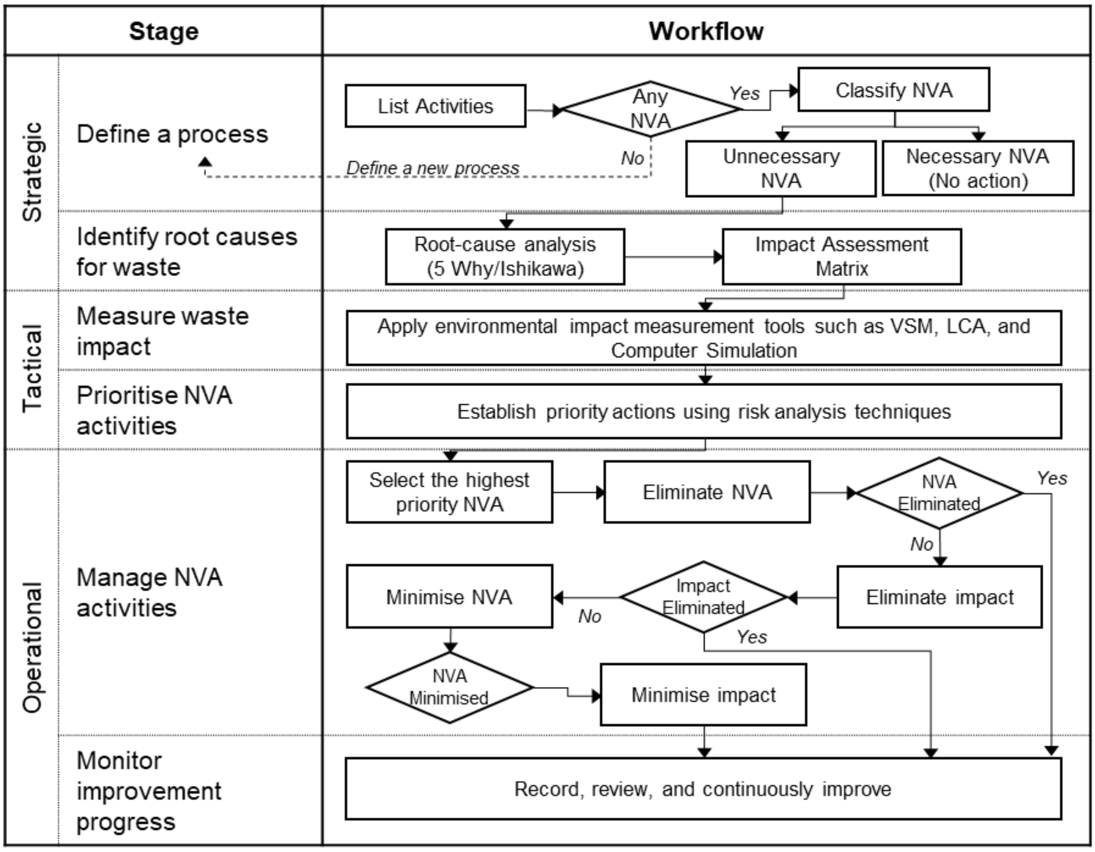

Figure 1: The Proposed Framework Stages and Workflow

The framework flow is designed in a straightforward approach to provide clear guidance to industry practitioners on production and environmental waste management in construction projects. The main aim of the framework is to capture NVA activities and recognise their impact across three production levels: strategic, tactical, and operational. However, it is essential to realise that some NVA activities are unavoidable in construction and that aiming to eliminate them completely is unrealistic. Therefore, the aim should be focused on minimising their existence or mitigating their impact as much as possible. The framework should be implemented iteratively to ensure that all NVA activities are identified and dealt with.

CASE EXAMPLE

To illustrate the application of the framework, a case example of the construction of cast-in-place reinforced concrete piles will be utilised. Piles are crucial structural elements in various construction projects. Piling operations are chosen for this example due to their complexity as they involve interrelated activities that require different materials and machinery. In addition, external factors, such as groundwater level, space constraints, and soil profile, can all contribute to the complexity of operations. This aligns with the findings of Banawi and Bilec (2014), who demonstrated the use of a Lean, Green, and Six Sigma (LG6) model on pile cap operations. Their study found that lean implementation in the construction of piling caps can reduce costs by 1% and environmental waste by 9%.

The case example is a retrospective study based on the construction project of an educational building in Auckland, New Zealand. The project faced several challenges as it was in a busy area with proximity to a hospital and residential buildings. Therefore, constraints on machinery types and numbers necessitated careful planning to ensure undisrupted production. The piling process involved seven main activities: site preparation, land survey, pile drilling, dewatering, steel cage insertion, concrete pour, and excavated soil removal. Additionally, two activities were required for the constant supply of steel cages and fresh concrete. The following subsections provide a detailed overview of each stage of the framework, followed by a demonstration of how these stages can be implemented in the case example.

STAGE 1: DEFINE A PROCESS

This stage of the framework aims to identify wastes generated during the construction phase, where their root causes will be investigated in the following stages. It begins by selecting a production process or sub-process in a construction operation to explore the reasons behind waste generation within the process. In this step, it is essential to assess the current state of the chosen process by identifying all activities and categorising them into Value-Adding (VA) or NVA. NVA activities should then be categorised into necessary and unnecessary. Necessary NVAs are unavoidable and integral to the production process, while unnecessary ones consume resources without directly contributing value to the final product. The primary focus of the framework is on addressing unnecessary NVA (i.e. waste). It is essential to indicate that activities like necessary NVA and VA can have environmental impacts. However, addressing them requires separate methods and falls outside the scope of the proposed framework.

Table 2 illustrates the analysis of the seven activities for the case example of piling operations. As can be seen, three activities are classified as VA, three as necessary NVA, and one as unnecessary NVA. It is important to highlight that this analysis depends on the project requirements, complexity, and circumstances. Thus, these activities can be classified differently in other contexts.

Table 2: 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.

STAGE 2: IDENTIFY ROOT CAUSES FOR WASTE

To address waste at its origin, it is essential to identify its root causes. Accordingly, this stage aims to identify the root causes of NVA activities and their impacts. It is proposed to utilise the 5-Whys technique developed by Sakichi Toyoda (Ohno, 1988) and Ishikawa diagram, also known as the fishbone diagram (Ishikawa, 1982). The 5-Whys technique is helpful in uncovering the origins of waste in the process. On the other hand, the Ishikawa diagram is effective in illustrating the cause-and-effect relationships among different causes of waste and their impacts. The outcome of this stage can be presented in a matrix that shows the connections between identified root causes and their potential impacts. The role of this stage is to ensure that the root causes and impacts of each identified NVA activity are transparent to facilitate actionable waste management strategies in the following stages.

For the case example, the Ishikawa diagram method was utilised to identify the following root causes for the soil removal activity:

- Excessive drilling leading to excavated soil surplus
- Incorrect geotechnical information leading to unnecessary excavation
- Poor maintenance of machinery leading to contaminated soil
- Lack of expertise in investigating soil types for recycling purposes

Table 3 illustrates the relationship and impact that the identified NVA for the case example could have on production and environmental waste generation during the construction process.

Soil removal may generate production and environmental waste due to the use of transportation within the construction site and outside to the dumping site. The removal of soil requires excessive movement of excavators to move the soil to a stocking area. In addition, it involves haul trucks to transport the soil from the construction site to the dumping station. These machines consume energy, generate pollutants, and create dust. Moreover, the use of heavy machinery increases the risk of hazardous material leakage and soil pollution.

Table 3: Impacts of NVA

NVA	Production waste											Environmental waste								
												Excessive Consumption				Excessive Emission				
	Transportation	Inventory	Motion	Waiting	Over-processing	Overproduction	Defect	Making – do	Rework	Work in progress	Unfinished work	Material	Energy	Water	Land	Air pollution	Solid Waste	Hazardous Materials	Water	Soil
Soil removal	✓	✓	✓	✓	✓							✓	✓		✓	✓	✓	✓		✓

STAGE 3: MEASURE WASTE IMPACT

This stage is designed to explore the environmental impact of NVA activities. Traditional lean practices primarily focus on enhancing productivity, time, and cost performance with less focus on the environmental impact (Teixeira et al., 2021). However, studies suggest that lean principles can be extended to include environmental measures (Arroyo and Gonzalez, 2016; Kosasih et al., 2023). To strengthen the environmental aspect of lean, the framework recommends employing 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 measure the environmental impact of targeted NVA. The selection of analysis techniques can vary depending on the types of waste and the available information and are within the discretion of the framework user. As the case example was a retrospective study, waste impact of soil removal activities was not measured. However, we envisage that the use of a simulation model can be very effective in facilitating impact measurement.

STAGE 4: PRIORITISE NVA ACTIVITIES

This stage operates at the tactical level of the framework. The identified NVA activities should be assessed using a risk assessment rating system (e.g., probability and impact matrix). Then, the risk matrix can be utilised to determine which NVA has a low, medium, or high risk in terms of both production and environmental waste. This prioritisation process helps to focus attention and resources on addressing the riskiest NVA activities to aid the following stages of defining a strategic and efficient approach to waste management.

For the case example, as illustrated in Table 2, three NVA activities were identified. Soil removal is the only unnecessary NVA, so it is the highest priority for management intervention. As illustrated in the next stage, other NVA activities should also be dealt with. Although site preparation and dewatering are assessed as necessary for the process, they should be further analysed to reduce the need for such NVA or minimise their impact on production and environmental wastes.

Stage 5: Manage NVA activities

This stage provides a series of tools and procedures to address NVA activities and their environmental impact. It begins by selecting the top prioritised NVA activities and proposing actions for their management. The ideal goal is to eliminate NVA activities to prevent the generation of environmental waste. If elimination is not feasible, alternative measures are taken to reduce the impact on the production and environmental waste of the process. To manage NVA activities and their impacts, the framework suggests using the following steps in the designated order to ensure a strategic and efficient approach to managing NVA and minimising their impact.

- Eliminating NVA activities in the currently selected process to address the problem at its root cause.
- Eliminating impact by focusing on immediate measures to prevent waste generation in the process.
- Minimising NVA activities by redesigning production operations to avoid unnecessary NVA activities.
- Minimising impact by utilising approaches to control waste generation in the process.

In the case example, it was found that soil removal can be partially eliminated as some of the excavated soil was unsuitable for other construction operations. A mitigation strategy was to re-examine the geotechnical report and update it based on the accurate information from the site, to avoid future errors. Also, the additional soil can be used as a temporary protective layer under heavy machinery and be removed by the foundation contractor as part of their site excavation activities to avoid the production and environmental wastes associated with the removal of the small amount of soil only excavated from piling operations.

Stage 6: Monitor improvement progress

In the last stage, the framework focuses on tracking the performance of the framework. Also, it aims to capture any new wastes that might emerge from the strategies implemented in the previous stage. To ensure continuous improvement, it is essential to maintain a record of current challenges and the decisions or solutions applied. These records can be used as lessons learned to facilitate knowledge retention and transfer to enhance the effectiveness of the proposed framework over time.

FRAMEWORK VALIDATION

Expert validation

The proposed framework was validated through input from academic and industry experts in the field of lean construction and sustainability. Expert validation is an exploratory qualitative method, which is a common practice for validating conceptual models and frameworks (Hancock et al., 2001). In this study, a sample of 10 participants was initially formed based on their extensive academic and/or industry experience in both lean construction and sustainability. Six experts from both academic and industry backgrounds agreed to participate. The demographic details of the participants are outlined in Table 4.

Table 4. Demographic details of participant

Interview Reference	Title of Interviewee	Education	Country	Years of experience in lean and/or sustainability	Experience
VAL01	Researcher/ Academic	Doctoral	USA	Over 15 years	Academic+ Practical
VAL02	Researcher/ Academic	Doctoral	Chile	Over 15 years	Academic + Practical
VAL03	Researcher/ Academic	Doctoral	Turkey	Over 15 years	Academic + Practical
VAL04	Researcher/ Academic	Doctoral	Malaysia	five to ten years	Academic + Practical
VAL05	Project Manager	Master	Saudi Arabia	five to ten years	Practical
VAL06	Construction Manager	Bachelor	New Zealand	Five years	Practical

Semi-structured interviews were conducted via Zoom with a focus on how to ensure the framework's alignment with advanced research outcomes and industrial best practices. The interview covered four key themes, and content analysis was performed to extract insights on these themes from the participants' responses. The following subsections cover the results of the expert validation process. Based on the outcomes of these interviews, the developed framework underwent refinement to incorporate feedback and recommended modifications.

GENERAL OVERVIEW OF THE FRAMEWORK

The initial part of the interview focused on obtaining the overall impressions of participants about the framework. The aim was to ensure the clarity, ease of understanding, and its effectiveness. Prior to the interview, the framework was shared with the participants for review. All six experts confirmed that the framework was well-structured, easy to follow, and has the potential to enhance waste management in construction projects. The following statements from experts affirmed this sentiment:

"It looks well organised. It looks relatively, going to be easy to follow…The flow of the framework is clear, easy to follow." (AVL02)

"I found your framework very useful, and it's a good idea to combine lean and sustainable concepts every time, in my opinion." (AVL03)

"The framework looks well-structured to me. It is good to have a framework that can manage waste and assist us to achieve sustainability at the same time." (AVL05)

The second question in the validation process investigated the framework's efficiency, with responses provided below:

"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." (AVL01)

"The framework consists of strategic, tactical, and operational levels...This will help in LEED accreditation...I notice that in your framework." (AVL02)

"This framework could definitely improve the efficiency of construction, provided the users could properly conduct and understand the impact measurement well." (AVL04)

APPLICABILITY OF THE FRAMEWORK

The next question aimed to explore the practical application of the framework to identify potential issues or limitations that could impede its implementation in real construction projects. Participants expressed confidence in the applicability in actual construction projects. They highlighted the ease of practical implementation and reported no significant impediments. Examples of participants' responses include:

"Yes, in my opinion, you can apply it to a real construction project." (VAL03)

"Absolutely yes...I would apply it straight away as we are suffering from a lack of attention in waste management." (VAL05)

BENEFITS AND DRAWBACKS OF IMPLEMENTING THE FRAMEWORK

To assess the practicality of the framework, the next question examined both the benefits and drawbacks associated with its implementation. The reported drawbacks were generally around the time and costs associated with implementing such a management intervention. Additionally, Expert VAL01 noted that *"Measuring NVA can be hard but depends on NVA types."* On the positive side, the participants found potential benefits for the framework in construction projects. These include a reduction in both production and environmental waste. Also, the framework can enhance productivity and improve time and cost performance. Moreover, the experts indicated that the framework can foster increased awareness about environmental waste and improve understanding of the relationship between lean and sustainability concepts.

CHALLENGES OF IMPLEMENTATION

While there was a consensus about the applicability of the framework, the experts raised awareness of potential challenges during implementation. Resistance to change was reported as a critical barrier. Another identified barrier was the lack of knowledge about lean and sustainability concepts among construction practitioners. Differences in regulations across countries also posed a challenge. Furthermore, the scope of implementation was considered, with a suggestion to apply the framework initially in smaller pilot projects before addressing entire projects. The experts highlighted the need for well-designed guidelines and clear demonstrations of the framework's benefits to overcome these challenges.

CONCLUSION

This study underscores the critical interplay between production and environmental waste in construction projects, emphasising the urgent need for a comprehensive waste management approach. The developed framework uniquely integrates lean and sustainability principles by addressing waste at strategic, tactical, and operational levels. Unlike previous studies that primarily focused on specific site operations, this framework systematically tracks waste's root causes and potential impacts across various production stages.

The application of lean concepts in construction offers a promising avenue for the simultaneous reduction of production and environmental waste. The framework equips construction organisations with the means to enhance operational efficiency while adopting environmentally friendly strategies. Practitioners can leverage this tool to identify and rectify inefficiencies in construction processes to enhance the overall performance of the industry in terms of cost, time, and environmental sustainability.

This paper has the following limitations. First, the proposed framework is limited to addressing unnecessary NVA. However, it is important to recognise that necessary NVA as well as VA can be sources for waste in construction operations. Addressing such activities requires redefining engineering methods to embed sustainability into the design of construction operations (and potentially the asset itself) to avoid any waste generation during the construction and operation of the asset. Another limitation is the use of a simple case example to illustrate the application of the framework, which might not represent the overall picture of real-life implementation. To address these limitations, further refinement of the framework will be conducted in future research. These refinements include the development of a holistic framework covering all lifecycle phases of construction projects and investigating the incorporation of cause-effect relationships between different waste types. The evaluation of the applicability of the framework and its impact in a real construction project is also recommended to validate its effectiveness in practical settings. Through these initiatives, ongoing advancements can be made to revolutionise waste management practices in the construction industry.

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