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ASSESSING ENVIRONMENTAL IMPACTS: A CASE STUDY OF CIRCULAR ECONOMY ON CONSTRUCTION MATERIALS

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ABSTRACT

The construction sector is a major contributor to environmental degradation, accounting for a significant portion of global energy-related carbon dioxide emissions. The traditional linear construction practices follow a “take-make-dispose” model, which entail the extraction of raw materials, manufacturing of construction products, their use in building projects, and ultimately the disposal of waste generated throughout construction projects. Both Lean and Circular Economy (CE) are philosophies that seek to minimize waste. While Lean promotes value through the reduction of production waste during design and construction, CE proposes the reduction of material waste by promoting closed-loop material flows throughout the construction lifecycle. Applying Lean and CE principles to construction waste management shows promise in reducing negative environmental impacts.

Despite increasing interest, a comprehensive assessment of CE’s impact in this context has not been thoroughly presented yet. This study aims to close this gap by analyzing the environmental performance within a case adopting CE principles using Life Cycle Assessment information. Results indicate significant reductions in Global Warming and Ecotoxicity using CE. Meanwhile, Lean provides another approach to waste reduction by avoiding the generation of environmental waste through production control. This research underscores CE’s efficacy in mitigating negative environmental impacts while identifying areas for further optimization.

KEYWORDS

Lean, Circular Economy, Life Cycle Assessment, Environmental Impact, Waste.

INTRODUCTION

The construction industry serves as both a vital component of global economic growth and a significant contributor to environmental degradation. According to the World Green Building Council (WGBC), construction activities contribute substantially to the waste stream and accounts for approximately 39% of global energy-related carbon dioxide (CO2) emissions during building construction and operation (WGBC, 2019). Traditional linear construction practices follow a "take-make-dispose" model, involving the extraction of raw materials, manufacturing of construction products, their utilization in building projects, and ultimately, the disposal of resulting waste (Ellen MacArthur Foundation, 2013). Due to the substantial waste generated, construction stands out prominently, making it a prime target for innovation within the framework of Circular Economy (CE) (Benachio et al., 2020). CE is diverse in its

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existing definitions, and includes all activities carried out in a society.. A holistic approach with the construction of circular loops of material, energy, and waste flows embracing all society activities is the main feature of a CE, setting it apart from other attempts to minimize energy and material consumption (Masi et al., 2018).

While CE literature is relatively novel, it has deep roots in green production literature (Vargas & Medrano, 2020). The development of a green production philosophy revealed the benefits of lean manufacturing in reducing waste and its negative environmental effects (Huovila & Koskela, 1998). Green manufacturing has gained traction with Lean approaches of value promotion as a deeper treatment of waste beyond the boundaries of construction and design phases in the form of product life cycles (Salibi et al., 2022) Concurrently, CE has garnered comparable attention for its efficacy in curbing waste across the economic supply chain (Adams et al., 2017).

Lean's focus on process waste reduction complements CE's closed-loop approach to waste reduction and recovery from various materials (Johns et al., 2023). Numerous studies have highlighted the potential advantages of CE in the building industry by drawing parallels between its waste reduction focus and the Lean philosophy (Chen et al., 2021; Schmitt et al., 2021; Johns et al., 2023). For instance, Chen et al. (2021) proposed that Lean approaches can complement CE efforts during the construction phase by minimizing waste generated in the execution of construction processes. Similarly, Johns et al. (2023) identified beneficial overlaps between the tactics used in the design and production (i.e., construction) stages.

A study by El Machi, A., & Hakkou, R. (2024) demonstrated that adopting CE practices in construction can lead to significant reductions in resource consumption and waste generation. However, despite the growing interest in exploring and applying CE principles within the construction industry, there remains a pressing need for a comprehensive evaluation of the tangible environmental impact reductions achieved through CE implementation for the management of construction waste. This study aims to start closing this gap by presenting the results of a thorough analysis of the environmental performance of a case study in construction adopting CE principles. To achieve this, a collaborative research project was carried out with a company leading the business of CE in Peru to assess the environmental impact changes when applying CE.

LITERATURE REVIEW

WASTE IN CONSTRUCTION PROJECTS

Waste, from the Lean perspective, can be understood as any "activity that takes time, resources or space but does not add value" (Koskela, 1992). Ohno (1978) identified seven types of production waste (or *muda*): overproduction, time on hand (waiting), transportation, processing, stock on hand (inventory), movement, and making defective products. With the application of Lean in the construction industry, additional proposals for an eighth type of waste have been introduced, such as Making-Do (Koskela, 2004). Womack & Jones (1996) further categorized waste into necessary waste, which supports value-adding activities but can be minimized, and unnecessary waste, which can be entirely eliminated.

Environmental waste is closely linked to production waste, encompassing the environmental impacts stemming from production waste activities such as increased energy usage for transportation, waste from deteriorating or damaged inventory, energy wastage during production downtime, disposal of obsolete products, unnecessary processing leading to increased energy consumption and emissions, and disposal of defective components (U.S. EPA, 2007). However, integrating environmental waste into traditional lean management practices presents challenges due to the primary focus on productivity improvement rather than environmental impact reduction (Belayutham & Gonzalez, 2013). In that sense, environmental waste is regarded as a distinct category, moving away from the activity-centered concept of production waste but keeping its core concept of non-value addition, and encompassing environmental-related waste types such as emissions, solid and liquid waste, and energy consumption, among others (Arroyo & Gonzales, 2016).

CIRCULAR ECONOMY

Circular Economy (CE) aims to reduce waste throughout a product's lifecycle by increasing value and decreasing waste (Geisendorf & Pietrulla, 2018). To do this, a pull system must be established, and linear waste that lowers system value must be closed off. CE principles such as the 3Rs (reduce, reuse, recycle), 6Rs, and 12Rs delineate the objectives of CE, minimizing resource consumption, repurposing goods, and parts, and ultimately recycling waste back into the system to optimize resource value (MacArthur, 2013). Refuse, reduce, repair, reuse, repurpose, regenerate, rethink, remanufacture, recycle, recover, rot, and re-evaluate are the extra details found in the 6Rs and 12Rs, which expand on the 3Rs (MacArthur, 2013).

The adoption of CE within the construction industry is still relatively young (Adams et al., 2017). However, given the significant waste generated in construction, this industry is a prime candidate for CE innovation. CE strives toward waste-reducing or waste-eliminating product designs (Caceido, 2017). According to Balboa and Domínguez (2014), CE is a framework for eco-design that is inspired by living things. It aims to shift from a linear economy (produce, use, and discard) that is becoming harder to implement due to resource depletion to a circular and regenerative model. The concept by Balboa and Dominguez (2014) is intriguing because they highlight it as a potential solution to the resource shortage issue.

CIRCULAR-LEAN SYNERGIES

Although the Lean and CE philosophies are well developed in their respective fields, the synergies among the two philosophies are not widely studied in the construction industry (Benachio et al, 2021). Common strategies between the two philosophies, particularly in waste reduction principles, have been identified, including a focus on consumer-driven value creation, waste reduction, process simplification, long-term orientation, and continuous improvement (Johns et al, 2023). However, their approach for value promotion and waste reduction is slightly different.

Both Lean and CE aim to reduce resource consumption. Johns et al (2023) suggests that the overall similarities of the strategies are vast enough to be used complimentary to each other. Moreover, Schmitt et al (2021) studied the potential of the interdependencies between Lean and CE. Lean is focused mainly on product and process level, and CE is more focused to the system level, showing that these three levels are interdependent, and there is a great potential for the use of Lean and CE together (Schmitt et al, 2021). According to Chen et al. (2021), integrating Lean principles with CE can extend efforts, particularly during the construction phase, by reducing waste generated from activities and processes.

Schmitt et al (2021) stated that there is yet a current need of a research path to understand the complementarities and conflicts between "lean" and "circularity". Lean is a concept that has been widely accepted within the construction industry practitioners improving its productivity and sustainability profiles (Babalola et al, 2019). Meanwhile, CE adoption in construction industry still faces cultural barriers that are entrenched to their historical linear economy nature (Hart et al, 2019). Some of the cultural barriers for linear production to prevail over CE are the lack of collaboration between business, business functions, and the lack of engagement throughout the supply chain (Hart et al, 2019). Although this is the common trend, much research has evolved over the advantages of working with both Lean and CE (Johns et al, 2023) Many authors agreed that the combination of lean and circularity could lead to significant improvements (Johns et al., 2023; Benachio et al, 2020; Schmitt, 2021).

LIFE CYCLE ASSESSMENT

The use of Life Cycle Assessment (LCA) as a systematic methodology for evaluating the environmental effects of the built environment is growing in acceptance. Although the building industry depends on LCA to address social and environmental issues associated with construction, some barriers prevent LCA from being broadly and confidently embraced in the industry (Ingrao et al., 2018). For instance, completing an LCA research based on primary data is challenging due to several factors, including the laborious inventory procedure that needs an abundance of data as input for the analysis (Hetherington et al., 2014). Another major barrier is the complexity of LCA results that makes it difficult for stakeholders in the construction industry to apply them to improve their environmental performance. (World Business Council for Sustainable Development, 2016).

ISO 14044 presented four steps that must be followed to evaluate the environmental loads of processes and products over the course of their life cycle as presented in Table 1.

Table 1: Life Cycle Assessment (ISO 14044)

Process	Description
Goal and Scope Definition	Define the purpose, objectives, functional unit, and system boundaries
Life Cycle Inventory (LCI)	Gather, describe, and verify all data pertaining to inputs, processes, emissions, and other aspects of the entire life cycle
Life Cycle Impact Assessment (LCIA)	Quantify the environmental consequences and resources used. Three mandatory components make up this step: • Assigning LCI results to the impact categories that have been chosen based on goal and scope parameters. • Calculating category indicators (characterization) • Selecting impact categories based on those parameters. ISO 14044 describes Normalization and Weighting as two additional possible steps in the LCIA process.
Interpretation	Analyse the findings

Although many construction companies are adopting the Lean principles in their projects (Babalola et al,2019), some studies have shown that there is still cultural resistance within the implementation of CE principles (Hart et al, 2019). Many theoretical studies have been framed to show the mutual advantage of Lean and CE when implemented together (Johns et al., 2023; Benachio et al, 2020; Schmitt, 2021). Therefore, more quantitative research in the construction industry is needed to support the benefits of working with Lean and CE principles together. The presented research gives a quantitative approach to understanding the environmental impacts that are avoided when implementing a CE approach.

RESEARCH METHODOLOGY

This research adopted a quantitative approach based on a single case study, in collaboration with Company A, a Peruvian company known by its focus on Circular Economy (CE). According to Yin (2009), case studies are particularly suited for investigating "how" or "why" questions within real-life contexts where the boundaries between the context and phenomenon are not clearly defined. This paper explores the connection between CE principles and the environmental impacts of resources (i.e., materials and equipment) from construction projects.

The methodology employed encompasses the logic of design, data collection techniques, and specific approaches to data analysis (Stoecker, 1991). Yin (2009) identifies six crucial sources of evidence, each offering complementary insights and commonly utilized in well-executed case studies. This research used three of the primary sources of evidence that were identified by Yin (2009), including:

- Documentation such as reports of CO2 emissions avoided from 2019 to 2022.
- Archival records such as the clients served from 2019 to 2022 and the worker energy consumption for their time frame.
- Interviews with stakeholders to better understand the data and processes involved.

After the data gathering from Company A, the emissions reported by Vahidi et al (2016) on pipe materials were used for the PVC pipes emission factor using the UCEPA TRACI methodology. The emissions of transportation were obtained from EcoTransIT software showing results for complimentary impact categories. Finally, the energy emission factors were considered from the results of Santoyo-Castelazo et al (2011) who used the ISO 14040 guidelines to inform the emissions generated by hydroelectric power plants.

CASE OVERVIEW

The case study addresses the interaction between company A, company E1, and company E2 within two different scenarios S1and S2.

Company A works as an online commercial platform that sells the disused goods of large corporations to avoid CO2 emissions from the production of more goods of the same category. Company E1 is a construction company that has finished its construction process. This company has used all the materials that it needed, and it has surplus materials (PVC pipes) that will typically go to storage over a big period. Company E2 is a Company that has started its construction process. This company is looking for materials (among them, PVC pipes) to enter their construction process.

Figure 1 shows the two scenarios that are discussed in this research to understand the environmental indicators that might be changed by company A's approach of CE. In Scenario 1, base scenario, material, equipment, and resources entered company E1's construction phase. Once their construction phase is finished, some good materials are left and normally disposed of in storage or landfills. In Scenario 2, materials left from company E1 are transported into a second company E2 whose construction process is still ongoing. Both Scenarios considered transport emissions. However, material production emissions are only included in scenario 1, and energy consumption emissions are only considered in scenario 2 from company A's activities.

Input data for our analysis include a carbon footprint analysis commissioned by a consultant for sustainability and climate change. The data from Company A's 2019-2022 carbon footprint report was used. Additionally, interviews with Company A's CEO were carried out to understand the life cycle of the materials and equipment they typically process.

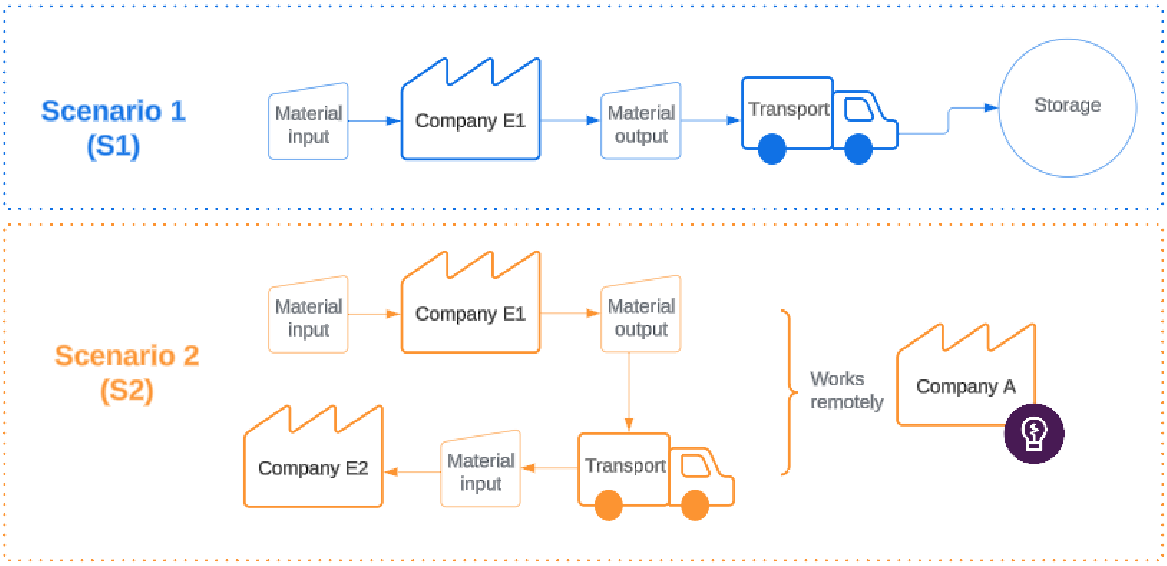

Figure 1: Scenarios with (S2) and without (S1) Circular Economy.

For over four years (2019-2022), Company A has worked with 33 companies, providing a recovery equivalent to 3006.6 ton of materials, including:

- Inoperative equipment (tractors, excavators, trucks, mining truck tires, telehandlers, cranes, mobile cranes),
- Damaged materials (industrial materials, paint, cement, iron rods, glue, personal protective equipment, pipe paint, pipe coating materials),
- Damaged equipment and minor tools (grinders, rotary hammers, drills, vibro-rammers, small equipment used for construction),
- Spare parts for inoperative equipment, computer equipment (laptops, computers), inoperative vehicles (trucks, cars),
- Furniture (office furniture, desks, campsites, containers, portable toilets).

This study scope is limited to the materials recovery analysis of one of Company A’s clients. Table 2 shows the scope of materials that this client reported as residue, which is analysed in this case.

Table 2: Case Study Scope Description

Item	Description	Ton	Initial Location	Destination with Company A	Destination without Company A
Material	PVC Pipe	10	Arequipa	Lima	Lima

In the context of LCA, “end of life” refers to the final stage of a product’s life cycle. It encompasses the product’s disposal, recycling, or any other fate after it has reached the end of its useful life (Sandin, 2014). Since the case study is based on the final stage of the PVC pipes in company E1, the results were based on an “End of Life” approach for the analysis.

In this research, LCA analysis from other authors (Vahidi et al, 2016, Santoyo-Castelazo et al, 2011) were introduced in the results to compare which of the two scenarios S1, S2 has a better environmental performance.

RESULTS

LIFE CYCLE ASSESSMENT

Goal and scope definition

According to Hauschild (2018), goal definition sets the context for the LCA assessment and provides the basis of the scope. Table 3 frames the goal and scope of our case:

Table 3: Goal and Scope Definition

Goal/Purpose	Evaluate LCA comparing environmental impacts of the management of Materials from the construction stage
Application	Basis for decision on recovering Materials from the construction stage
Functional Unit	Three functional units were taken into consideration as a unit of measurement that serves as the basis for comparing different alternatives: • Transportation emissions, km is the functional unit. • Emissions related to waste (such us materials and equipment), ton is the functional unit. • Emissions related to storage area, m2 is the functional unit.
System Boundary	The following considerations were taken to define the boundaries of our analysis: • Materials (PVC Pipes) that are covered by Company A from the construction stages from 2021. • All processes contributing significantly to the life cycle impacts are considered. • In S2, there is no more raw material extraction emissions since they use material from S1. • There are transportation emissions in both scenarios S1 and S2. Both are considered to have the same results since their destination are near each other.

A thorough analysis of the “End of Life” phase of residual materials is used to determine environmental impacts in two different scenarios, as depicted in Figure 1. One basic scenario S1 in which Company A is not involved, and a second scenario S2 in which Company A participates and applies their CE approach.

Figure 1 shows Product System of S1 that consists of two main processes which are production of PVC pipes, and transportation of residual pipes from company E1 to their storage. While information for the transportation system and its relating input-output data was gathered from EcoTransIT software. Information for the PVC pipe input-output data was gathered from Vahidi (2016) who explained the main materials and processes that are considered in a LCA of PVC pipe production. Product System of S2 consists of another two main processes which are transportation of residual pipes from company E1 to E2, energy usage of Company A’s workers to manage construction materials. The values and processes for electricity were considered to come from a hydroelectric source. In 2020 in Peru, electricity generation from hydroelectric plants increased their participation to 59.6%. Although electricity generation has year to year variations in the contribution of renewable energy sources (RESs), hydroelectric plants have been consistently producing around half of Peru’s electricity over the past years (Campodonico, 2022).

Inventory Analysis

The inventory analysis collects information about the flows of input-output of resources, materials, and energy. The inventory data consists of Company A emission reports from 2019-

2022. Table 4 shows a summary of the main inputs and outputs considered in the analysis for both scenarios.

Table 4: Input-Output flows from S1 and S2

Flows	S1	S2
Input Flows	Pipe Production (Vahidi et al, 2016)	Electricity (Santoyo-Castelazo et al, 2011)
	Transportation (EcoTransIT)	Transportation (EcoTransIT)
Output Flows	M&E transported (Company A reports)	M&E transported (Company A reports)

Impact Assessment

Life Cycle Impact Assessment methodology was studied to evaluate and quantify the environmental performance across two different scenarios for the End of Life of construction materials (pipe production). The UCEPA TRACI methodology was developed for the pipe production (Vahidi et al, 2016). The ISO 14040 was used to delve into the emissions of energy consumption from hydroelectric sources (Santoyo-Castelazo et al, 2011).

The UCEPA TRACI methodology included the impact categories of ozone depletion (kg CFC-11 eq), global warming (kg CO2 eq), smog (kg O3 eq), acidification (kg SO2 eq), eutrophication (kg N eq), carcinogenics (CTUh), non carcinogenics (CTUh), respiratory effects (kg PM2.5 eq), ecotoxicity (CTUe), and fossil fuel depletion (MJ surplus).

The LCA results from ISO 1404 showed results for global warming (kg CO2 eq), (CH4), terrestrial acidification (kg SO2 eq), ozone formation (kg NOx eq), respiratory effects (kg PM2.5 eq).

The emissions of transportation were obtained from EcoTransIT software showing results for respiratory effects (kg PM2.5 eq), global warming (kg CO2 eq), terrestrial acidification (kg SO2 eq), ozone formation (kg NOx eq).

Table 5 shows the results of Company A's avoided emissions and produced emissions from S1 and S2 respectively. For this results, two Life Cycle Assessment studies were considered, their resulting emission factors were multiplied by the activity level from both scenarios (Vahidi et al, 2016, Santoyo-Castelazo et al, 2011).

Twelve environmental impact categories were identified in this analysis. The second scenario S2 showed better or equal performance on all of the environmental indicators, but Global warming and Ecotoxicity. Smog, Acidification, Eutrophication, Respiratory effects, Fossil fuel depletion, Ozone depletion, Carcinogenic, Non-Carcinogenic, Ozone formation and Air pollution showed similar results for both scenarios.

The CO2 emissions for S1 is approximately higher by three times compared to S2, showing that the CO2 emissions related to PVC pipe production are greater than CO2 emissions from company A´s energy consumption. Greenhouse gases are contributors to global warming and climate change, CO2 is one of the most relevant in this matter (Yoro et al, 2020). Although, the pandemic has slowdown the expected increase of CO2 emissions, the UNEP Emissions Gap Report 2020 shows that this will be an insignificant reduction of 0.01ºC by 2050 if the international community doesn't prioritize green recovery. There are many opportunities that have been increasingly more visible to the construction sector that recycling construction waste and applying it to new construction sites will reduce carbon emissions and its impact to global warming (Yang et al, 2023).

Table 5: Life Cycle Assessment results for S1 and S2

Impact Category	Reference Unit	S1	S2
Ozone depletion	kgCFC-11 eq	2.79E-05	0
Global warming	kg CO2 eq	2.45E+03	8.30E+02
Smog	kg O3 eq	2.90	0
Acidification	kg SO2 eq	9.27	3.13
Eutrophication	kg N eq	1.81	0
Carcinogenic	kg 1,4-DCB	9.75E-05	0
Non carcinogenic	kg 1,4-DCB	2.4E-04	0
Respiratory effects	kg PM2.5 eq	0.77	0.19
Ecotoxicity	kg 1,4-DCB	6.890E+03	5.9E-06
Fossil fuel depletion	MJ	1.70E+04	1.27E+04
Ozone formation	kg NOx eq	8.40	8.40
Air pollution	kg NMVOCx eq	0.53	0.53

Ecotoxicity was a major environmental impact by S1. The production of PVC can contribute to ecotoxicity because of the chemical composition of toxic vinyl chloride monomers, and other additives such as pigments to improve its performance (Bidoki & Wittlinger, 2010). Pigments and other additives or stabilizers such as lead compounds in PVC pipes can be toxic and harm aquatic life if released into the environment (Bidoki & Wittlinger, 2010). Additionally, the production of PVC involves energy-intensive processes such as manufacturing, polymerization, and manufacturing which would eventually affect the ecotoxicity indicator by the energy consumption emissions.

This result adds to the body of knowledge of the well-known benefits of recycled materials in a context of construction companies applying principles to manage more efficiently their waste. Although these results are only based on the impacts of one company (company E1) recycling it PVC pipes, it should be highlighted that company A has worked with 33 different companies (including company E1) in over three years. Further research should explain the overall impact of more environmental indicators that are related to the manufacturing of other materials.

CONCLUSIONS

The construction industry’s significant environmental footprint necessitates urgent measures to reduce waste and mitigate environmental impacts. This paper examines the application of Circular Economy (CE) principles in construction waste management, aiming to evaluate its effectiveness in minimizing environmental degradation. By leveraging a case study approach and employing Life Cycle Assessment (LCA), the study provides valuable insights into the environmental performance of CE implementation within the construction sector. Our findings underscore the potential of CE to reduce environmental impacts associated with construction. Through the analysis of environmental indicators using different Life Cycle Assessment studies, it was evident that CE adoption led to notable reductions in various impact categories, aligning with the principles of waste reduction, resource optimization, and closed-loop material flows inherent in CE. Despite the promising results, our study highlights the need for further optimization and refinement of CE practices within the construction sector. Addressing regional energy sources and enhancing material recovery processes could further enhance CE's efficacy in mitigating environmental impacts.

In this study, data from the specific construction processes that produced the material wastes was not available. However, through diligent application, Lean principles provide an approach to reduce material waste before they are generated due to production wastes of inventory, overproduction, and rework from defective products. Therefore, the synergies between Lean and CE philosophies further amplify the potential for waste reduction and resource optimization within the construction industry. While Lean emphasizes process waste reduction, CE focuses on material waste throughout the lifecycle, offering complementary strategies for minimizing environmental impacts.

This study contributes to the growing body of knowledge on CE implementation in construction waste management, providing valuable insights for policymakers, industry practitioners, and researchers. By embracing CE principles and leveraging synergies with Lean methodologies, the construction industry can move towards a more sustainable and environmentally responsible future.

LIMITATIONS AND FUTURE RESEARCH

Despite the contributions of this study, several limitations should be acknowledged. First, while this case study provides in-depth insights into a specific context, generalizing findings to broader populations or contexts may be limited. Future research could complement the analysis with large-scale empirical studies to enhance the robustness and generalizability of findings. Second, the availability and reliability of data can pose challenges for conducting comprehensive assessments, such as the necessary for addressing material waste generation from the Lean perspective (production management) and CE perspective (construction life cycle). Future research can explore ways to improve data quality and accessibility. Third, certain assumptions and simplifications were made in the analysis, such as uniform transportation emissions and energy sources. Future research could consider certain nuances in the assessment. Fourth, this study was limited to a specific period, potentially overlooking long-term trends and changes in environmental performance. Future research could extend the analysis over longer durations to capture temporal variations and assess the durability of CE practices. By addressing these limitations, scholars and practitioners can continue to advance our understanding of CE implementation in construction waste management and contribute to the development of more sustainable construction practices.

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