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Strategic Integration of Lean Construction into Green Building Regulations: A Factor-Based Assessment of Green Construction Indicators

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Abstract. The construction sector plays a critical role in sustainability through effective construction waste management. In Indonesia, green building practices are guided by the Green Construction Site Index (GCSI) and the Minister of Public Works and Housing Regulation No. 21 of 2021; however, their strategic alignment with Lean Construction principles remains limited. This study examines the strategic integration of Lean Construction into green building regulations by validating regulatory-based indicators using the three Lean Construction pillars: Systems Management, Technology Management, and Culture and Behaviour. A questionnaire survey of construction practitioners was analyzed using Exploratory Factor Analysis (EFA). The results reveal a robust three-factor structure, accounting for 80.1% of the total variance, with Systems Management as the dominant dimension. The findings provide practical insights for strengthening regulatory coherence, improving waste reduction strategies, and enhancing sustainable performance during the construction phase of building projects.

Keywords: construction waste, green building, green construction, lean construction, assessment tool, comparative analysis

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1. Introduction

Building is a dominant type of construction in terms of numbers and continues to grow rapidly. Both during construction and later in operation, building construction continuously requires various resources, such as materials, energy, and labor. In addition, most construction sector resources rely heavily on non-renewable materials, resulting in significant carbon emissions [1]. Uncontrolled use of resources in construction often leads to adverse environmental impacts, including material waste, carbon emissions, and high construction waste [2]. The construction sector's impact is evident in its contribution to 40% of total rigid waste generation, 40% of global power consumption, and almost 16%

of worldwide water usage [3].
This tendency makes the construction sector one of the most significant contributors to environmental degradation. Environment is one of these three indicators, reflects high technical and operational efficiency, as well as promising long-term socio-economic returns [4]. Driven by shifting needs in a post-pandemic world, the construction industry is experiencing a period of rapid expansion as the demand for new infrastructure reaches new heights. According to a report by Oxford Economics, global construction activity is projected to grow faster than the labor force in developed countries, at more than 4.5%. This increase brings its own challenges, including the high level of waste in the construction process. The construction phase generates the most waste of all phases in the building lifecycle. Furthermore, the industry is known for inefficiencies, such as poor quality, flawed design, and unsafe working conditions, which lead to non-value-added activities, process uncertainty, and waste [5].

Thus, for now, the success of the construction industry is driven by project performance, as measured by several indicators, including but not limited to time, cost, quality, safety, and customer satisfaction. Efforts to build an environmentally friendly system are also applied in the transformation of raw materials into tangible construction forms [6]. Meanwhile, the concept of green construction emerges as a solution to reduce the environmental impact of construction activities through various measurement parameters implemented in existing regulations. However, the extent to which these parameters are effective in creating a more efficient and sustainable construction process remains a question that needs further study. The rapid growth of the construction industry has significantly contributed to the decline in environmental quality, including increased carbon emissions, construction waste, and inefficient use of raw materials.

The implementation of green construction is a form of support for halving greenhouse gas (GHG) emissions over the next 10 years and achieving reductions in carbon dioxide (CO2) emissions [7]. The implementation of green construction is strengthened through regulations that specify criteria and standards. To evaluate the effectiveness of green construction implementation, various rating instruments are used, including the Green Construction Site Index (GCSI) [8]. One Indonesian regulation is the Public Works and Housing Minister Regulation No. 21 of 2021 on Green Building Performance Assessment, which provides guidelines and measurable indicators for the application of green concepts in the construction process.

Based on this, construction activities generate more than 50% of waste [9]. Construction activities result in more waste than any other industry. An integrative approach to achieving 'real' value in the most effective way is to use the concept of 'Lean' [10]. Lean and sustainable development strongly favor limiting resource consumption, as they both aim to use resources efficiently by eliminating waste. Sustainability focuses heavily on minimizing energy, water, material, and pollutant use in buildings. Due to the higher initial costs of most sustainable technologies, a viable sustainability program is based on reducing lifecycle costs. Lean construction (LC), on the other hand, focuses on reducing waste generated during the construction phase of a building [11].

The need to change construction practices to improve efficiency is important to achieve the concept of sustainability. This importance entails a change in how construction is conducted and a deep focus on managing the entire construction phase. The principles of construction efficiency, which focus on improving efficiency and eliminating waste during the construction phase, should be aligned with green construction through regulatory frameworks and assessment tools. This is because the implementation of green construction, such as the Public Works and Housing Minister Regulation No. 21 of 2021 and measurement through the Green Construction Site Index (GCSI), will not be successful unless the principles of construction efficiency are aligned with the idea of LC. Therefore, the combination of the two will result in a framework that enables the optimal achievement of environmental goals while maintaining construction-phase efficiency and productivity [12].The model's effectiveness is primarily determined by the crucial role of environmental impact, in line with previous research findings that highlight the dominance of environmental factors in sustainable waste management [13]. It is necessary to identify the regulatory and assessment tools used to determine the extent and manner in which LC are adopted, especially during the construction phase, to reduce non-value-added activities. Therefore, increased integration between phases and stakeholders will generate value [14]. It is necessary to take a more in-depth look at the methods used to complete construction projects, starting from procurement, scheduling, and control.

2. **Methods**

2.1. Literature-Based Parameter Identification

Data collection in this study began with a structured literature review to identify green construction indicators derived from two primary sources: the Green Construction Site Index (GCSI) and the Public Works and Housing Minister Regulation No. 21 of 2021. Academic databases including Scopus, Web of Science, and Google Scholar were searched for peer-reviewed journal articles, conference proceedings, and regulatory or standard documents published between 2010 and 2024.

The search strategy employed combinations of keywords such as “lean construction,” “green building,” “construction waste,” “GCSI,” “green construction indicators,” and “sustainable construction regulations.” Inclusion criteria were: (i) relevance to lean–green integration in construction, (ii) explicit discussion of waste categories, performance indicators, or regulatory parameters, and (iii) applicability to the construction phase. Non-English articles, duplicate records, and sources lacking methodological transparency were excluded.

2.2. Mapping and Coding Protocol

The parameters extracted from GCSI and Regulation No. 21/2021 were systematically coded and mapped to the nine lean construction waste categories: transportation, defects (non-quality), waiting, inventory, over-processing, overproduction, motion, unused employee creativity, and accidents [15].

A coding matrix was developed to link each regulatory or assessment parameter to one or more waste categories based on operational definitions of lean waste provided in the literature. To enhance reliability, the mapping procedure was independently conducted by two researchers, and discrepancies were resolved through discussion until consensus was reached. This step ensured methodological transparency and reduced subjective bias in the classification process.

2.3. Grouping by Lean Construction Primary Pillars

Following the waste-category mapping, the identified parameters were grouped into the three Primary Pillars of Lean Construction: Systems Management, Technology Management, and Culture and Behavior [15]. This classification aimed to evaluate the extent to which existing green construction indicators and regulatory provisions support the systemic, technological, and behavioral dimensions required for effective lean implementation in construction waste management.

2.4. Expert Survey and Respondent Criteria

To empirically validate the conceptual grouping, a structured questionnaire was developed based on the mapped parameters and pillar classifications. The survey was distributed to expert respondents who met the following criteria: Formal educational background in civil engineering or a closely related construction engineering discipline; Practical experience in the execution or management of construction projects; Prior or ongoing involvement in green building, green construction, or sustainable infrastructure initiatives. These criteria ensured that the responses reflected informed professional judgment and practical industry perspectives. Respondents were asked to rate the relevance of each parameter to the three lean construction pillars using a five-point Likert scale.

2.5. Exploratory Factor Analysis and Validation Procedure

Exploratory Factor Analysis (EFA) was employed to validate the underlying factor structure of the green construction indicators and to examine whether the empirically derived factors aligned with the proposed three-pillar conceptual model. Prior to factor extraction, the adequacy of the dataset was assessed using the Kaiser–Meyer–Olkin (KMO) measure and Bartlett’s Test of Sphericity. Factors were extracted using principal axis factoring, followed by Varimax rotation to enhance interpretability. Indicators with factor loadings below 0.50 or with high cross-loadings were reviewed and, where necessary, excluded from the final model. The internal consistency of each factor was evaluated using Cronbach’s alpha. The validated factor structure was then used as the basis for a comparative assessment of how well GCSI and Regulation No. 21/2021 support each lean construction pillar and corresponding waste category.

2.6. *Comparative Analysis and Triangulation*

A comparative analysis was conducted by examining the distribution of validated indicators across the three pillars and nine waste categories for both regulatory and assessment frameworks. Quantitative summaries, including frequency counts and percentage coverage, were used to highlight dominant and underrepresented dimensions.

Source triangulation was applied by cross-referencing findings from the expert survey, regulatory documents, green building standards, and prior empirical studies. This approach enhanced the robustness of the results and supported the formulation of evidence-based recommendations for improving the integration of lean construction principles into green building regulations and construction-phase sustainability practices.

3. **Results and Discussion**

3.1. *Parameter Identification Results from the Green Construction Site Index and Public Works and Housing Minister Regulation No. 21 of 2021 Based on Nine Types of Construction Waste.*

The parameter identification results, as presented in Figures 1 to 3, illustrate the distribution and frequency of parameters associated with the nine types of construction waste as defined in Lean Construction across the Green Construction Site Index (GCSI) and the Public Works and Housing Minister Regulation No. 21 of 2021. This analysis provides an initial mapping of how regulatory and assessment frameworks align with the conceptual structure of waste minimization in Lean Construction. The findings indicate that both references contain a substantial number of parameters that can be systematically associated with Lean Construction principles, particularly in relation to waste prevention, process efficiency, and environmental performance. This suggests that, although the two regulatory instruments were developed from different institutional and policy perspectives, they exhibit a convergent orientation toward operational efficiency and sustainability in construction project execution. A closer examination reveals that the parameters are not evenly distributed across the nine waste categories. Certain waste types, such as defects, inventory, and over-processing, are more prevalent, reflecting a strong regulatory emphasis on quality assurance, material management, and procedural controls.

In contrast, waste types related to unused employee creativity and motion appear to be less explicitly addressed, indicating that human-centered and behavioral dimensions of waste reduction are comparatively underrepresented in formal regulatory frameworks. This pattern highlights an important structural characteristic of both GCSI and the Ministerial Regulation: the predominance of system- and technology-oriented controls over culture- and behavior-oriented mechanisms. While technical standards, documentation requirements, and environmental management procedures are clearly articulated, fewer parameters directly target workforce engagement, continuous improvement practices, and knowledge utilization at the project level.

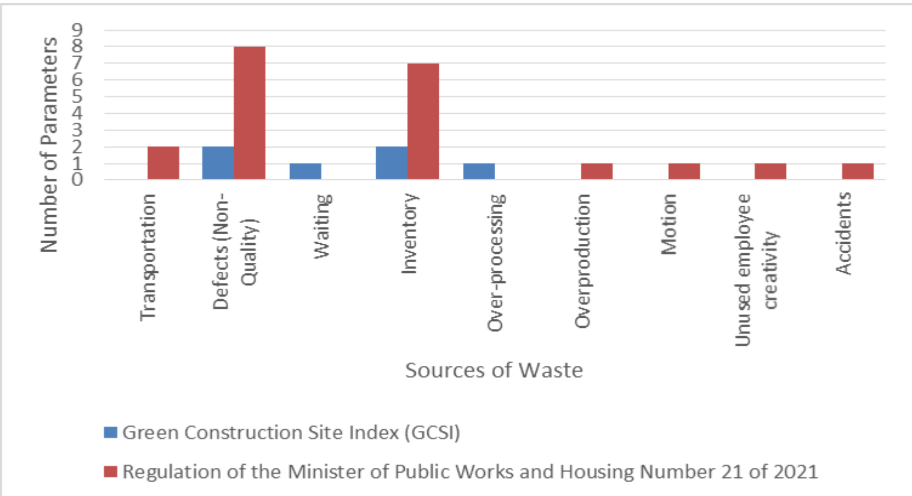

Figure 1. Comparison of Parameter Counts in Systems Management

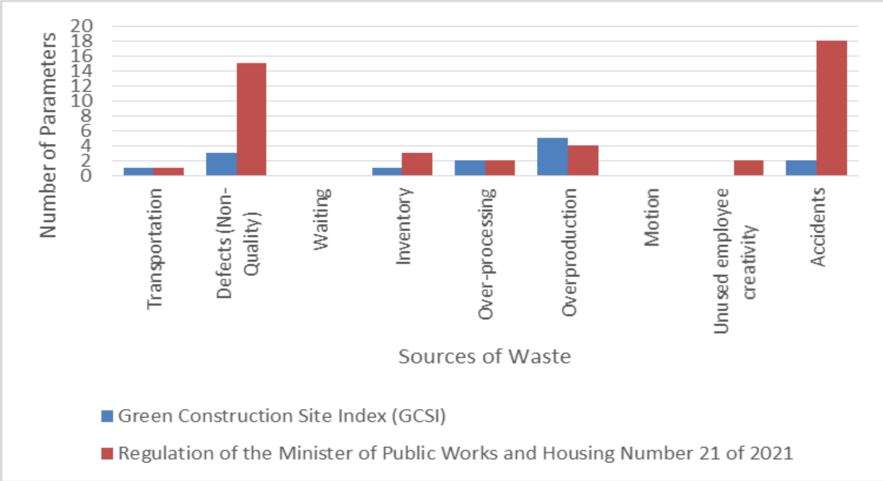

Figure 2. Comparison of Parameter Counts in Technology Management

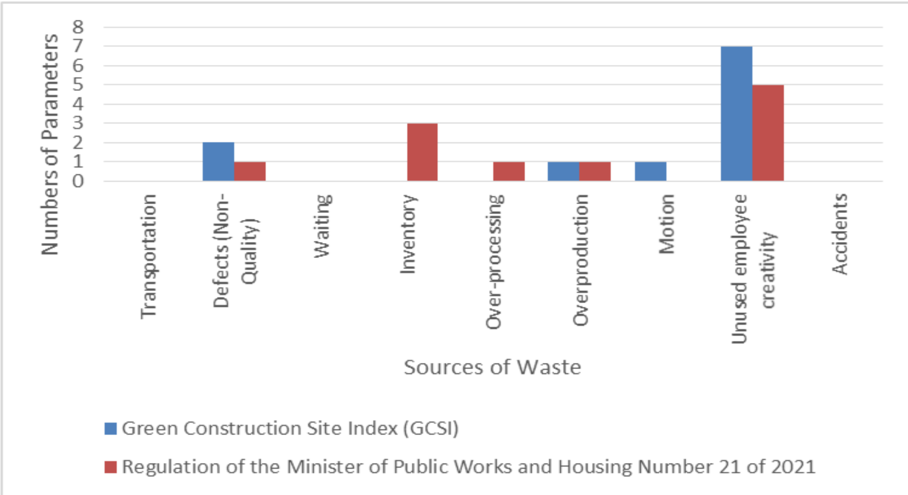

Figure 3. Comparison of Parameter Counts in Culture and Behaviour

3.2. Expert Validation

The distribution of respondents' perceptions based on mean scores and standard deviations, disaggregated by years of professional experience in building construction projects, shows that respondents with more than 10 years of experience are predominantly located in the high-mean, low-standard deviation quadrant. In Figure 4, this pattern suggests that senior practitioners not only assign greater importance to the assessed indicators but also show greater consensus. Overall, this reflects a more stable and consolidated understanding of green construction and lean management practices among experienced professionals.

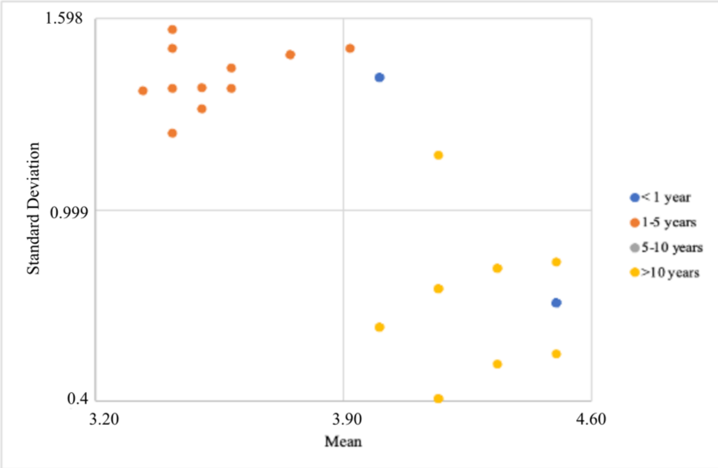

Figure 4. Expert Background

In contrast, respondents with 1–5 years of experience tend to cluster in the lower-mean, higher-standard deviation quadrant, reflecting more heterogeneous perceptions and lower levels of agreement. This dispersion suggests that practitioners in the early stages of their careers may still be developing their understanding of green construction principles and their practical implementation in construction projects. Respondents with less than 1 year of experience and those in the 5–10 years category are more sparsely distributed across the plot, occupying intermediate positions between the two dominant groups. This distribution reflects a transitional stage in perceptual development, in which practical exposure and organizational learning increasingly shape consistency in assessments. Overall, this pattern highlights the role of professional experience as a moderating factor in shaping both the perceived importance and the level of consensus regarding green construction indicators. The observed stratification supports the use of experienced practitioners' responses as a robust empirical basis for validating the indicators' underlying structure in the subsequent Exploratory Factor Analysis (EFA). By establishing this background, the analysis ensures that the factor structure derived from the EFA reflects not only statistical relationships but also meaningful, experience-informed professional judgment.

3.3. Exploratory Factor Analysis

Based on the EFA results, Table 1 presents the mapping of parameters A–W to the original questionnaire indicators, construction waste categories, Lean Construction pillars, and associated statistical measures, to ensure traceability across regulatory frameworks, the empirical structure, and practitioner perceptions. An EFA was conducted to identify the latent structure of the green construction parameters (A–W) derived from the Green Construction Site Index (GCSI) and the Indonesian Public Works and Housing Minister Regulation No. 21 of 2021, and to assess their empirical alignment with the three main pillars of Lean Construction, namely Systems Management, Technology Management, and Culture and Behaviour. The analysis employed the minimum residual extraction method with an oblimin rotation, which allows for correlations among latent factors. This approach was selected based on the theoretical assumption that the three Lean Construction pillars are conceptually interrelated in real-world construction project implementation.

3.3.1. Factor Structure and Explained Variance Transportation

The results indicate that a three-factor solution provides the most interpretable and statistically robust structure for the dataset. Collectively, the three factors explain 80.1% of the total variance, indicating a high level of explanatory power for the green construction parameters under investigation. The first factor accounts for 40.6% of the variance, reflecting the dominant role of system-oriented dimensions in green construction implementation. The second factor explains 24.2% of the variance, while the third factor accounts for 15.3%, representing the technological and behavioural dimensions that complement and reinforce the system's foundation.

3.3.2. Inter-Factor Correlations

The inter-factor correlation matrix reveals moderate positive correlations among the three latent constructs, with correlation coefficients ranging from 0.341 to 0.619. These values indicate that, although each factor represents a distinct conceptual dimension, they remain functionally interconnected in practice. This pattern supports the application of an oblique rotation. It reflects the integrative nature of Lean Construction, in which system governance, technological implementation, and cultural and behavioural practices operate synergistically rather than independently. A factor loading threshold of ≥ 0.50 was used to identify parameters with substantial contributions to each latent factor.

Table 1. Exploratory Factor Analysis Result

Indicators		**Factor**			
		1	**2**	**3**	**Uniqueness**
A	Use of precast/prefabricated units to reduce defects	0.491		0.376	0.3866
B	Material recycling and construction waste segregation			0.807	0.2442
C	Validated quality plan and lean behaviour training	0.977			0.1194
D	Use of precast units, completeness of contract documents, and component reuse	0.907			0.2117
E	Waste minimization, use of prefabrication, waste management, and documentation			0.965	0.0398
F	Implementation of the 3R principle and waste volume reporting	0.958			0.0703
G	Completeness of contract documents to avoid project delays	0.423		0.489	0.2932
H	Use of local materials ≥40%, compliance with domestic content (TKDN), and warehouse efficiency	0.844			0.1325
I	Reuse and recycle reporting, hazardous waste (B3) storage, and biopore systems	0.589			0.2174
J	Avoidance of groundwater use and identification of material requirements		0.903		0.0739
K	Efficient construction planning and design	0.688	0.310		0.1892
L	Use of environmentally friendly products and equipment certification		0.476	0.579	0.2197
M	Optimization of construction equipment usage		0.703		0.2920
N	Project electricity and energy usage planning	0.813			0.1472
O	Control of steel and concrete waste and energy management		0.809	0.361	0.2878
P	Rainwater harvesting and the use of environmentally friendly products		0.810		0.1406
Q	Efficient raw water distribution system	0.845			0.1733
R	Provision of segregated waste bins on site	0.342	0.728		0.1633

Indicators		Factor			
		1	2	3	Uniqueness
S	Visual information boards for environmental policies		0.886		0.1166
T	Documentation of equipment operator training and environmental impact monitoring		0.325	0.437	0.2969
U	Reward systems, environmental awareness, and worker-driven innovation	0.800			0.2283
V	HSE plan, emergency SOPs, and emergency response plans	0.441		0.353	0.4301
W	Control of water, air, and noise pollution	0.963			0.0972

3.4. Grouping of Identification Results Based on Waste Types in Primary Pillar Lean Construction (LC)

After identifying the parameters across the nine types of construction waste, the next step was to group them into the three primary pillars of Lean Construction: Systems Management, Technology Management, and Culture and Behaviour. This grouping provided a conceptual structure for organizing the indicators prior to empirical validation. The grouped parameters were subsequently examined using Exploratory Factor Analysis (EFA) to assess whether the empirical factor structure derived from practitioner responses aligned with the proposed theoretical classification. Parameters associated with Systems Management primarily focused on planning, documentation, and system-level controls that influence waste types such as defects, waiting, inventory, overproduction, and accidents.

Parameters under Technology Management reflected technical and procedural aspects of waste management, particularly in relation to over-processing and resource control. Meanwhile, parameters grouped within Culture and Behaviour emphasized workforce awareness, training, and engagement, especially for waste types related to motion and unused employee creativity. Overall, this step established a clear link between the conceptual grouping and the empirical validation process, enabling a systematic comparison between regulatory intent, theoretical structure, and the factor patterns revealed through EFA.

3.4.1. Transportation

Material transportation management is one of the most significant problems in the construction industry, often causing delays and value loss at the project site [16]. The scope of this activity includes the movement of materials between workstations and crane movements [15]. The application of Lean Construction (LC) principles makes a practical contribution in minimizing non-value-added transport activities, as shown in Table 2.

Table 2. Practical contributions of Lean Construction in minimizing transport actions

Primary Pillars	Practical Contributions	
	Green Construction Site Index	**Public Works and Housing Minister Regulation No. 21 of 2021**
Systems Management	-	The implementation of lean construction emphasizes just-in-time planning, procurement, and the use of materials, while ensuring that at least 50% of the required raw materials and/or equipment are supplied by vendors within a 200-kilometer radius.
Technology Management	The standard operating procedures for the use and operation of construction equipment.	Including a plan for the mobilization of construction equipment and monitoring the realization of its mobilization.
Culture and Behavior	-	-

3.4.2. Defects (Non-Quality)

Quality defects in construction projects not only cause material and labor losses but also directly affect potential revenue during the repair period, making them a double source of waste [15]. Strategic implementation of Lean Construction, including comprehensive pre-planning, can reduce quality defects by more than 90%. This reduction not only saves resources (materials, labor, and equipment) but also streamlines the overall project workflow [17]. Table 3 shows the practical contributions of Lean Construction principles in minimizing quality defects.

Table 3. Practical contributions of Lean Construction in minimizing quality defects

Primary Pillars	Practical Contributions	
	Green Construction Site Index	**Public Works and Housing Minister Regulation No. 21 of 2021**
Systems Management	The use of factory-made construction units, complete contract documentation, maximal reuse of building components, utilization of recycled materials, and the development of material procurement procedures within the construction environment.	The integration of systems, technology, and behavior in lean construction includes validated quality plans, waste reduction simulations and segregation, rainwater storage, energy-efficient systems (30% savings), energy audit reports, and green energy conservation policies.
Technology Management	Minimizing construction waste, using prefabricated units, ensuring contract document completeness, maximizing component reuse, utilizing recycled materials, establishing material procurement procedures, managing waste, and anticipating waste generation are essential in lean construction.	Ensuring compliance with planning criteria, document submission, as-built drawings, land revitalization, waste management, and rainwater retention for half of the site.
Culture and Behavior	Maximizing building component reuse, recycling materials, developing procurement procedures, and managing waste contribute to lean construction through systems, technology, and culture.	The efforts of 3R (reduce, reuse, recycle) of construction waste in the project are demonstrated by tracking and recording the volume of products generated.

3.4.3. Waiting

Waiting results from a lack of synchronization in the execution of planned tasks, the unavailability of materials, labor, validation, plans, or information required to perform the work, or even equipment failure. In construction project management practice, most of the time on construction sites is often wasted on waiting [17]. Table 4 shows the practical contributions of Lean Construction principles in minimizing waiting times.

Table 4. Practical contributions of Lean Construction in minimizing waiting times

Primary Pillars	Practical Contributions	
	Green Construction Site Index	**Public Works and Housing Minister Regulation No. 21 of 2021**
Systems Management	The thoroughness and completeness of contract documents ensure that all necessary terms, conditions, and specifications are clearly outlined and agreed upon.	-
Technology Management	-	-
Culture and Behavior	-	-

3.4.4. Inventory

The limited space available at the construction site, which does not allow for storing the entire material, is an important reason for implementing lean construction in construction projects to utilise resources without waste [18]. In addition, seasonal weather conditions suggest that external environmental factors may affect the defect rate[17]. Table 5 shows the practical contribution of LC principles to the inventory.

Table 5. Practical contributions of Lean Construction in minimizing inventory

Primary Pillars	Practical Contributions	
	Green Construction Site Index	**Public Works and Housing Minister Regulation No. 21 of 2021**
Systems Management	The completeness of contract documents, along with the selection and use of materials, are crucial aspects in ensuring effective lean construction practices.	The project uses water from a drinking water company or shallow wells, ensures at least 40% local content (TKDN), avoids harmful materials (CFCs, asbestos, mercury, VOCs), uses certified eco-friendly materials, minimizes packaging, applies environmentally focused supplier selection, and employs efficient warehousing.
Technology Management	A comprehensive report documenting the practices and strategies involved in the reuse and recycling of construction waste, highlighting their impact on sustainability and resource management.	The provision of designated hazardous waste storage, biopore holes for rainwater infiltration, and branch water meters from the raw water source for construction work, all in accordance with planning documents.
Culture and Behavior	-	The project avoids using groundwater for construction, utilizes dewatering water, and has a system to identify material and equipment needs based on scope, schedule, and required quantity, minimizing excess.

3.4.5. Over-Processing

Overly complicated processes or excessive processing can lead to this type of waste, involving extra tasks and work that do not need to be done. This includes the use of complex or more expensive tools than are needed. Unnecessary extra work is also considered wastage, increasing production costs and not adding value to the final construction product [19]. Table 6 shows the practical contribution of LC principles in minimizing redundant processing.

Table 6. Practical contributions of Lean Construction in minimizing over-processing

	Green Construction Site Index	Public Works and Housing Minister Regulation No. 21 of 2021
Systems Management	The thoroughness and completeness of construction design and planning ensure that all aspects are carefully considered and integrated for efficient project execution.	-
Technology Management	The application of environmentally friendly products and the evaluation of material waste.	The warranty certificate documents for the manufacturer's leading equipment, and the operation and maintenance manuals for the equipment systems, according to each manufacturer's criteria.
Culture and Behavior	-	Demonstrating efforts to leverage technology in optimizing the use of construction equipment.

3.4.6. Overproduction

Overproduction is among the most crucial categories of waste that affect the value aspect of construction. It occurs when manufactured items exceed customer demand, or when structures are built even though they are not needed and are planned for dismantlement in the near future [15]. Table 7 shows the practical contribution of the Lean Construction principles in minimizing overproduction.

Table 7. Practical contributions of Lean Construction in minimizing overproduction

Primary Pillars	Practical Contributions	
	Green Construction Site Index	Public Works and Housing Minister Regulation No. 21 of 2021
Systems Management	-	Having a table for the electricity usage plan of all equipment and facilities, both in the project area and the project office.
Technology Management	The practical contributions of lean construction involve minimizing construction waste, ensuring completeness in design and planning, assessing material waste, and controlling steel reinforcement and concrete waste.	The project will regularly monitor the usage of raw water, electricity, and carbon fuel, implement energy management procedures from planning to evaluation, and install kWh meters on the main and distribution panels for electricity supplied by the state electricity company.
Culture and Behavior	The implementation of environmentally friendly products in construction practices promotes sustainability and reduces environmental impact.	The utilization of rainwater as an alternative source of clean water during construction.

3.4.7. Motion

This wastage involves work that adds time to the overall activity but does not improve overall performance and is caused by three main problems: poor Design, Methodology, and Human Resources [20]. Table 8 shows the practical contributions of Lean Construction principles in minimizing motion.

Table 8. Practical contributions of Lean Construction in minimizing motion

Primary Pillars	**Practical Contributions**	
	Green Construction Site Index	**Public Works and Housing Minister Regulation No. 21 of 2021**
Systems Management	-	Providing an effective and efficient raw water distribution system that meets the construction needs.
Technology Management	-	-
Culture and Behavior	The provision of properly designated waste disposal bins at construction project sites ensures efficient waste management and maintains a clean and organized work environment.	-

3.4.8. Unused Employee Creativity

Work direction is generally top-down, so there is minimal room for initiative and creativity, both individually and collectively. This condition is inversely proportional to the potential for human resources to play a significant role in generating creative solutions to overcome the root problems in construction companies [21]. Table 9 shows the practical contributions of Lean Construction principles in minimizing waste generated by unused employee creativity.

Table 9. Practical contributions of Lean Construction in minimizing creativity

Primary Pillars	**Practical Contributions**	
	Green Construction Site Index	**Public Works and Housing Minister Regulation No. 21 of 2021**
Systems Management	-	Providing information boards with visual management for aspects that refer to management policies regarding environmental factors.
Technology Management	-	The documentation report for the training program on operating equipment systems includes regular monitoring of construction activity impacts such as vibrations, noise, and dust.
Culture and Behavior	Subcontractors' waste management ability, adherence to construction waste regulations, environmental performance, responsible behavior promotion, reward and sanction implementation, and awareness of construction equipment's environmental impact.	Innovating for efficient, eco-friendly construction, optimizing design, monitoring environmental impacts, promoting tree planting, and fostering sustainability through visual management and a rewards system.

3.4.9. Accidents

The construction sector has a threefold higher accident rate than other sectors. This condition calls for viewing workplace safety as part of an investment, not just a cost burden. Accidents not only cause financial losses but also hinder work [22]. Table 10 presents the practical contributions of Lean Construction principles to minimizing accidents on construction sites.

Table 10. Practical contributions of Lean Construction in minimizing work accidents

Primary Pillars	**Practical Contributions**	
	Green Construction Site Index	**Public Works and Housing Minister Regulation No. 21 of 2021**
Systems Management	-	Having an up-to-date and applicable Health, Safety, and Environment (HSE) Plan, Standard Operating Procedures (SOP) for handling infectious disease outbreaks (e.g., COVID-19), and an emergency plan.
Technology Management	The control and mitigation of water pollution, air pollution, and noise pollution to reduce their environmental impact and improve sustainability.	The project initiation document should include structured performance evaluation, safety measures, dewatering systems, permits, and compliance with worker facilities and safety standards.
Culture and Behavior	-	-

3.5. Discussion

Based on the identification of factors and mitigation efforts in [23], this study strengthens the argument that integrating lean (efficiency and waste reduction) and green (environmental sustainability) principles can deliver measurable sustainability benefits for construction projects. The comparative analysis demonstrates how existing regulatory and assessment frameworks adopt lean construction concepts and highlights which dimensions of construction waste management require further development across the nine waste categories. Fig. 4 shows the final result of the comparative analysis and clustering, as a conceptual model of the strategic integration of lean construction and green construction concepts, developed through a three-dimensional approach: system management, culture and behavior, and technology management.

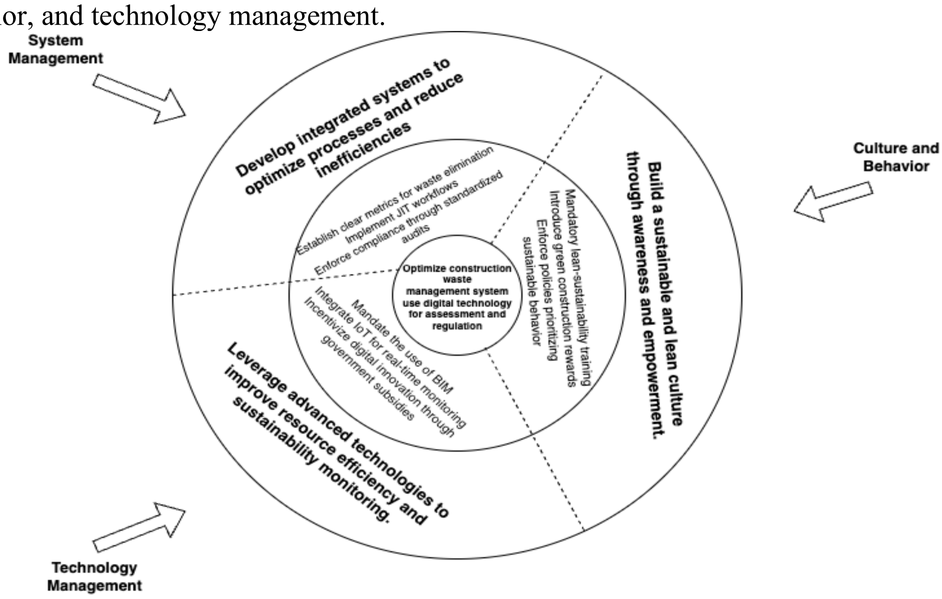

Figure 4. Result and Direction for Improvement

The inclusion of Exploratory Factor Analysis (EFA) provides empirical validation of the proposed three-pillar conceptual model. The factor extraction results confirm a robust three-factor structure, which collectively explains 80.1% of the total variance in the indicator dataset. This statistical outcome supports the theoretical alignment between regulatory and assessment parameters and the Lean Construction pillars of Systems Management, Technology Management, and Culture and Behavior. Indicators with high factor loadings (>0.60) show strong conceptual coherence within each pillar, while cross-loading items reveal areas where regulatory provisions simultaneously address multiple dimensions of lean and green performance. Fig. 4 presents the outcome of the comparative analysis and factor-based clustering, visualized as a strategic integration model developed through the three-dimensional approach. The validated factor structure provides a quantitative basis for prioritizing regulatory and managerial interventions rather than relying solely on descriptive mapping.

The EFA results identify Systems Management as the dominant factor, accounting for the largest proportion of explained variance. This finding indicates that regulatory and assessment tools place stronger emphasis on process integration, workflow optimization, and performance monitoring than on behavioral or technological enablers. High-loading indicators within this factor are associated with waste elimination metrics, standardized operational procedures, and just-in-time coordination mechanisms.

In practice, this is reflected in the pre-production and planning stages, where lean strategies such as just-in-time material delivery and standardized scheduling are used to minimize inventory-related waste and waiting time. The integration of digital fabrication techniques, such as 3D printing, further reinforces this pillar by reducing process complexity and eliminating time-intensive activities such as formwork design [2]. The empirical dominance of this factor suggests that regulatory frameworks currently favor systemic efficiency as the primary pathway for achieving green construction outcomes. The second factor extracted through EFA corresponds to the Culture and Behaviour pillar, highlighting the role of human and organizational dynamics in achieving lean–green integration. Indicators with strong loadings in this factor relate to training, stakeholder awareness, and institutional incentives for sustainable practices. This result empirically supports the argument that cultural readiness and workforce engagement are critical enablers of effective waste reduction and sustainability performance. The presence of moderate cross-loadings between this factor and Systems Management further suggests that procedural improvements alone are insufficient without parallel investments in behavioral change and organizational learning. Mandatory training programs, recognition schemes, and internal sustainability policies emerge as key mechanisms for strengthening this pillar and ensuring long-term adoption of lean and green practices.

The third factor aligns with Technology Management, emphasizing the role of digital and automation-based tools in enhancing resource efficiency and real-time performance monitoring. High-loading indicators in this factor are associated with Building Information Modeling (BIM), digital tracking systems, and data-driven control mechanisms [24]. Consistent with previous studies, the integration of BIM with lean methods has been shown to improve cost, time, and quality performance by enabling more accurate planning, coordination, and waste visualization [25]. The EFA results indicate that while technology plays a significant enabling role, it remains secondary to systemic and cultural dimensions in the current regulatory and assessment landscape. This imbalance suggests a gap in technological readiness and digital infrastructure, which may constrain the full potential of lean–green integration in practice.

The factor-based analysis reveals meaningful interdependencies among the three pillars. Cross-loading indicators related to monitoring, reporting, and compliance suggest that digital technologies can serve as a bridge between systemic control and behavioral enforcement. This finding supports the concept of continuous or incremental innovation, where real-time data and flow mapping enable ongoing process improvement and progressive reductions in resource use and environmental impact [[26,27]. Despite these synergies, several challenges persist. The limited technological emphasis in the factor structure points to barriers in infrastructure availability, data integration, and technical capacity within the construction industry. In parallel, resistance to cultural change remains a critical obstacle, particularly in conventional project delivery environments that prioritize short-term cost and schedule performance over long-term sustainability outcomes. The EFA-supported model also reinforces the close relationship between lean implementation and energy and emissions management. Prior research demonstrates that lean practices can systematically identify forms of energy waste, including underutilization, dispersion, and inefficient consumption patterns, thereby contributing to both cost savings and emissions reduction [28]. The validated factor structure indicates that such benefits are most likely to be realized when systemic process controls are complemented by digital monitoring tools and reinforced through organizational commitment and training.

4. Conclusion

This research shows that integrating lean and green construction principles can deliver sustainable benefits for construction project implementation. Through a comparative analysis of relevant regulations and assessment tools, it was found that the concept of waste management based on 9 waste categories is increasingly being adopted in construction practice. The analysis resulted in a conceptual model based on three Primary Pillars, namely Systems Management, Technology Management, Culture and Behavior, that synergistically aim to optimize the construction process to be more efficient and environmentally friendly. In the Systems Management Primary Pillar, efficiency is achieved through strategies such as just-in-time and standardized audits. Meanwhile, using technologies such as BIM and 3D printing within the Technology Management Primary Pillar has been proven to improve project performance. Meanwhile, the Culture and Behavior Primary Pillar emphasizes the importance of training, rewards, and policies that encourage sustainable behavior. However, the main challenges of this integration lie in harmonizing implementation standards, overcoming cultural resistance in the conventional construction industry, and ensuring technological infrastructure readiness.

Declaration of AI and AI assisted technologies in the writing process

During the preparation of this work the author(s) used Grammarly in order to improve and clarify of the sentences. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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.

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