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LEAN PRINCIPLES FOR DETERMINING GENERATIVE DESIGN BENEFITS

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ABSTRACT

Studies on generative design have increased over the past decade, particularly for enhancing design processes in AEC industry projects. While generative design has shown potential benefits across various applications, its role in value generation remains unclear. This paper seeks to better understand the advantages of generative design through the lens of Lean principles and practices. A literature review and content analysis were conducted to map the different uses of generative design and their associated Lean principles. The review identified ten distinct uses of generative design, which were linked to nine Lean practices categorized under three Lean principles: value generation, flow improvement, and waste reduction. The results show that generative design is a versatile, interdisciplinary tool, applicable across planning, design, and construction phases. By aligning generative design with Lean principles, this study highlights its substantial contributions to improving flow, generating value, and reducing waste in construction projects. However, the findings also reveal a lack of integration across systems and processes, with applications often focused on isolated project stages or disciplines. This fragmentation suggests a tendency toward local optimization, highlighting the need for future research on system-wide integration to fully align generative design with Lean principles.

KEYWORDS

Generative Design, Generative Design benefits, Generative Design uses, Lean Principles, Lean Practices, Lean Design.

INTRODUCTION

Construction 4.0 promises to revolutionize planning, design, construction, and operations through advanced digital technologies. Among these innovations, generative design is emerging as a key tool, offering significant capabilities to optimize and automate different aspects of the design process, thereby improving efficiency and sustainability in construction projects.

Generative design refers to a design process supported by generative algorithms, allowing designers to generate multiple design alternatives under specified parameters and constraints (McKnight, 2017). Researchers have uncovered several implementation opportunities. For example, through generative algorithms, authors have been able to create several design alternatives to optimize systems, buildings' sustainable performance, and construction processes (Kralj & Skejić, 2021; Lee et al., 2023; Pestana et al., 2024; Wang et al., 2024; Zhou & Xue, 2023). However, despite numerous studies presenting different applications of

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generative design, the mechanisms in which generative design supports the generation of value in construction projects have not been comprehensively investigated.

Lean philosophy focuses on delivering perfect value to the customer by continuously improving processes and eliminating waste, thereby enhancing overall project performance (Peruki et al., 2012). This study examines the relationship between generative design and lean principles, aiming to identify synergies and highlight areas where future generative design applications can focus to maximize project value generation.

To this end, this paper presents a systematic literature review of select research papers implementing different generative design applications and linking them to lean principles through content analysis. The article is divided into four main sections. First, the points of departure and methodology is presented. Next, the study's results are presented and discussed. Finally, the conclusions summarize the key findings and propose directions for future research.

POINTS OF DEPARTURE

GENERATIVE DESIGN IN THE CONSTRUCTION INDUSTRY

In the early 21st century, the first studies on generative design applied to the Architecture, Engineering, and Construction (AEC) industry emerged, promoting an increase in research on this tool to improve the design process for specific implementations (Chew et al., 2024). In this context, generative design has been investigated for design and process optimization for a variety of systems, including architecture (Lee et al., 2023), structural (Feng et al., 2023; Kralj & Skejić, 2021), and mechanical, electrical and plumbing (Pestana et al., 2024); sustainability, comprising passive energy savings (Zhou & Xue, 2023) and thermal comfort (Peng et al., 2023); and construction, involving scheduling (Nagatoishi & Fruchter, 2023), construction 3D printing (Garcia-Alvarado et al., 2024), offsite construction (Gan, 2022), and site layout (Jiang et al., 2024).

Given its diverse applications, the generative design framework is often adapted in each implementation to align with the specific goals of the study. Nonetheless, the framework can be broadly summarized in four steps: defining goals and parameters, creating design alternatives with the assistance of algorithms, assessing chosen alternatives, and selecting the final option based on alignment with design goals (McKnight, 2017). This methodology allows the design generation process to efficiently explore the design space, reducing both the time and effort involved in developing and evaluating design alternatives.

Generative design offers several benefits, including exploring the design space, reducing production time and costs, and optimizing both designs and processes (Singh & Gu, 2012). Depending on the implementation goal, generative design can provide more advantages for processes and final products. These benefits align closely with Lean principles and practices.

LEAN PRINCIPLES IN GENERATIVE DESIGN

Lean construction is a multifaceted philosophy comprising guiding principles, practices, and tools (Pekuri et al., 2012). At its core are the guiding principles, which focus on value generation, improving flow, and minimizing waste (Cifone et al., 2021; Herrera et al., 2019). These principles are realized through lean practices—specific techniques and activities designed to operationalize the principles and enhance project performance (Cifone et al., 2021).

In the context of generative design, specific Lean practices serve as effective tools for achieving lean principles effectively. For instance, the principle of flow improvement is supported by practices like BIM, reducing variability, standardization, simplification, and simulation. The principle of value generation is achieved through practices such as focusing on concept selection, ensuring comprehensive requirements capture, and deciding by consensus.

Lastly, waste minimization is addressed through strategies targeting specific types of waste, such as motion, overproduction, and transportation.

The framework selected was grounded in Lean principles and practices specifically related to generative design. Unlike general Lean frameworks, this one was developed to directly map generative design applications to Lean principles, ensuring a focused and relevant approach. Table 1 presents the framework that categorizes nine Lean practices identified in this study under the three guiding Lean principles: value generation, flow improvement, and waste minimization.

Table 1: Lean Principles and Practices framework for Generative Design.

Lean Principle	Lean Practice	Definition
Improving Flow	BIM	3D models for managing and visualizing the physical and functional characteristics of a building throughout its lifecycle.
	Reduce Variability	Variability reduction can be divided into two parts: the reduction of temporal variability and the reduction of flow variability (Sacks et al., 2010).
	Standardization	Work standardization accomplishes a variety of goals. Continuous improvement is made possible by reducing the variability of both product features and time (Sacks et al., 2010).
	Simplify	Minimize non-value-adding tasks and reorganize steps' value-adding components (González et al., 2022).
	Simulation	Simulation of project performance regarding an evaluation variable, such as cost or sustainability.
Value Generation	Focus on Concept Selection	Concept design and detailed design are distinct stages. While there is a tendency to hastily transition to detailed design, dedicating time to developing and evaluating multiple concepts ensures a robust project foundation. (Sacks et al., 2010).
	Ensure Comprehensive Requirements Capture	Comprehensive requirements capture allows value generation by ensuring client requirements are met. (Sacks et al., 2010).
	Decide by Consensus	A larger knowledge basis for the decisions can be guaranteed by expanding the group of decision makers, and the probability of discovering the practically optimal solution increases with the number of possibilities put into examination (Sacks et al., 2010).
Waste Reduction	Motion	Reduce the share of non-value-adding activities, related to unnecessary movement of personnel and equipment (Herrera et al., 2019).
	Transportation	Reduce the share of non-value adding activities related to excessive costs and efforts related to material transportation (Herrera et al., 2019).

RESEARCH METHOD

DATA COLLECTION

The objective of the literature review is to explore the relationship between generative design applications in the AEC sector and Lean principles, identifying how these concepts contribute to value generation in construction projects. To identify relevant generative design literature, the data collection process began with defining queries in the Web of Science (WOS) database. Boolean operators and generative design-related keywords were combined to refine the search, focusing on the main uses of generative design across different stages of the project life cycle. Keywords such as "generative," "design," "construction," "modular," "planning," and "prefabrication" were searched in titles, paper keywords, and abstracts. Accordingly, the following query was applied in WOS: TS=((generative) AND (design OR construction OR modular OR planning OR prefabrication)). In addition, the search was limited to research articles written in English categorized under the civil engineering WOS category. From the WOS search, an initial sample was selected. Subsequently, a screening process was carried out to eliminate articles that were not related to the study's aim. This step included analyzing the abstracts and keywords of each article to determine whether the content fits the study's goals. Articles without keywords were also removed from the sample. As the final step, a full-text reading of the selected articles was performed to corroborate their relevance.

As a result of the information collection process, a preliminary sample of 377 articles was obtained, and 50 were selected by title screening. After screening abstracts and keywords, the sample was reduced to 38 articles. A final full-text review led to the removal of 4 more articles. Figure 1 illustrates the study methodology, showing the sample size changes at each stage of the process.

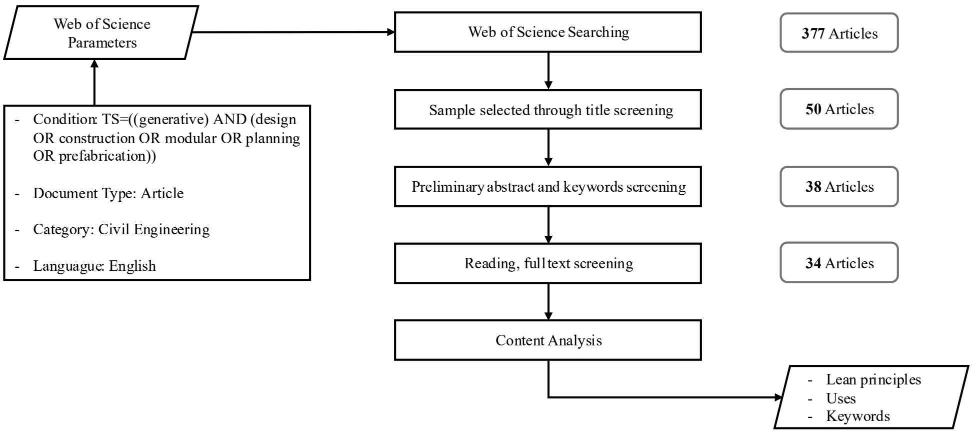

Figure 1: Research method workflow.

CONTENT ANALYSIS

The content analysis aimed to identify the uses of generative design, along with the Lean principles and practices, in each study. Ten distinct generative design uses were found: Architectural Design, Construction Equipment, Construction Planning and Management, Construction Sites, MEP Design, Modular Building Design and Planning, Performance and Sustainability, Prefabricated Construction Design and Planning, Structural Design, 3D-Printed Houses. These uses span the planning, design, and construction phases.

Additionally, nine Lean practices were identified: BIM, Decide by Consensus, Ensure Comprehensive Requirement Capture, Focus on Concept Selection, Reduce Variability, Reducing Wastes: Motion, Simplify, Standardization, and Simulation. Each practice aligns with one of the following Lean principles: flow improvement, value generation, and waste reduction. The Lean Principles and practices are shown in Table 1 along with their definitions.

RESULTS

The generative design uses and Lean principles found in each of the 34 articles were determined based on the content analysis and are summarized in Table 2. The distribution of uses across the articles reveals that Performance and Sustainability is the most frequent application in generative design, with seven articles (7). Other notable uses include Modular Building Design and Planning (6 articles), Architectural Design (5 articles), and Construction Sites, Structural Design, and Construction Planning and Management, each appearing in three articles (3). Meanwhile, several uses, such as Prefabricated Construction Design and Planning, MEP Design, and 3D-Printed Houses, are mentioned in only one article (1).

Table 2: Generative design uses results: Design Stage

Project Phase	Use	Reference
Design	3D-Printed Houses	T1 – (Garcia-Alvarado et al. 2024)
Design	Architectural Design	T2 – (Abrishami et al. 2021), T3 – (Lee et al. 2023), T4 – (Sydora & Stroulia 2020), T5 – (Tanasra et al. 2023), T6 – (Tang et al. 2019)
Design	Construction Equipment	T7 – (Wang et al. 2024), T8 – (Xia et al. 2024)
Design	MEP Design	T9 – (Pestana et al. 2024)
Design	Modular Building Design and Planning	T10 – (Gan 2022), T11 – (Ghannad & Lee 2022), T12 – (Liu et al. 2024), T13 – (Pibal et al. 2024), T14 – (Sheijani et al. 2024), T15 – (Zheng et al. 2024)
Design	Performance and Sustainability	T16 – (Banihashemi et al. 2018), T17 – (Gan 2022), T18 – (Hassan et al. 2024), T19 – (Peng et al. 2023), T20 – (Zhang et al. 2021), T21 – (Zhang et al. 2023), T22 – (Zhou & Xue 2023)
Design	Structural Design	T23 – (Feng et al. 2023), T24 – (Kralj & Skejic 2021), T25 – (Wang et al. 2023)
Planning	Construction Planning and Management	T26 – (Caneparo 2022), T27 – (Gordon et al. 2008), T28 – (Nagatoishi & Fruchter 2023)
Planning	Construction Sites	T29 – (Jiang et al. 2024), T30 – (Salah et al. 2024), T31 – (Tran et al. 2022), T32 – (Wefki et al. 2024)
Planning	Prefabricated Construction Design and Planning	T33 – (Li et al. 2024)
Construction	Construction Equipment	T34 – (Wang et al. 2024)

The Lean practices identified in the articles were distributed across three Lean Principles: Improving Flow, Value Generation, and Reducing Waste. The most frequently mentioned practices in the Improving Flow category include Standardization (19 articles), BIM (16 articles), and Reduce Variability (15 articles). Other notable practices include Simulation (9 articles) and Simplify (4 articles). In the Value Generation category, Focus on Concept Selection appears in 26 articles, followed by Ensure Comprehensive Requirement Capture (11 articles) and Decide by Consensus (10 articles). Lastly, under the Reducing Waste principle, Motion reduction was identified in 3 articles, while Transportation optimization was mentioned in 1 article. The Lean principles identified in each article are summarized in Table 3, where a checkmark indicates the presence of a Lean practice in a given article. For instance, article T1 includes the practices of BIM and Focus on Concept Selection.

Table 3: Lean Principles and Practices by Article.

ID	Flow Improvement					Value Generation			Waste Reduction	
	BIM	Reduce Variability	Simulation	Simplify	Standardization	Decide by Consensus	Ensure Comprehensive Requirement Capture	Focus on Concept Selection	Transportation	Motion
T1	✓							✓		
T2	✓	✓			✓	✓				
T3	✓				✓	✓		✓		
T4	✓	✓				✓		✓		
T5					✓	✓				
T6		✓								
T7	✓	✓	✓					✓		
T8					✓			✓		
T9	✓				✓		✓	✓		
T10	✓	✓			✓					
T11		✓			✓			✓		
T12					✓		✓	✓		
T13	✓						✓			
T14		✓						✓		
T15		✓			✓			✓		
T16					✓			✓		
T17	✓	✓	✓		✓	✓	✓	✓		
T18			✓	✓	✓	✓		✓		
T19			✓		✓			✓		
T20	✓		✓	✓		✓		✓		
T21	✓		✓	✓	✓	✓		✓		
T22			✓	✓				✓		
T23		✓					✓	✓		
T24		✓	✓		✓	✓	✓			
T25							✓	✓		
T26						✓		✓		
T27		✓						✓		✓
T28	✓		✓		✓			✓		
T29							✓	✓		
T30	✓				✓		✓	✓		
T31	✓						✓	✓		
T32	✓	✓						✓	✓	✓
T33	✓	✓			✓		✓			
T34		✓			✓					✓
Total	16	15	9	4	19	10	11	26	1	3

DISCUSSION

GENERATIVE DESIGN USES ACROSS PROJECT STAGES

The analyzed implementations highlight the diverse applications of generative design within the AEC industry, spanning multiple stages of construction projects. In the planning stage, generative design is primarily applied to site layout and construction planning. During the design stage, its most notable applications focus on building system design, including architectural, structural, and MEP systems, as well as performance and sustainability and modular construction. In the construction stage, fewer applications are evident, only related to equipment operation on construction sites.

Generative design proves to be a comprehensive tool that allows addressing different industry challenges; however, the results indicate that this tool lacks integration of systems and processes. Although generative design is present at different stages of the project, the main focus of this tool lies in the design stage, and its solutions are not transferred between stages. Similarly, applications within the same stage address problems separately and without connection. For example, academics have researched architectural, structural, and MEP design in isolation, also separated from the planning and construction process that could be supported by the use of such algorithms. This compartmentalized use reflects a tendency toward local optimization, which contradicts Lean principles that emphasize system-wide efficiency.

This also opposes the Lean principle of value generation and waste reduction, as the fragmentation of systems and processes caused by particular applications can lead to a misalignment with value generation in the project (Fischer et al., 2017); In Lean thinking, focusing on isolated project phases without considering their impact on the overall system can lead to inefficiencies, waste, and missed opportunities for value generation (Thangarajoo & Smith, 2015)

LEAN PRACTICES AND PRINCIPLES IN GENERATIVE DESIGN APPLICATIONS

For each implementation, various benefits associated with by Lean practices were identified and mapped to Lean principles. A Sankey diagram in Figure 2 illustrates the relationship between the uses and the Lean principles. The size of each node reflects its significance, with larger nodes representing a higher number of related Lean principles. For instance, 'performance and sustainability' is the largest node in the category of uses, indicating that it is the application with the most Lean practices associated. This also applies to the design node in the project phases, the 'focus on concept selection' practice, and the 'improving flow' principle. These nodes have the highest number of Lean practices implemented through the sample reviewed. Additionally, the link illustrates whether two nodes are related, and the size of the link reflects the number of practices connecting them.

According to the Lean principles, the results analysis is divided into three sections: improving flow, value generation, and reducing waste.

Flow Improvement

A total of 55.3% of the flows identified in the sample articles were related to flow improvement. Standardization, BIM, reduce variability, simulation, and simplify comprised this category with 16.7%, 14.0%, 13,2%, 8.0%, and 3,5% of the total flows, respectively. The weights of each practice reflect their relevance and are directly related to the implementation purposes, with standardization and BIM being the most considered practices by the authors for flow improvement.

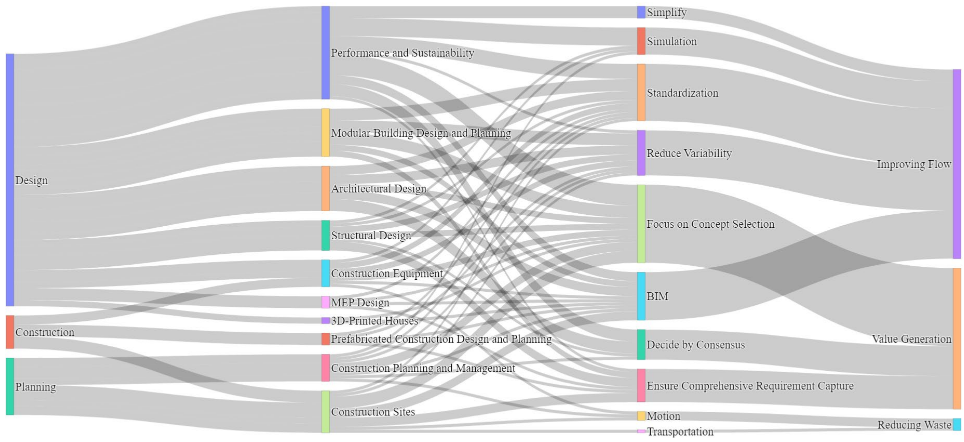

Figure 2: Project Stages, Uses, Lean Practices, and Lean Principles relations.

This demonstrates that generative design is not only effective in generating alternatives but also provides tangible benefits for flow improvement, aligned with Lean principles. One key area of focus for generative design implementations was the standardization of work processes, where several studies defined frameworks for replicating implementations. Additionally, generative design shows significant synergy with BIM. In cases where both were used together, BIM served as a parametric tool to support the generation of alternatives, as well as a source of information and visualization for evaluating those alternatives. The use of algorithms to reduce variability in design times is also a key takeaway, particularly in the design stage, though this effect extended to planning and construction phases as well, as shown in Figure 2. Generative design is also linked to the development of simulations, enabling the evaluation of alternative designs based on specific performance and behavior criteria. Finally, studies highlighted that in conceptual or early design stages, generative design algorithms helped simplify the number of steps required, optimizing the overall design process.

Value Generation

The principles of value generation accounted for 41.2% of the 114 identified principles. The principles classified in this category were ensure comprehensive requirement capture, focus on concept selection, and decide by consensus, representing 9.7%, 23.0%, and 8.8% of all principles, respectively.

Value generation is one of the primary objectives of generative design, where an initial goal is defined to guide the design generation process. The studies confirmed this purpose, highlighting focus on concept selection as one of the main advantages of this tool. This literature review supports the intention of implementing generative design to explore the design space by generating multiple alternatives that can be evaluated and compared to the design objectives. For this reason, this principle is present in planning, design, and construction processes.

It is also evident that this tool facilitates capturing requirements to generate project value, where the definition of parameters and optimization variables represents this information. Finally, it can be affirmed that generative design is a decision-support tool. While some implementations aim for the algorithm to produce the optimal or best performing alternative, other authors focus on selecting a set of alternatives, enabling decision-making while considering the trade-offs of each option. Figure 2 illustrates how this principle was mainly present in design processes.

Despite various applications contributing to value generation, the number of uses and their scope reveal a lack of integration between implementations. Although each process's value is being maximized separately, the integration of all applications may not be aligned with the client's and the project's objectives.

Waste Reduction

The reduction of waste accounts for less than 4.0% of the Lean principles identified in this study. Motion reduction was primarily observed in applications aimed at minimizing unnecessary personnel movement on-site, optimizing tower crane operating routes, and planning support for on-site construction inspection. Similarly, transportation optimization was identified in efforts to reduce material transportation costs, ensuring more efficient logistics and minimizing waste associated with excessive movement of resources. Despite the low weight of this category, generative design contributes to the prevention of overproduction by exploring the design space and evaluating multiple alternatives. Although overproduction mitigation was not explicitly included as a principle in this study, it is considered implicitly covered under the principle of focus on concept selection. By generating and assessing a wide range of design alternatives, generative design helps avoid unnecessary iterations and excess work, ensuring that only the most viable concepts are pursued, thus reducing the potential for overproduction.

CONCLUSIONS

This study systematically examined how generative design aligns with Lean principles, identifying both its potential and limitations within the AEC industry. Through a systematic literature review and content analysis, the research mapped ten generative design applications to three Lean principles: flow improvement, value generation, and waste reduction. The findings highlight generative design as a versatile tool that enhances design efficiency, optimizes decision-making, and reduces inefficiencies in construction projects.

Generative design enhances flow by promoting standardization, reducing variability, and simplifying workflows. In terms of waste reduction, it minimizes unnecessary movement and optimizes logistics, particularly in site layout planning and equipment operations. Moreover, its integration with BIM and simulations strengthens requirement capture and structured decision-making, ensuring alignment between design solutions, project objectives, and stakeholder needs.

Despite these benefits, a critical challenge identified is the fragmented application of generative design across project phases and disciplines. While effective in isolated instances, its disconnected use contradicts Lean’s emphasis on system-wide optimization. This fragmentation leads to inefficiencies, misalignment between stakeholder-defined value and project objectives, and missed opportunities to enhance constructability, operability, and sustainability. Without a structured integration framework, generative design risks being underutilized as a tool for holistic value generation.

This paper advances the emerging field of generative design by analyzing its primary applications and their alignment with Lean construction principles. It enhances understanding of how generative design supports value generation while identifying critical gaps that limit its impact on project efficiency and integration.

Future research should prioritize the development of integration frameworks that enable generative design to function as a cross-disciplinary tool rather than a phase-specific optimization method. Empirical studies are needed to validate its impact on project outcomes, particularly in aligning Lean principles with real-world construction processes. Additionally, expanding research beyond Web of Science sources and incorporating case studies will provide a more comprehensive understanding of its practical applications and limitations. By adopting a holistic approach, generative design can move beyond isolated improvements to optimize the entire project lifecycle, reinforcing its role as a key enabler of Lean construction.

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