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Generative Design as A Decarbonization Strategy in Space Layout Planning of Modular and Off-site Construction: A Systematic Review on Early Design Stage Parameters

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ABSTRACT: Decarbonizing the construction industry has been a significant focus of researchers in recent years. Modular and off-site construction (MOC) has been implemented since to be a solution to this purpose. Embodied and operational emissions are connected to non-optimized space layout planning (SLP). However, three major problems have contributed to the non-optimized space layout planning: underutilization of floor area, inefficient connectivity, and under-optimized functional performance. These problems results in larger module sizes, poorly planned connections between modules and panels, underutilized spaces, and poor functional performance. Finally, it results in overuse of material, wastes and complicated transportation which are the primary causes of the emission. Generative Design (GD) has a potential to overcome the non-optimized space layout planning. There is a gap in identifying and categorizing the key parameters that can help the process of decarbonization through GD in MOC SLP. To address these problems, this study identifies the key parameters in early design stage decision-making that contribute to variables and constraints controlling MOC's floor area, connectivity, and functional performance. The systematic review used the Population Intervention Comparison Outcome (PICO) model and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) model as the method of the research. The analysis revealed several parameters influencing the early design stage decision-making which are key inputs for GD, such as design, cost, sustainability, time, constructability, and health and safety parameters. This study reveals the relationship between these parameters and non-optimized space layout planning to explore generative design's potential as a decarbonization strategy in MOC.

1. INTRODUCTION

The construction industry contributes significantly to global greenhouse gas (GHG) emissions, accounting for a substantial portion of CO_2 emissions through material production, transportation, and construction processes. Decarbonizing construction is vital for environmental reasons and presents economic and innovation opportunities. Reducing embodied carbon through material efficiency, life cycle optimization, and the adoption of circular economy principles can significantly lower the sector's carbon footprint (Iqbal et al. 2023; Karlsson et al. 2020).

Modular and Off-site construction (MOC), a less explored sector of the construction industry that encompasses modular approaches, offers similar benefits by minimizing on-site inefficiencies and streamlining logistics. By reducing rework, transportation emissions, and material wastage through factory

production, these methods address and reduce carbon emissions at key lifecycle stages, mainly A1–A5 of product and construction phases which are raw material extraction (A1), transportation to the manufacturer (A2), manufacturing process (A3), transportation to the construction site (A4) and installation activities on site (A5) (Achenbach, Wenker, and Rüter 2018; Paneru et al. 2024; Rahman and Han 2024a, 2024b; Rahman and Sobuz 2018).

Space Layout Planning (SLP) is a fundamental aspect of architectural design, involving the arrangement of spaces within a predefined boundary to fulfil functional, aesthetic, and regulatory requirements. Historically, SLP has been characterized by its complexity, stemming from balancing numerous interdependent criteria, including spatial efficiency, accessibility, and environmental considerations. Despite decades of research and technological advancements, the architectural community grapples with achieving automated, optimal solutions for space layout planning (Ching 2023).

Three primary issues associated with SLP, which are underutilized floor areas, inefficient connectivity, and suboptimal functional performance, significantly contribute to carbon emissions in the construction industry. Underutilized spaces waste resources and increase embodied carbon due to the unnecessary use of materials. Similarly, inefficient connectivity can lead to higher operational energy demands through increased circulation and reduced efficiency of mechanical systems. Finally, functional inefficiencies often necessitate costly retrofits or design modifications, further exacerbating the environmental footprint.

On the other hand, the construction industry is now moving towards the era of generative design and artificial intelligence. These design aspects are more likely to be mathematical and algorithmically computational. However, in the real world, SLP is not something that can be coded numerically to maximize efficiency. There are rational criteria, such as aesthetics, accessibility, the efficiency of circulation, the efficiency of the volume of usable space, and other factors (Benevolo 1977; Ching 2023; Neufert and Neufert 2012).

As the construction industry seeks to align with global decarbonization goals, addressing these inefficiencies at the design stage is paramount. Generative design leveraging computational algorithms to explore various design possibilities offers a promising avenue to integrate environmental, economic, and functional parameters early in the design process.

Despite the potential to decarbonize the construction industry by optimizing SLP in early design stages through GD, there are no current assessments on the specific parameters in MOC. This research aims to systematically review the available studies to discover critical parameters in MOC that influence the SLP and decarbonization using GD. Pointing out these parameters can lead to a successful understanding of the variables and constraints related to the process of SLP and having a clear knowledge before developing a generative design system for automatically generating floor plans and using it as a decarbonization strategy. The findings of this study will help future researchers gain valuable insight for future steps toward developing decarbonization strategies in SLP with the help of GD in the MOC industry.

2. METHODOLOGY

This methodology section aims to introduce the methods applied to achieve the objectives of this study. Figure 1 illustrates the methodology adopted in this research. The research methodology is divided into three parts, namely (i) constructing a good research question, (ii) conducting the literature review, and (iii) reporting the literature review. The Population Intervention Comparison Outcome (PICO) model was used to construct a good research question. The purpose of this model is to think about the study's target population, the intervention areas, the comparative factors and the final outcome and develop a research question for the search strategy. Secondly, to conduct the literature review, two methods were applied: conducting bibliographic mining using VOSviewer and doing critical study manually. The last stage of the methodology was to report the findings systematically, using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) model for global recognition among researchers. The literature review was conducted on available databases from SCOPUS and Google Scholar. Further development of

the reporting process was conducted using PRISMA. All three steps are separately described in the sections ahead.
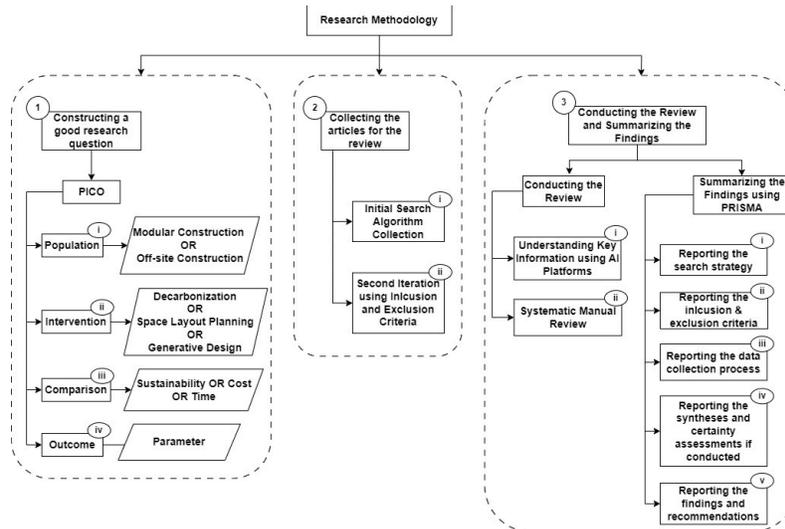

Figure 1: Research methodology.

2.1 Constructing a good research question

This section describes the procedure for developing the research question for this study. The PICO framework is a model that helps a researcher to systematically think about creating a good research question (Frandsen et al. 2020). The process is to structure a research question based on the population targeted, intervention areas of that population, comparative factors and the final output of the desired study. For this study, the population was MOC, and the intervention areas were decarbonization, SLP and generative design (GD). The search algorithm was as shown in Figure *1*. The study focused on exploring decarbonization parameters based on sustainability, cost, and time, which were the comparative factors. The outcome that the study was looking for is the parameters that influence the intervention sectors mentioned above. The search algorithm was filtered using publication year from 2004 to 2024.

2.2 Collecting the articles for the review

At the beginning articles were collected from SCOPUS using the above-mentioned search algorithm. The next step was to eliminate papers based on a manual study with the inclusion and exclusion criteria and with the help of keywords generated by VOSviewer version 1.6.20. The inclusion and exclusion criteria were connected to identifying papers trying to decarbonize MOC by optimizing design, cost, environmental and time parameter. In the process of inclusion and exclusion stage another two criteria were generated namely constructability and health and safety parameters.

Google Scholar was used for a second iteration of search after the initial 80 papers to look for specific studies from the references of already found articles. Afterwards, the papers were initially eliminated by manually studying the title and abstract. After elimination, a critical study was completed on the selected 30 papers that resulted from the elimination.

2.3 Conducting the review and summarizing the findings

The data collection process was solely manual. The selected studies were first understood using mass-available artificial intelligence (AI) applications like Chatgpt, and then the primary author critically reviewed them. Figure 2 describes the data collection and inclusion and exclusion stages in the literature review.

Figure 2: Inclusion-exclusion scenario.

After the data from the 30 papers selected through the inclusion and exclusion criteria were collected, they were systematically presented in this study following the PRISMA framework. The results of the findings are illustrated in section 3 of this study.

3. RESULTS

This section discusses the findings of this study, which are presented in the sub-sections below in a manner that follows the methodologies stated in the above sections.

3.1   Results of the initial search iteration using the PICO model

Figure 3 shows the findings of the bibliographic mining. It was conducted to identify keywords from the initial database after applying the first search algorithm.

Figure 3: Bibliographic mining using VOSviewer.

The search algorithm generated using the PICO model was "Modular Construction OR Off-site Construction AND Decarbonization OR Space Layout Planning OR Generative Design AND Sustainability OR Cost OR Time AND Parameter." The algorithm resulted in 80 papers and the above bibliographic mining results from those 80 papers. It illustrates that recent improvements in MOC SLP decarbonization strategies have focused on genetic algorithms, architectural designs, generative design, crane layout planning, structural design, and modularization using GD as a decarbonization strategy.

3.2   Results of manual literature review and reporting using PRISMA

This sub-section presents the findings of the critical review of the 30 papers selected from the PRISMA model outcome. The categories mentioned in the table derived during the critical study of the papers and divided in such a manner that readers can understand which parameters can be a direct input to GD in MOC SLP. The actual findings included objectives, methodologies, input, process, output, and future research direction. For example, Greer and Horvath (2023) tried to explore MOC's capacity to reduce embodied carbon in California's housing sector. Their identified problem statement included the increasing housing demand and construction sector's contribution to greenhouse gas (GHG) emission. The objective of that study was to quantify and compare embodied GHG emission of MOC versus conventional construction. The researchers conducted life cycle assessment (LCA) for life cycle phases A1-A5 and scaled it from building prototype to country level needs emphasizing factory proximity, material selection and delivery location. This study pointed out gaps in lack of data on material waste in on-site assembly, limited study in operational and end-of-life phases and uncertainty in upstream logistics and supply chain. The identified parameters from this study were module size, material, transportation, factory capacity and ease of fabrication. Due to length restrictions, only the key findings related to this research are presented in Table 1.

Table 1: Summary of the Findings

Paper Reference	Category	Main Objectives of the study	Parameters Identified
(Greer and Horvath 2023)	Decarbonization	Quantifying and comparing embodied GHG emission and identifying the factors.	Module size, material, transportation, factory capacity, ease of fabrication
(Klammer et al. 2021)	Decarbonization	Exploring the incremental cost to NZE achievement and GHG emission in MOC.	Material, material recyclability, location or climatic zone
(Paneru et al. 2024)	Decarbonization	Assess decarbonization strategies across the whole life cycle.	Material, material embodied carbon, material recyclability, degree of prefabrication, life span of building, location and climatic zone, energy source
(Almashaqbeh and El-Rayes 2021)	Design	Develop an optimization model to minimize modular construction cost through minimizing transportation and storage cost.	Type of module, size of module, functional zone, type of component, transportation
(Sharafi et al. 2017)	Design	Identifying a unified matrix method to optimize spatial design for minimizing cost and maximizing plan regularity.	Size of module, material, transportation
(Liu et al. 2021)	Design	Exploring a BIM-enabled generative design framework	Ease of manufacturing and assembly,

		that maximizes productivity and minimizes construction cost.	transportation, material, energy source
(V. J. L. Gan 2022)	Design	Creating a BIM-based generative design method for modular construction space layout planning using graph data model.	Module size, floor area, horizontal and vertical joints, horizontal and vertical circulation, location of the core, material
(V. J. Gan 2022)	Design	Developing a BIM-based generative design model with 3D geometric modeling to optimize carbon footprint and construction cost in MOC.	Material, transportation, compactness of shapes, building shapes
(Sheijani, Momenaei, and Hassanzade 2024)	Design	Developing an automated space layout planning for modular open-plan office using generative algorithm as per client preference.	Vertical circulation, horizontal circulation, location or climatic zone
(Lopez and Froese 2016)	Cost	Developing a framework to understand the implications and tradeoffs in cost factor for panelized and modular single family houses.	Insulation thickness, transportation, material
(Kamali and Hewage 2017)	Cost	Developing sustainability performance indicators for modular construction life cycle sustainability using environmental, economic and social aspects.	Material, material recyclability, energy source, transportation
(Bertram et al. 2019)	Cost	Exploring modular construction's potential in reducing time and cost.	Material, insulation thickness, transportation, building area, location, type of component, life span of building
(Abdul Nabi and El-adaway 2020)	Cost	Providing a framework as decision-making tool leveraging social network analysis in MOC.	Material recyclability, level of modularization, material, transportation
(Almashaqbeh and El-Rayes 2022)	Cost	Developing an optimization model to minimize transportation and storage cost in MOC leveraging mixed-integer programming.	Transportation, material, energy source
(Quale et al. 2012)	Environmental	Evaluating the potential of MOC compared to conventional one by conducting life cycle assessment (LCA).	Material, transportation, energy source, material recyclability
(Hammad et al. 2019)	Environmental	Developing a BIM-based framework to evaluate modular and conventional methods against sustainability.	Material embodied carbon, energy source, insulation thickness, material recyclability
(Aye et al. 2012)	Environmental	Evaluating life cycle performance of modular steel and timber buildings using hybrid energy analysis to assess material savings potential.	Material embodied carbon, material recyclability
(Tumminia et al. 2018)	Environmental	Evaluating energy performance of a modular building using LCA and dynamic building simulation.	Material embodied carbon, life span of building, material recyclability, climatic zone

(Pervez, Ali, and Petrillo 2021)	Environmental	Exploring a case study to two single family modular and conventional building using LCA to compare GHG emission.	Material, transportation, energy source
(Kamali and Hewage 2016)	Environmental	Literature review on previous studies conducting study on environmental performance of modular buildings.	Material embodied carbon, material, transportation, energy source, climatic region, building life span, material recyclability
(Boafo, Kim, and Kim 2016)	Environmental	Conduct a case-study based review on modular prefabrication architecture considering acoustic constraints, thermal behavior	Material, energy source, transportation, material embodied carbon
(Kamali, Hewage, and Sadiq 2019)	Environmental	Conduct a case-study on single family building using cradle to gate LCA to understand	Material, transportation, energy source, life span
(Alshamrani 2022)	Environmental	Evaluating environmental and economic impacts of offsite, onsite and conventional construction using LCA.	Material embodied carbon, material recyclability, energy source
(Shewchuk and Guo 2012)	Time	Exploration of lean approaches into panel stacking, panel sequencing and stack locating.	Ease of fabrication and assembly, transportation, size of panel, adaptability to lean construction
(Altaf et al. 2018)	Time	Developing an integrated production planning and control system using RFID and Simulation.	Factory capacity and resource allocation, ease of fabrication, adaptability to lean construction
(Ahn et al. 2022)	Time	Utilizing discrete event simulation (DES) to optimize logistics by synchronizing off-site and on-site works.	Transportation, factory capacity, ease of fabrication
(Bhatia, Han, and Moselhi 2022)	Time	Applying a simulation-based statistical method to optimize production planning and labor allocation.	Adaptability to lean construction, factory capacity, predictable lead time
(Wei, Lei, and Altaf 2024)	Time	Exploring push-based and pull-based approaches in MOC using DES and agent-based modeling (ABM).	Transportation, adaptability to lean construction, factory capacity
(Rahman and Han 2024a)	Time	Exploration of a hybrid scheduling method using linear scheduling and monte carlo simulation (MCS) to minimize time.	Adaptability to lean construction, factory capacity, panel size
(Sharafi et al. 2018)	Constructability and Health and Safety	Creating a decision-making framework for MOC focused on factors influencing level of modularization.	Lead time, weather condition, highly skilled workforce, ease of fabrication, exposure to accidents, damage during handling, laborer's safety

*This table summarizes the findings of the systematic study and provides a brief view of the parameters identified.

4. DISCUSSION

This section's objective is to present and discuss the findings in a structured manner. Based on the information collected from the targeted studies, a mind map was developed to report the study findings. Figure 4 illustrates the findings of this study as an integrated version of MOC, SLP, and decarbonization parameters.
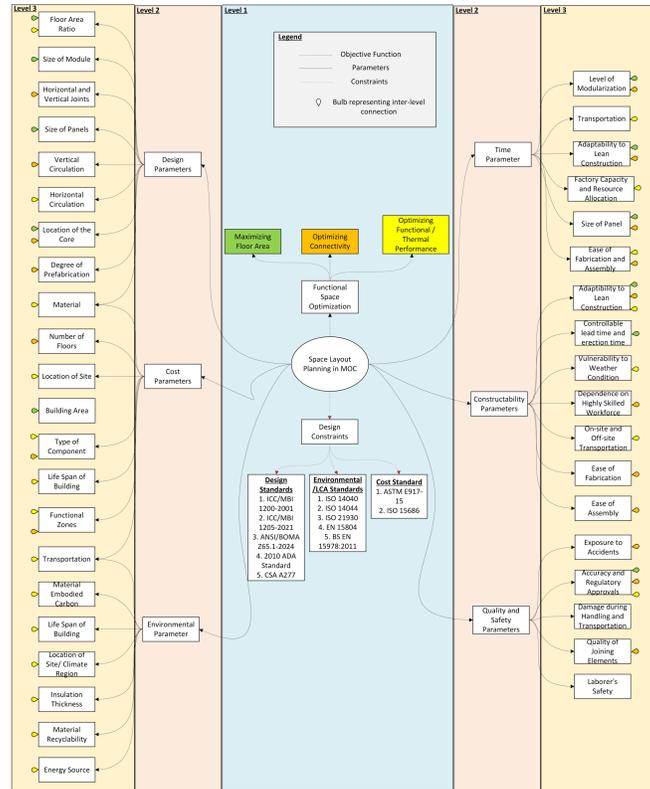

Figure 4: Mind map identifying the parameters influencing early design decisions of SLP which are inputs for GD as a decarbonization strategy.

The map has three levels, where Level 1 indicates the direct connections between decarbonization strategies and objective functions for optimization of SLP through GD in MOC. Level 2 is the significant parameter category. Level 3 presents the granular level of parameters. The inter-level connection of these parameters with objective functions is also demonstrated using color bulbs. For example, if a researcher wants to develop an early design stage decarbonization strategy focused on GD in SLP, and the objective function is to maximize floor area, the consideration must be focused on design, cost, time and constructability. As the map demonstrates, maximizing floor area may result in larger modules which need design approval, will increase building area, which will increase cost and has a role to play in level of modularization, which will affect time and constructability that affects lead time and erection time. So, only maximizing the floor area might result in an unoptimized condition in other sectors which may work as an isolated island. Rather the researcher must focus on multi-objective optimization. This map will be valuable for future researchers focusing on GD as a decarbonization strategy in MOC SLP to identify the exact parameters they need to control and dictate their models.

5. CONCLUSION

In MOC SLP, optimization is a multi-objective criterion. Implementing decarbonization strategies through GD approaches aligning with these multi-objectives is critical. At the same time, solving the problems associated with SLP, considering design, cost, time, and emission, would be another big challenge. The study presented has contributed to the body of knowledge in this sector by identifying the granular or dictating parameters for developing future decarbonization strategies using GD in this field. The determined

parameters, objective function, and constraints can pave concrete pathways for any researcher to develop multi-objective optimization frameworks and algorithms that will be the foundation for the decarbonization strategies and GD models. Future researchers can work on the results obtained from this study and direct their work toward an optimum solution based on higher-level client requirements. Furthermore, the findings of this study can be used as scalable inputs into other fields of construction, such as conventional construction methods. This approach lays the foundation for implementing multi-objective optimization models using GD focused on developing decarbonization strategies and goals.

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