

# IDENTIFICATION AND AUTOMATED EXTRACTION OF KEY PARAMETERS IN SPACE LAYOUT PLANNING FOR ENHANCED LIFE CYCLE ASSESSMENT OF MODULAR BUILDINGS

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**ABSTRACT:** In modular building, space layout planning (SLP) involves the strategic arrangement and dimensioning of modules to enhance space efficiency and functional performance. Since SLP has a major influence on reducing the environmental burden when influential attributes are being decided, integrating SLP with Life Cycle Assessment (LCA) is important for enhancing the sustainability of modular buildings. However, most LCA studies have primarily emphasized the construction and operation phases as key stages for impact reduction, often neglecting the design stage. Even when the design stage is considered, modular specifications are frequently neglected. To address this gap, this study aims to extract specific modular SLP factors that significantly influence the comparative LCA of potential SLP alternatives. This paper builds on identifying key SLP parameters affecting the comparative LCA of modular buildings. By identifying influential SLP parameters on comparative LCA, we refine the methodology to accurately capture these parameters in existing layouts, thereby enhancing the precision and applicability of LCAs in modular construction. The research methodology begins by filtering SLP parameters through defined criteria to reach the main list of factors that can be affecting comparative LCA. Based on these factors, a novel method is developed to effectively extract SLP parameters from the layout. The SLP is prepared to extract the identified factors by identifying, labeling, and/or numbering modular components in this method. This research develops a structured methodology for identifying and extracting key SLP parameters, improving LCA integration, and supporting sustainable modular design.

**Keywords:** Space Layout Planning (SLP), Modular and Off-site Construction (MOC), Life Cycle Assessment (LCA)

## 1. INTRODUCTION

The growing emphasis on sustainable construction practices has brought modular building design to the forefront of architectural innovation, primarily due to its potential to enhance environmental performance through efficient space layout planning (SLP) (Al-Najjar and Doodoo, 2023; Kim, 2008; Teng and Pan, 2020). Decisions made during the early design stages significantly influence a building's lifecycle environmental impacts. SLP is crucial in modular construction, where modules' strategic arrangement and dimensioning determine not only functional efficiency but also the overall environmental impact. As the construction industry seeks to reduce its carbon footprint and manufacturing efficiency, integrating SLP with life cycle assessment (LCA) becomes essential for evaluating and improving the sustainability of modular buildings (Sokhangoo et al., 2024).

LCA provides a comprehensive framework for assessing environmental impacts across all stages of a building's lifecycle, from material extraction to reuse (Environmental Management — Life Cycle Assessment — Requirements and Guidelines, 2006). Although LCA has been widely applied to evaluate traditional construction methods, its application to modular construction poses unique challenges. The distinctive modular specifications (e.g., fabrication and assembly process) and design parameters (e.g.,

module dimensions, module connections) necessitate a tailored LCA approach that accurately reflects the environmental performance of modular buildings.

Despite the recognized potential of modular construction, the current LCA literature often focuses on the construction (Campbell et al., 2020; Greer and Horvath, 2023; Tavares et al., 2019) and operational phases (Al-Najjar and Dodoo, 2023; Pons and Wadel, 2011), overlooking the critical design stage and the specific modular attributes that influence environmental outcomes. This oversight underscores a critical gap in understanding how modular SLP factors influence the LCA of modular construction, especially during the design phase when various alternatives are considered. Key decisions at this stage, particularly those affecting the layout's environmental impact, can significantly reduce the building's overall carbon footprint. This study aims to bridge this gap by identifying and extracting the specific modular SLP factors influencing comparative LCA and integrating the outcomes with LCA. This paper refines the methodology for identifying key space planning parameters. The research employs a novel approach to extracting these parameters from existing layouts, using automated processes integrated with Building Information Modeling (BIM) tools and custom scripts to enhance the precision and applicability of extracting required data from layout plans in modular construction. This method helps the designer and decision maker to summarize and shorten the process of assessing various layout alternatives in terms of environmental impact.

This study enhances the understanding of SLP's role in modular building sustainability by developing a structured methodology for identifying and extracting key parameters, enabling more accurate LCA integration. It contributes to sustainable architectural practices by providing insights to improve the environmental assessment of modular layout alternatives.

## **2. BACKGROUND**

The literature review on improving the LCA of modular buildings through SLP is divided into two main categories: The first category gathers the SLP parameters that influence carbon emissions, as identified in previous research (Almashaqbeh and El-Rayes, 2022; Al-Najjar and Dodoo, 2023; Cheng et al., 2022; Chippagiri et al., 2023; Salama et al., 2017; Shrestha, 2021; Teng et al., 2018; Tian and Spatari, 2022). The second category investigates the method used for extracting SLP factors from existing layouts.

### **2.1 Impact of Modular SLP Parameters on LCA**

Understanding the factors that affect embodied carbon emissions in modular buildings is essential for enhancing their potential for decarbonization. While numerous studies have been conducted, only a select few have examined the variations in carbon emission quantification or investigated the relationship between influencing factors and the resulting quantification (Cheng et al., 2022). Some research has focused explicitly on identifying factors that influence the LCA of off-site buildings. For example, Teng et al. (2018) pinpointed twelve variables impacting the carbon emissions of off-site construction, such as building lifespan, life cycle phases, geographic and climatic conditions, LCA methodology, research approach, functional unit, building type, height, material choice, and degree of prefabrication. These findings underscore the complexity and significance of considering a wide range of factors when designing and evaluating modular buildings to boost their decarbonization capabilities (Teng et al., 2018).

Construction materials account for about 86.3% of a building's global warming potential (GWP) (Spudys et al., 2024). Careful planning and the use of eco-friendly materials during the design phase can reduce overall CO<sub>2</sub> emissions by 13 to 15% (Jia Wen et al., 2015). Several studies explored the impact of various construction materials on carbon emissions, underscoring the importance of selecting environmentally sustainable materials to mitigate environmental impact during the installation phase (Chippagiri et al., 2023; Shrestha, 2021; Tian and Spatari, 2022). Building orientation, building types, and size of the building are other SLP-affecting parameters on carbon footprint that were investigated in the study by Spudys et al., 2024.

In modular construction, previous studies investigated the effect of the module's specifications on different life cycle aspects. Salama et al. (2017) examined the impact of module dimensions on the emissions related to the construction and transportation process (Salama et al., 2017). Other factors, such as the method of prefabrication (e.g., prefabricated component, panelized, volumetric), finishing level (e.g., semi-finished and finished), and source of energy related to the manufacturing process, were investigated in previous studies (Almashaqbeh and El-Rayes, 2022; Al-Najjar and Dodoo, 2023; Jellen and Memari, 2018).

Previous studies from various perspectives have identified scattered parameters that can effectively reduce the carbon footprint of different life cycle phases. However, these factors (SLP factors) that affect carbon footprint have not been systematically classified.

## **2.2 SLP of Modular Building: Data Extraction Methods and Techniques**

In the context of architectural design, extracting data from layout plans serves a crucial role in design reuse and decision-making processes for regenerating the layout for many purposes. The advent of digital technologies and methodologies has significantly transformed how architects and developers approach floor plan analysis. Qiu and Hancock, (2006), employed spectral embedding techniques that facilitate the matching and clustering of floor plans by breaking down graphs into non-overlapping neighborhoods. This method aids in organizing and analyzing spatial data, making it easier to efficiently retrieve similar layouts from repositories. For handling larger repositories Sharma et al., (2017), developed a deep learning framework known as DANIEL (Deep Architecture for fiNdIng alikE Layouts), utilizing Convolutional Neural Networks (CNNs) to examine floor plan images and extracting both low-level and high-level semantic features for data extraction from SLPs.

Another approach to extracting data from layouts involves processing images based on their features. This includes techniques like Histogram of Oriented Gradients (HOG) by Dalal and Triggs (2005), Bag of Features (BOF) by Lazebnik et al. (2006), and Local Binary Pattern (LBP) by Ahonen et al. (2006). These methods are designed to identify and compare images by analyzing specific features, simplifying the task of retrieving similar images from extensive databases (Ahonen et al., 2006; Dalal and Triggs, 2005; Lazebnik et al., 2006). Zhi et al., (2003) transformed the unit extraction process into a graph problem and solved it using graph theory. This study used a graph-based algorithm to extract units and loops from the layout plan and automate the building fire evacuation model. For retargeting existing designs, studies break down the layout and extract the information. For example, (Lin et al., 2011), used axis-aligned extracted from the architectural plan to regenerate plausible variations by resizing and reshaping the extracted boxes. All the previous studies applied their method on the conventional building to extract any related layout plan component (e.g., spaces) for various purposes such as regenerating, reshaping, and creating a database. While previous studies have focused on conventional buildings, there is a significant gap in the literature regarding the detection of modular building components (e.g., modules) and their specifications (e.g., connections), which differ from the approaches used in conventional buildings. However, based on the review of existing methodologies for extracting data from architectural layout plans, a significant insight emerges: the integration of graph-based algorithms and axis-aligned box extraction offers a foundation for addressing the unique challenges posed by modular building components. The selected method in this research combines these two approaches, adapting them to meet the specific requirements of modular specifications. Further details on the implementation and adaptation of these methods will be discussed in the next section (Section 3).

## **2.3 Research Gaps and Opportunities**

Despite the increasing emphasis on sustainable modular construction, a significant gap persists in the literature concerning the integration of SLP with Life LCA during the design stage. The research gaps could be:

1. **Design Stage Neglect:** Most LCA studies in modular construction emphasize the construction and operation phases, often neglecting the critical design stage where key environmental decisions are made.
2. **Overlooked Modular Specifications:** Even when the design stage is considered, specific modular attributes that influence environmental outcomes, such as fabrication and assembly processes, are frequently overlooked.
3. **Scattered Parameters:** Previous identified SLP factors affecting carbon emissions have not been systematically classified. The systematic classification of modular SLP parameters allows designers to distinguish between parameters that are changeable and those that remain constant across alternatives in different life cycle phases. Moreover, the classification supports the development of an automated method for data extraction, streamlining the integration of these parameters into comparative LCA models. In section 3.1, the systematic identification of the SLP factors' impact on carbon footprint is discussed.

4. Data Extraction Methods: While methods for extracting data from conventional building layouts exist, there is a significant gap in methodologies specifically tailored for modular buildings, which require different approaches due to their unique specifications and connections.

### 3. METHODOLOGY

In residential modular buildings, different spaces and elements to be used in comparative LCA are required to be identified and extracted, such as modules, elements surrounding each module (e.g., exterior walls or equivalent elements like mate walls), and interior walls that separate each module into different functional spaces. Moreover, some modular building specifications needed to be identified and extracted, such as vertical and horizontal connections between modules or inter-module connections, which could have a tremendous impact on the LCA. Such information can be significant input data for a comparative LCA model. However, all this information does not exist in CAD or any other plan layout files.

To compare layout plan alternatives based on their environmental impact, this study employs a methodology that systematically identifies and extracts SLP parameters from existing layout plans for use in comparative LCA analysis. This involves developing a process that applies various criteria to identify, filter, and classify modular SLP parameters that significantly impact LCA outcomes. By preparing the layout

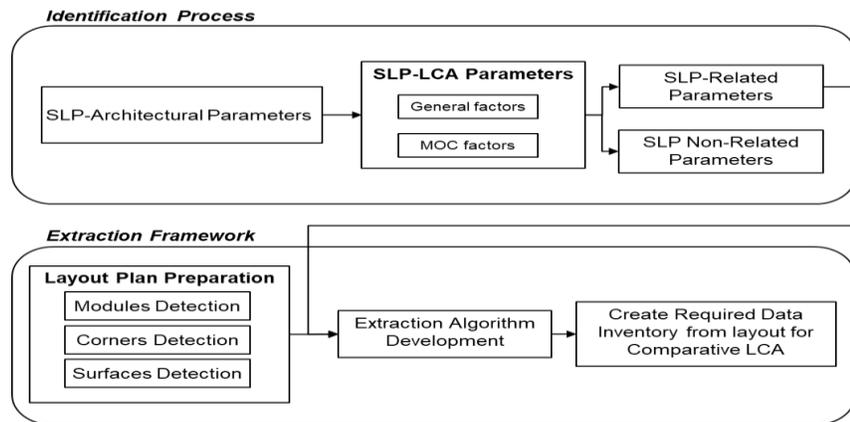


Figure 1: High-level Methodology

for data extraction through a novel method that leverages graph theory, the study transforms the module extraction process into a graph problem. This approach allows for the efficient identification and labeling of modular components and involves developing algorithms specifically designed to extract layout-related parameters. In other words, graph theory is employed to reverse-engineer the layout for module identification, providing a structured approach to detect and label modules. Once the modules are found using graph theory, the proposed algorithm (section 3.2.2) comes into play, focusing on detailed components like connections. The methodology outlined in this research is applied to existing or pre-designed modular building layout alternatives, implying that the algorithm is applied after the feasibility stage, when detailed design information is available. Consequently, the study establishes a comprehensive framework for obtaining the necessary data to assess the environmental impacts of different modular design alternatives. An overview of the high-level methodology is illustrated in Figure 1.

#### 3.1 MOC-SLP Parameters Identification: A Systematic Approach

Identifying the affecting modular SLP parameters on comparative LCA includes five main steps, including 1) identifying SLP parameters related to architectural considerations, 2) scrutinizing the LCA-related parameters, 3) filtration based on comparative LCA requirements, 4) classification based on the specification of the parameter, and 5) validation. The complete list of identified SLP factors from an architectural point of view affecting the LCA of modular buildings is shown in Table 1.

The initial step involved identifying SLP parameters and architectural considerations. This foundational work is guided by existing scientific reports and literature, and the design requirement manual (DTIR Document DC350, 2010). The SLP architectural considerations review includes but is not limited to the plan orientation, building boundary, function, material, and interior elements. This review also considers the user

requirement, which focuses on the occupants' needs and preferences, ensuring that the design is functional (first column, Table 1). Due to their variability and localized nature, a detailed examination of building codes and regulations falls outside the scope of this research.

In the next step, these parameters are scrutinized through a critical review of LCA scientific literature and ISO14040-14044 standards (Environmental Management — Life Cycle Assessment — Requirements and Guidelines, 2006) to determine their impact on the life cycle behavior of modular buildings. For example, site-specific factors such as location and orientation, which influence natural lighting and ventilation and affect energy efficiency and carbon footprint, are selected in the second filtration step. Parameters are classified based on construction type, distinguishing those applicable to any building type (general factors) from those specific to modular construction (MOC factors). Table 1 (second column) shows this systematic classification of SLP parameters that influence the LCA of modular buildings. The table distinguishes between "General Factors" and "MOC Factors," which are essential for understanding their impact on layout design and environmental performance. General factors that are applicable to all types of construction, including modular and conventional buildings. They encompass common architectural elements such as site location, orientation, material choice, and building type. These factors are universally present and influence the environmental assessment across various construction methods. On the other hand, MOC factors are specific to Modular and MOC buildings. They include unique attributes related to modular construction, such as module geometry, level of finish, prefabrication level, and the source of energy used in manufacturing. These factors are critical in assessing environmental performance specific to modular designs.

In the context of comparative LCA, the methodology omits similar items across layout alternatives to concentrate on differences, selecting parameters that significantly influence comparative LCA. These parameters are categorized based on their specifications into SLP-related parameters, directly related to the layout design that designers can adjust. SLP non-related parameters are predetermined and remain constant in any design alternatives.

The complete list of the identified factors is shown in Table 1. Additionally, the methodology applies another step that categorizes SLP-related factors into changeable and fixed parameters. Changeable parameters refer to those aspects of the design that designers can adjust to improve the environmental performance of modular buildings. These parameters are integral to the design process, allowing for flexibility and adaptation to different sustainability goals. On the other hand, SLP-related fixed parameters remain fixed across various design alternatives. By distinguishing between modifiable parameters and constants, the study enables a focused approach to enhancing sustainability, allowing designers to concentrate on elements that offer the greatest potential for environmental improvement without overextending resources on fixed factors. The final step involves validating the identified parameters through a literature-based approach, confirming their relevance and accuracy.

This structured methodology provides a clear framework for identifying the design choices affecting future modular building design.

Table 1: MOC-SLP Influential Parameters on Comparative LCA

SLP- Architectural Parameters	SLP-LCA Parameters		MOC-SLP Comparative LCA Parameters	
	General Factors	MOC Factors	SLP-Related Factors	SLP- Nonrelated Factors
Site & Location	Site & Location	Module Geometry	Material	Site & Location
Plan Orientation	Orientation	Level of Finish	Geometry	Level of Finish
Material	Material	MOC Manufacturing Source of Energy	Building Size	MOC Manufacturing Source of Energy
Building Boundary	Geometry	Prefabrication Level	Building Type	Prefabrication Level

Distribution of Spaces	Building Type	Building Orientation
Building Type	Building Size	
Interior Elements		
Lightening & Ventilation		
User Requirement		
User Satisfaction		

### 3.2 MOC-SLP Extraction Framework

The second part of this research focuses on extracting modular building-specific SLP parameters that directly affect the LCA analysis. The methodology is designed to systematically detect, label, and extract required layout design factors to provide a comprehensive database for comparative LCA analysis of alternative modular building layouts. Identifying the influential parameters of MOC-SLP provided the groundwork for integrating layout design with LCA. These parameters were identified in section 3.1. Based on these identified parameters from the previous section, the core methodology of this section involves a structured approach to extracting and analyzing layout data to enable a comprehensive comparative LCA. In modular residential buildings, different spaces and elements (SLP-related factors) are required to be extracted, such as materials, geometry, including module shape and dimensions, and orientation. The proposed method for extracting the SLP-related data from the layout has two steps: 1- preparing the layout for data extraction, and 2- developing data extraction algorithms based on the graph method.

#### 3.2.1. Preparing Layout for Data Extraction

The initial step in extracting the requisite data for a comparative LCA of modular building layouts involves the preparation of layout plans. The layout preparation for SLP data extraction has four main steps. 1. Convert the plan to an object graph, 2. Modules identification process, 3. The corners identification process, and 4. Side surface identification process. This preparation step is pivotal in facilitating the efficient extraction of data necessary for evaluating the environmental impacts of different modular design alternatives. Method inspired by Zhi et al. (2003), the process adapts graph theory principles to transform module extraction into a structured problem-solving approach and then modifies it to be suitable for modular buildings. Graph theory principles include converting the architectural plan into an object graph, facilitating the detection and extraction of modules. By treating the module extraction process as a graph problem, the approach enables the systematic identification of module boundaries that shape the building layout. This structured representation allows for efficient identification and manipulation of the modular components within a building layout.

The preparation begins by simplifying the layout plans according to module boundaries, which involves creating a systematic framework for detecting, labeling, and numbering each module (denoted as  $m: \{1, \dots, M\}$ ). In this study, each module is defined by exterior and interior mate walls. The modules are assumed to be box-shaped (rectangular), with the essential structure being formed by exterior walls connected to at least one interior mate wall. This configuration outlines the shape and boundaries of each module. This organized methodology ensures that each module's spatial attributes are accurately captured and cataloged, forming a comprehensive database for subsequent analysis.

Key parameters to be detected and automatically quantified include the corners and side surfaces of each module ( $c: \{1, \dots, C\}$  and  $s: \{1, \dots, S\}$ , respectively). These elements are crucial for understanding the spatial configuration and connectivity within the modular layout, influencing the overall environmental performance assessed through LCA. The structured preparation not only ensures the systematic cataloging of necessary components but also enhances the precision of data extraction, thereby improving the reliability of the LCA outcomes. This process is illustrated in Figure 2. By establishing a clear framework for the layout preparation, this approach supports the development of an extraction model and achieves accurate data extraction results for modular construction projects.

### 3.2.2. Developing Extraction Algorithms for Layout-Related Parameters

This section outlines the methodology for creating algorithms tailored to extract detected data from modular building layouts, focusing on SLP-related parameters that significantly influence environmental assessments. SLP-related parameters refer to those that are directly associated with the design and configuration of the building layout. These parameters can be adjusted or modified by designers to improve the environmental performance of modular buildings. Examples include module geometry, level of finish, and building orientation. These factors are integral to the design process and influence the building's lifecycle environmental impact. On the other hand, non-SLP-related parameters are those that remain constant across different design alternatives and are not directly influenced by the layout design. With the classified parameters into layout-related ones and those not, and the layout prepared (Table 1), the next step involves extracting the required data from the layout based on modular building specifications to provide the layout required data for a comparative LCA dataset. BIM tools, Revit, are utilized in conjunction with Dynamo scripts to automate the extraction of SLP parameters from building layouts. This integration facilitates the efficient identification and labelling of modular components, enabling precise data extraction for LCA. By using BIM, the process not only enhances accuracy but also streamlines the workflow, allowing designers to evaluate various layout alternatives.

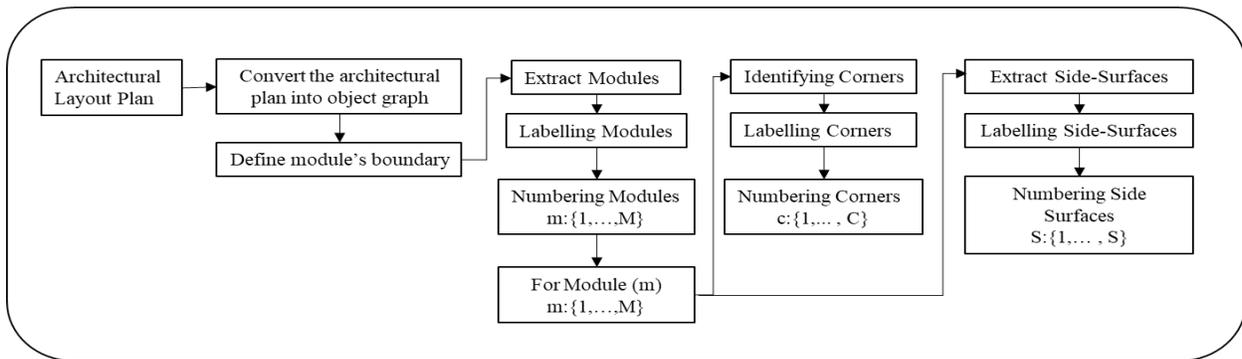


Figure 2: Process of Modular Building Layout Plan Preparation

One of the primary focuses of these algorithms is module geometry, which encompasses the shape and size of each module. The dimensions and shape of exterior walls or equivalent elements (e.g., mate walls) surrounding each module define these geometries. As a result, the module geometry could be simplified by considering the dimensions and shapes of exterior and mate walls. The algorithms identify and measure these dimensions, ensuring precise data capture for LCA. Furthermore, the extraction process extends to the internal configuration of modules (e.g., interior walls), where different functional spaces are delineated by interior walls. Capturing this aspect is essential for a complete comparative environmental analysis, as it impacts material usage.

Another SLP-related parameter that shapes the geometry of the modular buildings is the connection type. The extraction algorithms were developed to address connection types and their orientations - vertical and horizontal - within the entire layout. This algorithm is composed of two main processes: Process A and Process B. Process A is responsible for detecting and quantifying inter-connections, while Process B focuses on intra-connections. The first process focuses on inter-connections, which include both vertical and horizontal linkages between multiple modules. In multi-story layouts, vertical connections are essential for attaching modules. There are three specific types of vertical connections: Inter Vertical Corner Connections (IVCC), Inter Vertical End Connections (IVEC), and Inter Vertical Internal Connections (IVIC). These connections are identified by the number of columns associated with each, allowing the algorithm to accurately count the quantity of each type. Horizontal connections occur when multiple modules are involved, utilizing mating beams for attachment. The algorithm measures Inter-Horizontal Connections (IHC) by counting the connected surfaces. The second process addresses intra-connections within a single module. Each module corner has an Intra Corner Connection (InCC), equivalent to the number of corners in the module. Additionally, when a module's length surpasses 13 inches, Intra Internal Connections (InIC) are required. The algorithm determines the InIC based on the length of the module's longer sides. Figure 3

provides a visual representation of these processes, illustrating the comprehensive functionality of the algorithm. By automating the identification of these connections, the algorithms ensure a thorough analysis of how different assembly types affect the LCA outcomes.

Another critical parameter is the Bill of Materials (BoM), which reflects material differences across layout alternatives. The algorithms are designed to identify variations in wall assemblies, openings, and connection materials, both intra-module and inter-module. These variations are crucial for understanding the environmental impact of different design choices.

The final step involves creating specific algorithms tailored to each category of required data from the layout. These algorithms automate the extraction process, ensuring both accuracy and efficiency in gathering data essential for comparative LCA. It provides a solid foundation for integrating SLP data with environmental assessment tools, ultimately contributing to the optimization of modular buildings for low-carbon designs.

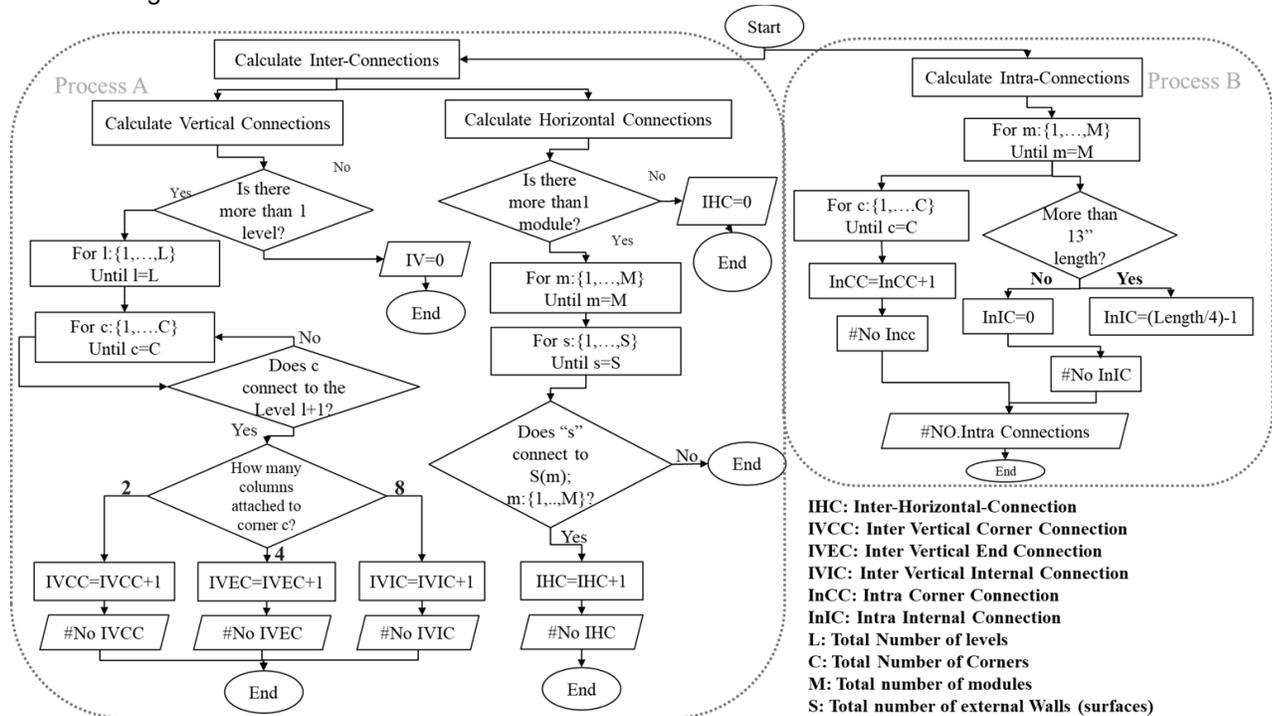


Figure 3: Extraction Algorithm for Module Connections

#### 4. DISCUSSION

The process of identifying and classifying modular SLP parameters for comparative LCA highlights the importance of understanding the environmental impacts associated with modular building design. This methodology provides a framework for examining how architectural elements (SLP factors) contribute to lifecycle outcomes in modular buildings. Figure 4 provides a summary of these findings, illustrating the key parameters identified at each stage of the MOC-SLP parameter identification process. In other words, each subsequent step in the methodology involves filtering the parameters identified in the previous steps based on specific criteria relevant to the current analysis phase. This process ensures that only the most pertinent SLP parameters are retained for further evaluation, enhancing the precision of the comparative LCA analysis. By systematically narrowing down the parameter set, the result focuses on the parameters that most significantly influence comparative LCA outcomes for layout alternatives.

One of the significant aspects of this study is the ability to pinpoint which parameters most significantly influence environmental performance. This insight allows designers and engineers to prioritize modifications that enhance sustainability. Furthermore, the classification of parameters into those modifiable by the designer (changeable parameters) and those that are constant across alternatives enables a focused approach on elements that offer the greatest potential for environmental improvement without overextending resources on fixed factors. Moreover, the algorithm developed for extracting these

factors (layout-related factors) further enhances this methodology by automating the data acquisition process. This automation streamlines the integration of identified parameters into comparative MOC-LCA models.

## 5. CONCLUSIONS

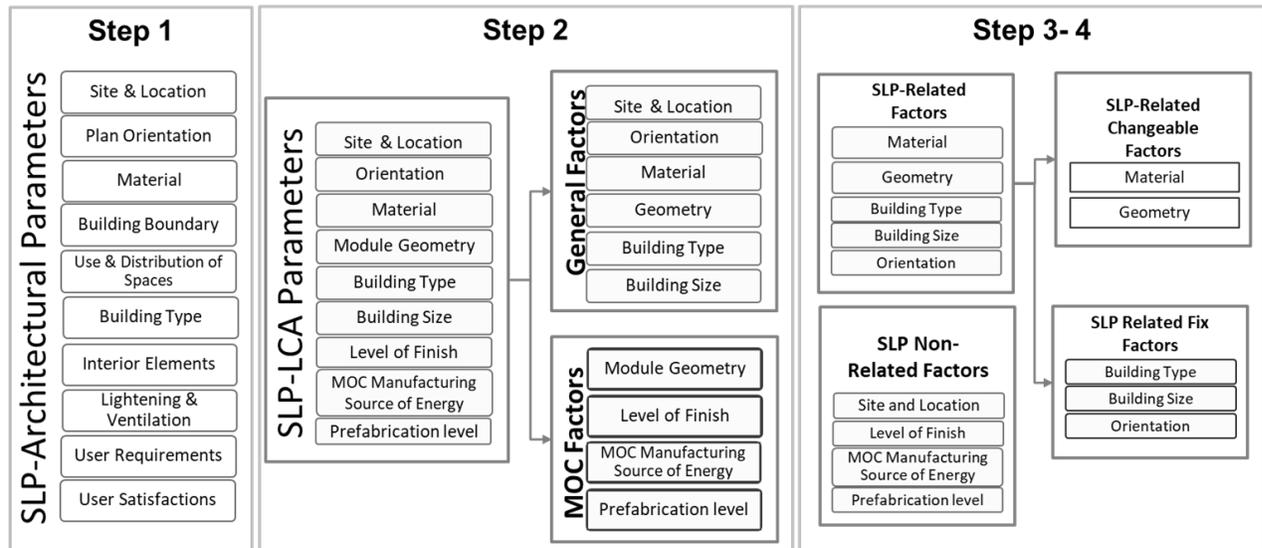


Figure 3: Key Identified Parameters of MOC-SLP

In conclusion, incorporating the structured methodology presented in this research, designers and decision-makers can effectively identify and extract key SLP parameters critical for integrating LCA in modular construction. By automating the extraction process, the framework enables a streamlined assessment of various layout alternatives, focusing on parameters that significantly influence environmental performance. This approach not only enhances the precision of LCA but also supports sustainable modular design by prioritizing modifications with the greatest potential for environmental improvement. By offering insights into the key factors affecting carbon emissions, the study contributes to developing sustainable architectural practices. It supports the broader goals of reducing the carbon footprint in the construction industry. This work underscores the potential of modular construction to lead the way in sustainable design innovation through informed decision-making at the design stage.

A significant limitation of this research is the exclusion of building codes and regulations, primarily due to their variability and localized nature. Moreover, the lack of a case study to validate the proposed framework will be addressed in future work.

Future research could address current limitations by incorporating building codes and regulations for a more universal application of findings, and adding a case study can be useful to validate the proposed framework. Additionally, developing advanced parametric design tools that integrate LCA objectives into early design stages could allow designers to input sustainability goals, automatically generating multiple configurations that meet environmental criteria. These tools would leverage computational algorithms for a dynamic design process, embedding environmental considerations into core planning and promoting sustainable modular construction practices.

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## REFERENCES

Ahonen, T., Hadid, A., and Pietikä, M. (2006). *Face Description with Local Binary Patterns: Application to Face Recognition*. <http://www.ee.oulu.fi/research/imag/texture/lbp/bibliography/>

- Almashaqbeh, M., and ElRayes, K. (2022). Multiobjective Model for Optimizing the Planning of Floor Plans, Finishing Level, and Transportation in Modular Construction. *Journal of Architectural Engineering*, 28(4), 1–12.
- Al-Najjar, A., and Doodoo, A. (2023). Modular multi-storey construction with cross-laminated timber: Life cycle environmental implications. *Wood Material Science and Engineering*, 18(2), 525–539.
- Campbell, A., Hairstans, R., and Jones, G. (2020). Refocusing modern methods of construction on the climate emergency: a 'five capitals' model for action. *Structural Engineer*, 98(9), 22–28.
- Cheng, B., Huang, J., Lu, K., Li, J., Gao, G., Wang, T., and Chen, H. (2022). BIM-enabled life cycle assessment of concrete formwork waste reduction through prefabrication. *Sustainable Energy Technologies and Assessments*, 53(March).
- Chippagiri, R., Biswal, D., Mandavgane, S., Bras, A., and Ralegaonkar, R. (2023). Life Cycle Assessment of a Sustainable Prefabricated Housing System: A Cradle-to-Site Approach Based on a Small-Scale Experimental Model. *Buildings*, 13(4).
- Dalal, N., and Triggs, B. (2005). *Histograms of Oriented Gradients for Human Detection*. <http://lear.inrialpes.fr>
- DTIR Document DC350. (2010). *Design Requirements Manual 2010 Edition*.
- Environmental management — Life cycle assessment — Requirements and guidelines*. (2006).
- Greer, F., and Horvath, A. (2023). Modular construction's capacity to reduce embodied carbon emissions in California's housing sector. *Building and Environment*, 240(March).
- Jellen, A. C., and Memari, A. (2018). Residential Vertical Expansions Using Modular Construction. *Journal of Architectural Engineering*.
- Jia Wen, T., Chin Siong, H., and Noor, Z. Z. (2015). Assessment of embodied energy and global warming potential of building construction using life cycle analysis approach: Case studies of residential buildings in Iskandar Malaysia. *Energy and Buildings*, 93, 295–302.
- Kim, D. (2008). *Preliminary life cycle analysis of modular and conventional housing in Benton Harbor, Michigan. A practicum submitted in partial fulfillment of requirements for the degree of Master of Science*.
- Lazebnik, S., Schmid, C., and Ponce, J. (2006). *Beyond Bags of Features: Spatial Pyramid Matching for Recognizing Natural Scene Categories*.
- Lin, J., Cohen-Or, D., Zhang, H., Liang, C., Sharf, A., Deussen, O., and Chen, B. (2011). Structure-Preserving retargeting of irregular 3D architecture. *ACM Transactions on Graphics*, 30(6).
- Pons, O., and Wadel, G. (2011). Environmental impacts of prefabricated school buildings in Catalonia. *Habitat International*, 35(4), 553–563.
- Qiu, H., and Hancock, E. R. (2006). Graph matching and clustering using spectral partitions. *Pattern Recognition*, 39(1), 22–34.
- Salama, T., Salah, A., Moselhi, O., and Al-Hussein, M. (2017). Near optimum selection of module configuration for efficient modular construction. *Automation in Construction*, 83, 316–329.
- Sharma, D., Gupta, N., Chattopadhyay, C., and Mehta, S. (2017). DANIEL: A Deep Architecture for Automatic Analysis and Retrieval of Building Floor Plans. *Proceedings of the International Conference on Document Analysis and Recognition, ICDAR*, 1, 420–425.
- Shrestha, J. K. (2021). Assessment of energy demand and greenhouse gas emissions in low-rise building systems: Case study of five building systems built after the Gorkha Earthquake in Nepal. *Journal of Building Engineering*, 34.
- Sokhangoo, L. R., Nik-Bakht, M., and Han, S. (2024). *Optimal Space Layout Generation for Modular Offsite Construction for Whole Life Cycle Costs—Gaps and Requirements* (pp. 395–411).
- Spudys, P., Osadcha, I., Morkunaite, L., Manhanga, F. C., Georgali, P. Z., Klumbyte, E., Jurelionis, A., Papadopoulos, A., and Fokaidis, P. (2024). A comparative life cycle assessment of building sustainability across typical European building geometries. *Energy*, 302.
- Tavares, V., Lacerda, N., and Freire, F. (2019). Embodied energy and greenhouse gas emissions analysis of a prefabricated modular house: The "Moby" case study. *Journal of Cleaner Production*, 212, 1044–1053.
- Teng, Y., Li, K., Pan, W., and Ng, T. (2018). Reducing building life cycle carbon emissions through prefabrication: Evidence from and gaps in empirical studies. *Building and Environment*, 132(January), 125–136.
- Teng, Y., and Pan, W. (2020). Estimating and minimizing embodied carbon of prefabricated high-rise residential buildings considering parameter, scenario, and model uncertainties. *Building and Environment*, 180(February).
- Tian, Y., and Spatari, S. (2022). Environmental life cycle evaluation of prefabricated residential construction in China. *Journal of Building Engineering*, 57(March), 104776.
- Zhi, G. S., Lo, S. M., and Fang, Z. (2003). *A graph-based algorithm for extracting units and loops from architectural or plans for a building evacuation model*. [www.elsevier.com/locate/cad](http://www.elsevier.com/locate/cad)