Optimal Space Layout Generation for Modular Off-site Construction for Whole Life Cycle Costs – Gaps and Requirements

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Abstract. Modular and Offsite Construction (MOC) is extensively accepted and utilized in the construction sector to enhance efficiency. Recent studies have shown that the key advantages of MOC are in the context of cost, quality, and time. With the construction industry shifting towards sustainable and circular practices, it has become critical to incorporate sustainability measures in the design of MOC buildings. Conceptual design is one of the most critical phases where most decisions that affect the result of performance and cost are made. To involve Life Cycle Cost (LCC) optimization in space layout selection, several factors are involved from each phase of the life cycle. With the development of computational methods, automatic generation of Space Layouts Planning (SLP) helps to generate various layouts which could help to investigate the involved design parameters on the total cost of MOC projects. Therefore, combining SLP with LCC is expected to be greatly helpful for cost-efficient design in MOC projects. This research investigates studies combining SLP and LCC on MOC projects and analyses their gaps. Further, we extend the analysis separately search on MOC-SPL and MOC-LCC separately. SLP methods are categorized and discussed based on studies in the MOC-SLP area. Regarding MOC-LCC, the requirements for cost assessment and optimization are analyzed.

Keywords: Modular Offsite Construction, Space Layout Planning, Life Cycle Cost.

1 Introduction and Background

The world's population will reach 9.3 billion people by 2050. This rise in population will result in an increase in the number of buildings (almost 88 percent rise in the number of households between 2009 and 2050), resulting in increased service demand. The buildings industry in Canada, which includes both residential and commercial subsectors, consumes around half of all natural resources [1], producing pollutants such Green House Gases (GHG) during extraction, production, operations, and end-of-life and have a significant influence on other environmental concerns. Furthermore, the demand for cost-efficient building design is essential due to the crucial need to have more affordable housing. Many approaches have been presented to save cost and energy in various phases in the building sector. As a result, prefabricated construction is becoming a part of several countries' programs due to the remarkable potential of these types of buildings to reduce the total cost.

The successful design of buildings requires special attention to the conceptual stage. Conceptual design is known as one of the most critical phases in which the majority of the decisions that affect the result of performance and cost are made [2]. Regarding Caldas (2008), the majority of a building's cost-energy saving potential is determined by decisions made early in the design process when a large number of potential design alternatives are generated [3], [4].

It is challenging to design an energy-cost-efficient building that meets all limitations and identifies the best trade-off between the user requirements and the energy-cost-efficient constraints. It needs numerous factors and parameters to be analyzed [5].

Space layout design is one of the early design processes that entail a coordinated arrangement of architectural elements within the constraints of a floor plan [6]. The importance of early design in assuring building performance cannot be overstated. Regarding Baušys Pankrašovaité (2005), space layout design is concerned with "finding feasible locations and dimensions for a set of interrelated components that meet all design requirements"[2]. Up to 80% of the operation costs are determined by decisions made during this phase [7]. Regarding Soleiman (2017), early design choices substantially impact a building's energy and cost performance throughout its operational phase[5]. Du et al. (2020) mentioned that space layouts had been demonstrated to impact energy performance significantly [8]. Various factors about building form and orientation, as well as envelope openings, are considered early in the design process [9].

Although early design choices have a substantial influence on the energy performance of buildings [4], only a small percentage of feasible early designs is evaluated, which does not guarantee an optimum building design [5]. Space layout planning of modular construction in the early stages can help to optimize space, improve functionality and flow, speed up construction, reduce costs, and create a building that is easily adaptable to future changes [10], [11].

1.1 Modular Construction

There is a range of terms that have been used for offsite construction, including industrialized building systems and open building manufacturing. According to the National Institute of Building Sciences Off-Site Construction Council, offsite construction defines as construction that involves the planning, design, fabrication, and assembly of building elements at a location other than their final point of assembly on site. Modular and prefabricated structures fall under the offsite construction category. Prefabricated refers to any system that has its section designed in a factory [12]. Modular construction is a set of modules built and preassembled in factory environments, shipped to the project site, installed, and placed on the permanent foundation [1]. Studies show that offsite construction is overgrowing and becoming an effective alternative to conventional building methods in the construction industry [13],[1]. The global modular construction market is expected to grow at a compound annual growth rate of approximately 6% from 2018 to 2023 [11]. The key advantages of modular construction are in the context of cost, quality, and time.

Reduced construction timelines result in lower site management expenses and a faster return on investment. Moreover, the client's design cost is reduced (i.e., most of the detailed design work is carried out by the modular supplier. According to Lawson et al. (2012), another advantage of modular construction is due to the double-skin structure of the building, and each module is well insulated from its neighbors, providing excellent acoustic and thermal insulation as well as fire protection [14]. The set of attributes stated by the Modular Building Institute (MBI 2009) as significant advantages of modular buildings include built-to code with shorter construction time; safer construction site; less waste of material; less site disturbance; less material exposure to adverse weather conditions; flexibility; and adaptability [15]. Lawson, et al. (2012) list lower construction cost, shorter construction time, and higher quality production as the three main benefits of modular building construction [14]. Higher quality and productivity, greater return of investment, and fewer environmental issues are the primary benefit of modular construction regarding the AEC Market Report [16].

1.2 Space layout design of MOC buildings

The Modular and Offsite Construction (MOC) building design is a complicated interaction between the required space and function of the building and the cost-effective usage of similar-sized modules. In other words, modular building design should allow for internal planning flexibility while maintaining the constraint of offsite manufacturing in terms of modular component standardization and manufacturing regulations. General guidelines should be followed in designing buildings using modular units. Building shape, planning grid, and transportation constraints (access and installation) are among other parameters affecting the plan design of modular buildings [17]. Tenant requirements for access and spaces impact the building shape, and interior fitments influence the planning grid. Module size has to meet the transportation, local access, and installation requirements as some of the most critical constraints in developing this system. Moreover, repetition in designing the modules in terms of size and fit-out should be considered [14]. Regarding Dino and Üçoluk (2017) space layout design as an essential aspect of architectural design includes searching for an ideal spatial arrangement that meets a set of constraints. The shapes, dimensions, and spaces positions are determined to meet the functional requirement and also architectural principles [9]. Space Layout Planning (SLP) plays a critical role in the success of MOC by optimizing the placement of modules, standardizing module sizes, planning for transportation and assembly, and ensuring compatibility with building systems. By using SLP to plan and design modular components thoughtfully and strategically, MOC can offer significant benefits in terms of speed, efficiency, and cost savings.

1.3 Research Method

The purpose of this paper is to detect the gaps and requirements of space layout planning of MOC on Life Cycle Cost (LCC) optimization. This topic is relevant to three research domains: Space Layout Planning of Modular and Offsite Construction (SPL-MOC), Life Cycle Cost assessment of Modular and Offsite Construction (LCC-MOC), and optimization of SPL-LCC. Analyzed parameters included research domain, article type, subject area, publication language, keywords, and duration.

Data Sources

Science Direct is the most widely used citation database among academics all over the world. It is an authoritative data platform for articles that span several fields of study. In the first step, main databases (i.e. Scopus) were used to locate literature related to space layout planning of MOC on LCC. The search was restricted to journal articles and review articles in the "Engineering" and "Environmental science" subject areas.

Analysis Method

The keywords used for searching references are shown in Table 1. The existing studies have attempted to address four main categories of keywords (i.e., space layout, life cycle cost, MOC, and optimization). Keywords within each category are based on a "OR" relationship, meaning that the literature only needs to contain one of the keywords listed under each category. The "AND" logical connection links the four categories to screen literature that targets all categories. These four groups of terms are used to collect references for SLP-LCC optimization in MOC projects, and the terms space layout and optimization and MOC are used for MOC-layout design optimization, which will be discussed in the literature review section. Only literature published in English was selected as the sample for the follow-up analysis. At the data filtering level, the time period from 2000 to 2023 was selected.

In the following step, the abstracts of the initially selected literature were reviewed to weed out the literature that did not focus on the aforementioned areas and remove publications irrelevant to the scope of this study. Following the initial literature screening, the secondary screening aimed to exclude the remaining literature that did not focus on building design. Although some studies used space layout as the keyword, they actually belong to the facility layout, as in [18]. The workflow for the literature search related to the space layout planning of MOC on life cycle cost optimization is described in Fig. 2.

Table 1. Keywords used for searching references.

Space Layout Planning	Life cycle cost	MOC	Optimization
Space Layout	LCC	Modular	Automation
Space Planning	Whole cost	Prefabricated	Generation
Floor Plan	Total cost	Off-site	
Interior layout	Construction cost	Industrial	

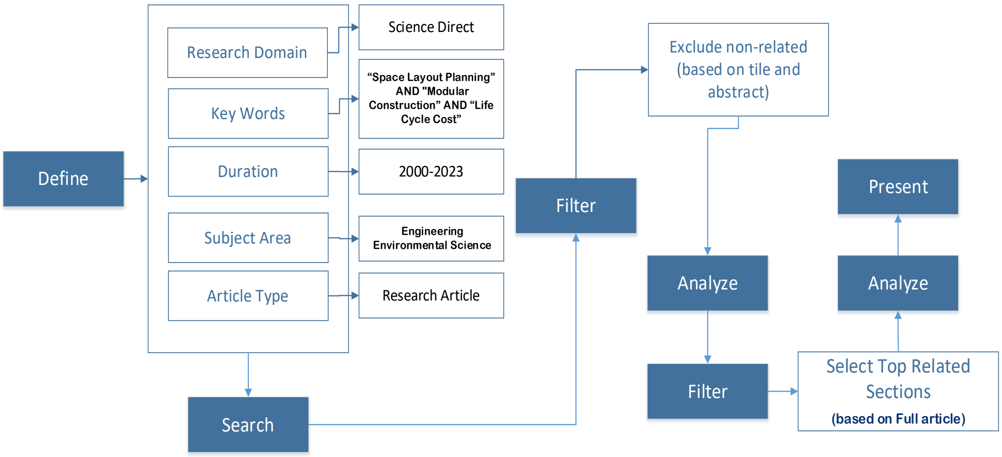

Fig. 1. Research Design Diagram

2 Literature review

The design of buildings using modular construction is a complex inter-relationship between the desired space and function of the building and the economical use of similar-sized modules. Functional considerations may be divided into two areas: performance and regulatory requirements. Structural, thermal, acoustic, and fire resistance requirements are part of the design and manufacture of the modules and are therefore the responsibility of the modular supplier. However, the effective integration of modules into a complete building is more the responsibility of the client's design team.
In addition to architectural requirements, factors such as cost, efficiency, the impact on land use and the stability and stabilizing system, transportation and installation limitations, and many others should be addressed when developing a multi-story modular structure [19]. An optimized modular system should allow for flexibility in internal planning, but must retain the discipline of offsite manufacture in terms of standardization of components and manufacturing efficiency. This researches cover the architectural design of MOC and consider various building construction phase including but not limited to fabrication, transportation, and assembly, and also some studies investigated the operation phase as well.

2.1 Life cycle cost combination with optimization in MOC studies

Offsite construction is a shift toward a more efficient building process to minimize cost and decrease the duration of projects. Hence, many studies have been carried out to reduce the cost of modular buildings in different stages by optimizing floor plan designs. In order to achieve the crucial goal of decreasing the overall cost of modular building, the design of floor plans in modular building projects must be thoroughly studied and optimized [20]. Almashaqbeh et al. (2021) used a mathematical optimization method to find the best performance forms in the field of costs, environmental impacts, and structural performance [21]. They evaluated modular building geometric design options by offering the planner cost-effective floor plan layout options. This study considered different design aspects including architectural, structural, and construction. Apart from minimizing the construction cost, this study aimed to have maximum plan regularity. Combinatorial challenges led to the invention of three-dimensional matrices. Then, a design structure matrix is created that breaks the building down into smaller components such as modular parts, connections, and bracing systems. Finally, the problem is solved by formulating a three-dimensional matrix. Salama et al.,(2017)used a BIM-based optimizer to find the best solution to reduce the cost of assembly. They created a methodology to reduce the cost of modular construction assembly by maximizing the use of building façade materials that minimize assembly time and waste [22]. In 2009, Shahtaheri (2017) proposed multiple optimization strategies that used evolutionary algorithms and mixed-integer programming to maximize site facility layout plans and reduce overall transportation costs for modular building projects [23]. Kamali and Hewage(2016) used tolerances in manufacturing to solve an optimization problem between cost, quality, and customer satisfaction using design principles. Improved modular assembly configurations to reduce module dimensions and geometric variability, as well as the costs associated with it, throughout manufacture, shipment, and on-site assembly [24]. Salama (2017) investigated finding a near-optimal module configuration to reduce the cost of modular construction, including transportation, crane, module interconnection, and on-site concrete costs [22]. There is no optimization method in this study.

2.2 Categorization of the MOC costs

Off-site construction methods could yield a lower overall project cost due to many related factors such as reduced material usage, increased manufacturing efficiency, less labor on site, avoidance of weather extremes, standardization of design, high level of energy efficiency, and higher efficiency in installation [25], [26]. The total modular whole life cycle cost comprises module fabrication cost, module transportation cost, module assembly cost, onsite structural frame cost, operation cost, and end-of-life cost. In this section, several studies that have been conducted to estimate or minimize the cost of modular construction are reviewed. No study in the MOC area includes all the phases of the life cycle. Some recent studies on MOC cost are listed in Table. 2 to show the coverage phase of LCC assessment.

Table 2. The coverage of life cycle phases in some MOC studies on LCC Assessment.

Author(s)	year	Prefabricated building cost/phase						Design Variable		
		MC	TC	AC	Onsite C	OC	EoL C	dimension	Material	Geometry
Wong et al.	2009	✓	✓					✓		
Sharafi et al.	2017	✓		✓				✓		

Salama et al.	2017		✓	✓	✓	✓		✓		
shahtaheri et al.	2017	✓						✓		✓
Almashabeq et al.	2021	✓	✓	✓	✓	✓		✓		
Zheng et al.	2022	✓	✓	✓				✓		✓

Manufacturing Cost

The Manufacturing Cost (MC)of modular buildings is an important aspect to consider as it directly affects the overall cost of the project. This cost is influenced by several factors, such as the materials used, design specifications, and the size and complexity of the structure. Sharafi et al. (2017)considered the fabrication and assembly costs of prefabricated tourist accommodation to evaluate the spatial design options [19]. In this study, the land cost and the cost of construction of the ground level are considered in the calculation and the final cost is obtained by multiplying the ground floor cost by the adjustment factor [19]. Hsu et al., (2018) designed a mathematical model to decrease module manufacturer inventory costs by optimizing the manufacturing, shipping, and inventory of modular building projects. To calculate the fabrication cost, this study divided the fabrication cost into two major costs; factory fixed production cost and factory variable production cost. The fixed production cost is related to the daily fixed overhead of the factory, which is multiplied by the time spent from inventory until the start of construction. The variable cost is calculated by multiplying the quantity of the product by the unit cost of manufacturing [27]. Hamdan et al. (2016) created a decision-making tool that used simulation to reduce indirect and inventory costs in modular and panelized construction projects by reducing the time it takes to start the module manufacturing process. The main factor in calculating the fabrication cost in this study is the manufacturing duration (time) [28]. To calculate the cost of prefabrication in residences, Wasim et al. (2020) used a "design for manufacture and assembly" method on non-structural parts, such as wood-frame walls and plumbing drainage systems [29].

Construction Cost

About 20% of the overall life cycle cost performance of modular buildings is attributable to the construction phase [30]. The construction cost, including transportation cost (TC), Assembly Cost (AC), and installation costs, was also studied in many types of research.

To analyze and improve transportation planning for modular buildings, several research studies have been carried out. For example, Almashabeq et al. (2021) [20] developed a model to minimize the total transportation and storage costs of prefabricated modules in modular construction projects. In this method, they selected an optimal module truck assignment from a feasible set of trucks, identifying an optimal delivery day for each module, its location, and orientation on the assigned truck, and complying with relevant constraints e.g. module non-overlap, shipment weight distribution, and aerodynamic drag reduction. Another related study developed an index to evaluate the effect of module dimensions on transportation and identify the required number of trucks and developed another index to evaluate the distance between the module production factory and the construction site [22]. Yi et al., (2019) developed a model to minimize the transportation and inventory holding costs of prefabricated modules. They used mixed-integer programming and took the weight and size of the modules into account to reduce transportation costs by reducing the number of trucks needed to move the modules and to reduce inventory holding costs by sending the modules to the building site as late as possible [31]. Hsu et al., (2018) made a two-stage stochastic programming model to optimize the production, transportation, and inventory of modular construction to reduce the initial inventory cost for the manufacturer. The model takes into account the total number of modules and the amount that can be placed on one truck [27]. In a study by Wong and his colleague, they came up with a two-approach optimization method that used a genetic algorithm and mixed-integer programming to find the best site facility layout plan to minimize the total transportation cost of modular construction [32]. Liu & Chen (2019) interestingly found that the cost of transportation drops as the rate of prefabrication increases [33]. Lu & Yuan (2013)reported that the cost of road transportation is about 20% of total costs[34].

The assembly cost in modular construction refers to the cost of putting prefabricated modules together on site. This cost is typically lower compared to traditional construction methods, as the prefabrication process allows for more efficient and controlled construction, reducing on-site labour costs, and minimizing weather-related delays [35]. The direct construction costs, including the material and labour costs, and expenses incurred during the construction phase of two similar modular and conventional residential buildings were evaluated by [35]. In another study, Shahtaheri et al. (2017) optimized modular assembly configurations by considering associated costs during manufacturing, transportation, and assembly onsite of modular buildings[23]. Assembly time was optimized in the study by Gbadamosi et al., (2019) through applying the principles of lean construction on modules and integrating it with building information modeling [36].

Operation Cost

The Operation Costs (OC), as an important part of a building's life cycle costs, are mainly attributable to electricity usage for lighting, heating, and cooling. Only a few studies (e.g., [10], [37], and [38]) in the literature have examined the operation costs of MOC buildings in detail. Nevertheless, it is proven that the quality of construction and the energy-efficient equipment installed in a building during the design and construction phases have impacts on its operational performance during the use phase. As mentioned in a study by [39] the higher quality and durability of prefabricated buildings can contribute to lower operating costs.

Naji (2021) considered the life cycle cost of the prefabricated house including the initial construction cost of the building envelope and operation cost during the operating years to optimize the envelope components of a prefabricated house to minimize thermal discomfort and life cycle costs while meeting the requirement of Australian

National Construction Code (NCC) on energy efficiency[13]. Samani et al. (2018) compared the annual and lifecycle operation costs of the prefabricated and masonry buildings in the three locations[38]. Tumminia et al. (2018) indicated that the use stage is the second most impactful stage of the life cycle of prefabricated buildings[10].

End-of-Life Cost

The End-of-Life cost (EoL C) of modular buildings refers to the expenses incurred at the end of a building's useful life, such as demolition and removal, site restoration, and disposal of materials. Factors that influence the end-of-life cost include the type of materials used, building design, construction type, i.e., the proportion of offsite prefabricated to onsite connections, and local regulations and policies. Careful planning and consideration of end-of-life costs during the design and construction phase can help minimize waste and promote sustainable and environmentally responsible practices. Some studies confirmed that the deconstruction cost in prefabricated buildings is lower than in conventional construction [30], [38]. This is mainly due to lower labour needs, ease of deconstruction, and higher recovery rate of prefabricated buildings [38]. Wuni et al. (2021) address the gap through empirical evaluation of the challenges of implementing a Design for Excellence (Dfx) application in prefabricated projects in China [40]. Dfx methods for prefabricated projects include the Design for Manufacture (Dfm), Design for Assembly (Dfa), design for quality, design for lifecycle, and design for the circular economy. Reuse and recycling of modular components could be performed easily, while they reduced construction waste and waste treatment costs [30].

Table 3. Studies investigating the effect of floor plan designs on MOC's cost.

Autor(s)	**year**	**Building Type**	**Weather**	**Life Cycle Cost**					
				MC	**TC**	**AC**	**onsite C**	**OC**	**EoL C**
Wong et al.	2009	residential	N/A	✓	✓				
Salama et al.	2017		Canada		✓	✓	✓		
Sharafi et al.	2017		Australia	✓		✓			
Wasim	2020		Australia	✓					
Naji et al.	2021		Australia	✓				✓	
Hsu	2018		Various	✓	✓	✓			
Gbadamosi et al.	2019	Non-Residential	N/A	✓					
Almashaqbeh et al.	2021		N/A	✓	✓	✓	✓		
Shahtaheri et al.	2017		N/A	✓					

3 Categorization of SLP methods in MOC studies

When designing the space layout for MOC, it is important to consider factors such as the size and shape of the modules, the access and delivery routes to the site, and the availability of the markets. Overall, effective space layout planning is essential to ensure that MOC projects are completed on time, within budget, and to the highest possible standard of quality. Automatically generated design alternatives give a series of alternatives for specific design exploration rather than a single best solution, which can improve or replace traditional manual design approaches [30]. Nearly 50 years ago, the first automated floor plan-generating techniques were presented [8]. The graph technique was initially used to identify feasible solutions. Over the time, the method has changed and varies between different projects and tools. In this section, different methods which were used in MOC studies are discussed. The summary is shown in Table 4.

Table 4. Categorization of SLP methods in some MOC studies and combination with optimization.

Autor(s)	**year**	**Design Variable**			**SLP Method**	**Optimization Method**
		dimension	**Material**	**Geometry**		
Wong et al.	2009	✓			Graph	Evolutionary algorithms
Sharafi et al.	2017	✓			Matrix	Linear optimization
Salama et al.	2017	✓			Matrix	N/A
Almashaqbeh et al.	2021	✓			N/A	Linear optimization
Zheng et al.	2022	✓		✓	Cell /Matrix	Genetic algorithm
Gan	2022	✓		✓	Graph	Metaheuristic optimization
Naji	2021	✓	✓		N/A	Pareto optimization

3.1 Graph Method

The graph method is widely used in generating the space layout for conventional buildings and MOC projects. In this method, the generation process is divided into topology and geometry design. Graphs allow users to handle and visualize complex information and relationships.

[41] used the graph method to find the best adjacencies between functional spaces. This study stored the space adjacency preferences in a 2D matrix. The matrix was then converted into a planar graph where the nodes represent spaces and links represent connections, turning the planar graph into a graph that can be used as the basis for an efficient layout. Geometric data is inserted into the graph to produce the final space arrangement. In this research, the geometric information was inputted manually by the

designers. This study showed that a form of Evolutionary Algorithm (EA) called Evo-arch can be a very useful and scalability tool for architectural layout design tasks. In a recent study, the graph method was integrated with BIM (Building Information Modeling) to automatically generate the space layout of the modular building. Firstly, the Industry Foundation Classes (IFC) model view definition (MVD) to systematically describe the required information for designing modular buildings was established. The IFC MVD was then translated into a graph data model. Data transformation methods were created in accordance with the graph-theoretic representation to convert the necessary BIM data to the graph model for various necessary information [42].

3.2 Matrix/Cell Method

The cell or matrix method is used when the building geometry is fixed, so it is predefined in this process. The predefined space is divided into the same size 3D cells. In this method, different spaces assign to the cells. Users first establish a matrix to represent the building's cells, and the value of the matrix indicates which space is given to each associated cell. Next, spaces are suitably allocated to the building geometry's cells. Then, by altering the matrix's values, a functional design that satisfies both geometric and topological constraints could be achieved.

In conventional buildings, Takizawa [43] used a cell method to generate all feasible layouts that satisfy all available constraints. With this technique, an area is partitioned into a number of cells, some of which are arranged into polyomino-like arrangements. Then, using an effective combinatorial search method, list all cell combinations that may be tiled in the specified space. Yi (2016) used the cell technique to automate creating zones and integrated it with the whole building simulation tool (Ecotect) to present a decision support tool named EASL (Environmental Architecture Space Layout. Within architectural processes, this tool fills the gap between thermal and spatial zoning [6].

In MOC studies, Sharafi et al., (15) created a matrix-based method to evaluate modular building geometric design options by offering the planner cost-effective floor plan layout options. This study solved the space layout planning problem by formulating a three-dimensional matrix[19]. Salama et al., (2017) used the matrix method to find a near-optimal module configuration to reduce the cost of modular construction, including transportation, crane, module interconnection, and on-site concrete costs[22]. Zheng et al., (2022) used the matrix method to represent the layout of the modular building based on the suggestion by Sharafi et al., (2017) [44]. They mathematically formulate the cost in each phase base and the related factors according to the experts. The authors used a multi-population genetic algorithm to optimize the layout fitness.

4 MOC-SLP and LCC optimization requirements

Optimal layout design for MOC buildings to minimize the LCC needs two major components to be integrated in SLP, which are the optimization and LCC assessment. This section will discuss both these concepts and their requirements.

4.1 Requirement for MOC space layout design

In order to be successfully combined with LCC assessments, an SLP method should be used to calculate a set of meaningful indicators for cost performance. Based on the aforementioned works of literature, these factors could be categorized as dimension, connection, and module transportation constraints.

Module Transportation

Many research on transportation techniques, transportation routes, and transportation handling equipment are included in modular transportation and trucking designs. One of the main design criteria defined for a modularized manufacturer is the maximum size and weight of a module that is practicable and affordable to transport from its production line to the final site.

Module Dimension

As long as transportation constraints are fulfilled, increasing module size or in other words reducing the number of modules in any modular design is cost-effective. This is due to the fact that growing module connections raise construction and maintenance expenses. Apart from transportation costs, the module dimensions could directly affect the operation phase costs through the size of thermal zones.

Module Assembly

To properly understand the resources and costs required for each connection included in the modular design, it is important to look into the connection types included in each space layout planning for each module. The connection type depends on the module's dimension, module shape, and even the module's materials. Most of the modular studies do not consider the connection cost separately and pinning the cost of connections included in the construction cost. However, considering the cost of module connection and assembly and disassembly costs could have a significant influence on total LCC.

4.2 Requirement for LCC optimization

In order to be successfully combined with the computational parametric optimization for life cycle cost, the SPL method should be used to generate different layout alternatives based on the design variables meaningful for LCC optimization. Moreover, based on the LCC formulation, the optimization method could be adopted.

Design variable

The creation of design alternatives is the foundation of computational parametric optimization. Based on design factors, the design possibilities are different from one another. The design factors that might impact the cost based on the cost equation in each phase of the project are concluded and classified in Table 5 according to their significance with space layout design when focusing on the life cycle cost of layouts. The design variables belonging to the MOC space layout planning can be divided into 'dimension' [20],[22], [42],[44], [17], "material" [13], "geometry" [23],[44], and other variables such as the location and function [19], [41]. The design variable could change with the objective(s) of the optimization if different than cost. Examples include using function and location as a design variable of SLP for functionality optimization, or the material for optimizing the waste.

Table 5. Design variables for LCC optimization, relating to space layout design.

Author(s)	year	Optimization objective (s)	Design Variable			
			Dimension	Material	Geometry	other variables
Wong et al.	2009	Functionality	✓			function
Salama et al.	2017	Cost	✓			
Sharafi et al.	2017	Cost Functionality	✓			location
Wasim et al.	2020	Cost		✓		
Gan	2022	Plan Function-ality	✓			
Naji et al.	2021	Cost Daylight unsat-isfied hours	✓	✓		
Hsu	2018	Cost		✓	✓	
Gbadamosi et al.	2019	Cost Reduce waste	✓	✓	✓	
Almashaqbeh et al.	2021	Cost Functionality	✓			
Shahtaheri et al.	2017	Project Risk	✓		✓	

Optimization Method

Optimizing the cost of a building based on layout design can be achieved through a variety of optimization methods. such methods which are vastly used in this area are the Genetic Algorithm [41], [44] and linear optimization [20], [42]. GA can be applied by creating a population of possible layout designs, then using genetic operators to evolve the population over multiple generations until an optimal solution is found while the mathematical method tries to solve the developed model which is to identify the given problem.

5 Discussion and recommendations

To summarize, the size, shape, and allocation of modules in the space layout plan for MOC should be carefully considered during the design phase. By taking into account these design factors and carefully planning the space layout of MOC projects, it is possible to achieve significant cost savings, and reduce construction timelines of the finished product. Moreover, considering the location of each module within the building plan will result in optimizing the assembly process, reducing equipment (joints) costs, and ensuring that the assembly process is cost-efficient.

Space layout design and the cost-effectiveness of MOC projects have been optimized using optimization techniques such as genetic algorithms. More studies investigated the integration of these optimization methodologies with space layout design, taking into account the total cost of the MOC projects during their whole life cycle including before the operation phase and no study considered the after-operation phase in the whole life cycle.

Other gaps in the literature include not considering the MOC constraints and limitations in terms of the size of the module. Module size range is limited to the manufacturer's capacity and the production line. However, this limitation of MOC products is not considered in the designing process.

Moreover, the uninvestigated part of LCC-SLP optimization in the MOC project is identified which would help future research. Generally, there is a tradeoff between LCC and SLP. The automatic generation of space layout planning is developed from the architects' perspective and the outcomes have a high variety, which requires fast feedback from a cost-performance point of view. In contrast, in order to have a high accuracy of cost performance, LCC needs detailed models, which are dependent on various criteria. Regarding the integration of LCC and SLP, the LCC formulation part is the main concern since it could identify the most suitable optimization method(s). As for future research, the LCC model which obtains all the requirements for LCC assessment and optimization (discussed earlier) is proposed.

Furthermore, considering all constraints of MOC could be a challenge for MOC designers. However, through the SLP of MOC, designers could save time while reaching the optimum cost-effective design. Moreover, this would be beneficial for MOC manufacturers to achieve a space-efficient design and reduce the waste during fabrication phase.

6 Conclusion

The review of relevant literature highlighted the significance of space layout design in MOC and its integration with optimization techniques. Several areas of space layout planning have been investigated by researchers, including modular design, construction process, and optimization. Regarding SLP generation methods, two methods mostly used in MOC projects were discussed. based on each method's limitations and capability, the designers should choose the proper method suitable for their purpose.

The size of modules used in modular offsite construction (MOC) can have a significant impact on the success of the project, and careful consideration should be given to these factors during the design phase. For example, the size and weight of modules must be considered to ensure that they can be safely transported from the offsite fabrication facility to the project site. This can involve designing modules that are small enough to be transported on flatbed trucks or shipping containers, or that can be easily lifted by cranes. The shape of modules can also affect the efficiency and cost-effectiveness of MOC projects. Rectangular or square-shaped modules are typically the most efficient, as they can be easily stacked and joined to create larger spaces. In contrast, irregularly shaped modules can be more difficult to integrate into the overall design and may require custom transportation and handling solutions, which can increase costs and complexity. Last but not least, the number of connections and connection types play an important role when it comes to calculating the cost of module assembly and disassembly in the space layout plan for MOC.

The main contribution of this paper includes classifying a set of meaningful indicators for cost performance considering the combination with the SLP method. The requirements for its combination with optimization are also investigated. Despite the contribution, the paper also has some limitations including comparing the MOC-SLP methods to generate speed, the ability to consider multi-floor buildings, the competency of irregular modules, and the requirements for predefined input. Future works are expected to cover the comparison and capability of each MOC-SLP method, in terms of requirements and adaptability with MOC conditions.

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