Delft University of Technology

Product Complexity Analysis of Hybrid Panelized-Volumetric Prefabricated Buildings

Cao, Jianpeng; Said, Hisham; Hall, Daniel M.

Publication date
2024

Document Version
Final published version

Citation (APA)
Cao, J., Said, H., & Hall, D. M. (2024). *Product Complexity Analysis of Hybrid Panelized-Volumetric Prefabricated Buildings*. Paper presented at 2024 ASCE International Conference on Computing in Civil Engineering, Pittsburgh, Pennsylvania, United States.

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright
Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy
Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

This work is downloaded from Delft University of Technology.
For technical reasons the number of authors shown on this cover page is limited to a maximum of 10.

Product Complexity Analysis of Hybrid Panelized-Volumetric Prefabricated Buildings

Jianpeng Cao, Ph.D.,[1] Hisham Said, Ph.D.,[2] and Daniel Hall, Ph.D.[3]

[1] Design & Construction Management, Architecture and the Built Environment, TU Delft, Julianalaan 134, 2628 BL Delft; e-mail: c.j.p.cao@tudelft.nl

[2] Department of Civil, Environmental and Sustainable Engineering, Santa Clara University, 500 El Camino Real, Santa Clara, CA 95053; e-mail: hsaid@scu.edu

[3] Design & Construction Management, Architecture and the Built Environment, TU Delft, Julianalaan 134, 2628 BL Delftt; e-mail: d.m.hall@tudelft.nl

ABSTRACT

Modularization aims to decompose a building or system into modules of components with controlled interdependencies to allow for the parallelization of their design tasks and the transfer of the work from the construction site to an efficient offsite manufacturing environment. However, these design and construction benefits of modular building decomposition may result in increased complexities that amplify the impact of design changes. This study proposes a quantitative methodology for assessing the complexity of hybrid building modularization strategies that combine the use of volumetric and panelized modules. The methodology integrates novel graph-based modeling schema, graph algorithms, a hybrid modularization modeling approach, and a structural complexity metric. The proposed methodology was assessed using an illustrative project case. The main contributions of this study is the development of a graph-based modeling approach for hybrid modularization and a quantitative approach for assessing the complexity of modularized buildings.

INTRODUCTION

Modularization is one of the fundamental requirements of construction industrialization to achieve a paradigm shift from delivering projects to developing products (Costa et al. 2023). Building modularization entails breaking it down into a set of modules that group independent components with standardized interdependencies (Voordijk et al. 2006). Developing modular products is one of the principles of redesigning the business processes of a construction towards its journey to industrialization (Costa et al. 2023). Also, building modularization defines the product architecture that forms the foundation for industrialization phases of prefabrication, mechanization, automation, and robotics (Richard 2005).

Modularization can be performed in a spectrum, where buildings can be prefabricated in a set of components, two-dimensional (2D) panelized modules, or three-dimensional (3D) volumetric modules (Boafo et al. 2016; Smith 2010). Building components is the lowest level of modularization and has been utilized in the traditional stick-built approaches in the form of structural steel, precast concrete, prefabricated trusses, stairs, and elevators. Panelized 2D modules maintain acceptable levels of customization while allowing for higher onsite efficiency through offsite prefabrication and stacked shipping. Finally, volumetric 3D modules allow for prefabricated larger scopes of work offsite, including the mechanical, electrical, plumbing (MEP), flooring, painting, ceiling, etc. The level of modularization can negatively and positively affect multiple performance metrics. For example, volumetric modularization results in the highest overall production efficiency but it limits the design customization (Said et al. 2017).

The relation between the system modularity and complexity has received little attention in previous studies of construction industrialization and modularization. Per Baccarini (1996), the complexity of a system can be described by the differentiation and interdependencies of the system's parts, which is described as *structural complexity*. Other researchers have expanded the complexity of a system to include structural complexity and *uncertainty* of goals and methods (Williams 1999). A system is more complex with the increase of the number of varied parts and the interconnectivity between these parts. To handle complexity, designers have resorted to different approaches: such as process decoupling, smaller kit of parts, tolerance control, and modular design (Viana et al. 2017). Most of the literature concur on the role of modularity to reduce the system complexity while satisfying the increasing demand for customization (Jensen et al. 2008). This is done by the modular architecture of the system that localizes the overall complexity within the modules and hides it behind their abstraction and interfaces (Baldwin and Clark 2000). Despite the rich literature of the modularity-complexity nexus in the mechanical product engineering domain, there has been limited quantitative exploration of this critical topic in the industrialized construction domain (Jensen et al. 2008; Viana et al. 2017).

As such this paper presents a complexity assessment methodology for hybrid modular buildings. The paper is organized in four sections: a review of the literature on construction modularization and complexity measurement; a description of the proposed methodology, its case-based illustration, and an outline of the research limitations and future possibilities.

LITERATURE REVIEW

The authors performed a comprehensive literature review of three domains: modularity in building construction, modularization computational modeling, and complexity measurement.

Modularity in building construction

The construction industry lacks a consistent definition of modules (Gosling et al. 2016). Modules are often seen as volumetric units, like factory-made "boxes," transported to construction sites. Murtaza et al. defined a module as a volume containing all structural elements and components, irrespective of their function or installation (Murtaza et al. 1993). To address this ambiguity, concepts from manufacturing were examined. Salvador (2007) identified five aspects of product modularity: component commonality, combinability, function binding, interface standardization, and loose coupling (Salvador 2007). Additionally, Ericsson and Erixon (1999) emphasized two key characteristics of modular products: the alignment of physical and functional design, and minimizing coupling between physical and functional components (Ericsson and Erixon 1999). To this regard, the modular product design problem refers to the designation of any main component, such as volumetric elements and wall panels, that can benefit from standardized and reusable design in multiple projects.

Quantitative and computational models of modularization

This research specifically focuses on studies on quantitative and computational models of modularization. In general, three computational strategies are suggested: independence-driven modularization, commonality-driven modularization, and index-driven modularization. *Independence-driven modularization* focuses on maximizing internal interactions and minimizing external ones among modules. Key tools include the design structure matrix (DSM), graph-based approaches, modular identification matrix (MIM), and generational variance index (GVI) (Wee et al. 2017). Samarasinghe et al. (2019) applied DSM to modularize MEP systems, noting its limitations in considering structural elements. Schmidt et al. (2014) used DSM for subsystem interactions in house construction , while Isaac et al. (2016) employed a graph-based approach for MEP and structural elements, focusing on minimizing renovation efforts. Both methods overlooked practical construction stage constraints, particularly topological considerations. On the other hand, *commonality-driven modularization* seeks to identify shared features among product variants for standardization. This method, applied in VM and PW systems, involves feature extraction and clustering of product variants (Cao et al. 2022; Feist et al. 2022). Key features include architectural dimensions, element typologies, and structural composition. Said et al. (2017) and Ghannad and Lee (2023) developed optimization strategies for balancing commonality and fabrication costs in specific projects. However, this approach is limited in addressing diverse topologies and focuses only on post-modularization optimization. Lastly, *index-driven modularization* quantifies the suitability of a module design in building construction. Salama et al. (2017) introduced several quantifiable indices, such as the construction index and crane cost index, to facilitate near-optimal module configuration selection. Aiello et al. (2012) used multi-objective genetic algorithm optimization to design facility layouts. Sharafi et al. (2017) integrated considerations like plan irregularity, energy efficiency, and construction cost into modularization. Almashaqbeh and El-Rayes (2021, 2022) employed linear programming for optimizing VM configurations, considering both construction costs and functional performance. Tidhar et al. (2021) used a greedy algorithm to adjust VM boundaries in architectural floor plans, evaluating cost, speed, and quality of design solutions. However, these studies generally don't account for diverse module topologies in customized architectural design, limiting their application to standard four-sided enclosed VMs.

Complexity Measurement

Researchers, mostly from industrial/mechanical engineering domains, developed methodologies for quantifying a system complexity, which can be categorized in two main groups following the two main sources of complexity: structure-based methods and process-based methods (Allaire et al. 2012). Structure-based methodologies are simpler as they utilize mostly graphs and networks to represent the physical aspects of the system (the parts and their connectivity). For example, a planarity-based complexity metric was developed to assess the complexity by utilizing the concept of planar graphs as a measure of the existence of complex topology with interconnectivity crossings (Kortler et al. 2009). A more comprehensive metric named *structural complexity metric* (Sinha et al. 2013; Sinha and de Weck 2013) was developed to assess three network-based sources of complexity: the complexity of the elements, the complexity of their interfaces, and the complexity of the overall architecture of the system network. On the other hand, limited research has proposed process-based methods to assess the system complexity due to the challenges of formulating and quantifying the uncertainties arising from the system goals methods. For example, an entropy-based complexity metric was developed (Allaire et al. 2012) that utilizes computer simulation to analyze the uncertainty associated with the design objectives of performance, cost and other relevant values of interest.

PROPOSED METHODOLOGY

The proposed computational methodology involved developing three graph-based main modules: extraction and modeling of building floor plan data, representation of hybrid modularization strategies, and complexity measurement of modularized buildings.

Floor Plan Data Extraction and Modeling

In this study, the building is represented as Building Information Models (BIM), where a repeated floor of the building is modeled with focus on the wall elements. We employ an attributed graph to depict each floor plan, defined by a system $G = (N, E, A_N, A_E)$, where:

- N: Node set representing building elements.
- E: Edge set representing connections between elements.
- A_N: Node attributes indicating properties of building elements.
- A_E: Edge attributes indicating properties of connections.

For graph construction, the virtual programming tool Dynamo is used to extract BIM information. The process involves extracting two primary data: node and edge entities. For node entities, elements are filtered with the “Element Classes” function. Element IDs are retrieved using “Element.ID”, and additional properties, such as length, are accessed through “ParameterByName”. For edge entities, the “Element.Geometry” and “Geometry.DoesIntersect” functions can be used to obtain the geometry models of building elements and determine connections between two geometry entities. Connections can be stored in a set of node pairs <node_i, node_j>. Besides, the connection types and connection angles are extracted as edge attributes. Finally, the node and edge information can be transformed to a graph structure. A floor plan (Figure 1) is transformed to a graph as an example . Here, walls and connections between walls are modeled as nodes and edges, respectively. The wall types and wall dimensions are modeled as node attributes and connection angles are modeled as edge attributes.

Hybrid Modularization Strategy Modeling

The hybrid modularization strategy takes a list of the connection types between the wall segments as design binary variables. Each variable has two categorical values: “1” represents offsite connection and “2” represents onsite connection. Using these decision variables, the floor plan of discretized wall segments can be grouped into a hybrid set of VM units and PW two-dimensional panels by three graph operations. Three graph operations, including room detection, VM detection, PW detection, are performed sequentially on the graph model of the analyzed floor plan to translate it into a modularization solution (shown in Figure 2).

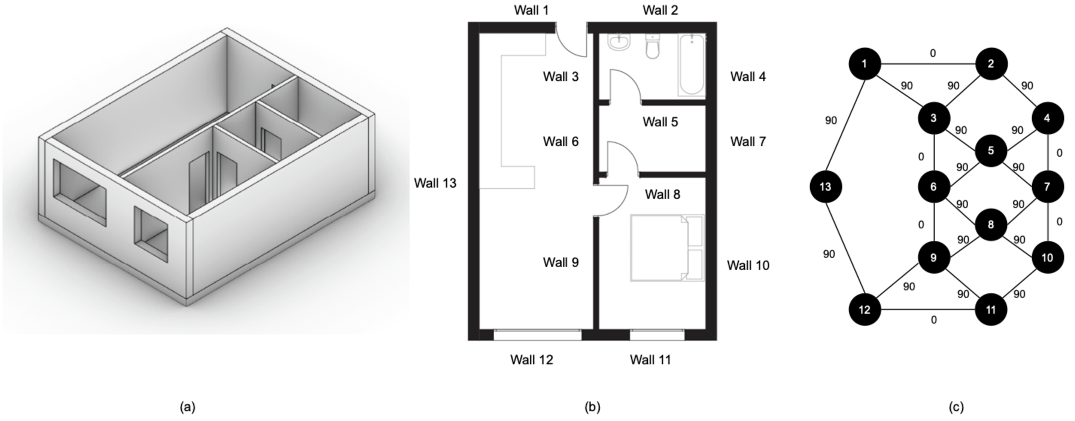

Figure 1. Graph representation of floor plans. (a) 3D model of a floor plan. (b) 2D view showing the wall segments. (c) the graph representation.

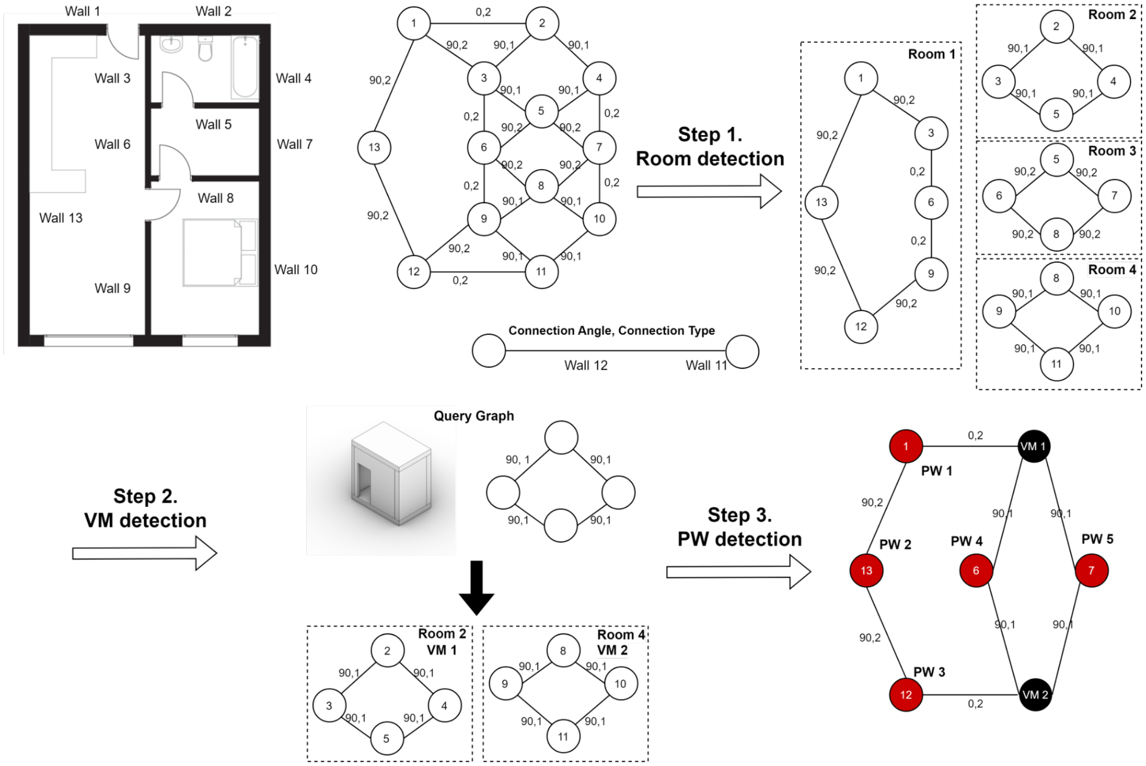

Figure 2. The implemented hybrid modularization strategy

Room detection. A room is an enclosed space in the floor plan. Enclosed rooms are detected by finding all simple cycles. A cycle is a simple cycle if it cannot be broken down to two or more cycles. In this sense, a simple cycle represents an enclosed room which is not partitioned into more rooms. From the cycles detected, a filtering operation is conducted to identify the cycles with the number of edges (walls) to be more than three. This criterion aims to avoid detecting a cycle that represents an intersection between three wall segments.

VM detection. For each detected room, the VM topology is determined at this step via subgraph matching by detecting the presence of a given query graph in a target graph. If the graph contains the node and edge properties, both the topology and the properties should be matched. The user-**defined** VM are modeled as meta graphs, and used as query graphs to find VM in a target floor plan graph. The node properties, including element types and edge properties, including angles and connection types, are taken into a matching process.

PW detection. After finishing the VM detection, the unmatched part of the floor plan is constructed using panels. The panel length can be maximized by merging multiple wall segments into one within the predefined length limitation. The merging of wall segments is performed using a node contraction operation, where a pair of nodes w1 and w2 in a graph are replaced with a single node pw1 such that pw1 is adjacent to the other graph nodes that are adjacency to the original node pairs w1 and w2. When two nodes are **contracted** as one, the edge property and node property are updated. For example, the "Length" property of the replaced single node is recalculated as the sum of the length property values of the original two nodes.

Modularization Complexity Measurement

This research utilized the structural complexity metric developed by Sinha and de Weck (2013) due to its simplicity and comprehensive capturing of component, interface, and architectural contributions to the overall system complexity. As shown in Equation 1, the complexity of a floor plan is calculated using three major terms, C1, C2, and C3:

$$\begin{aligned} C &= C_1 + C_2 C_3 \\ &= \sum_{i=1}^{n} \alpha_i + \left(\sum_{i=1}^{n} \sum_{j=1}^{n} \beta_{ij} A_{ij}\right) \frac{E(A)}{n} \qquad (1) \end{aligned}$$

- C_1 sums up the complexity (α_i) each component *i* of the system components n, i.e. the PW and VM units. The PW complexity depends on the wall geometry and openings, while the VM internal complexity is calculated using Equation 1 considering its own decomposition of walls and their connectivity.
- C_2 sums up the complexity of the pairwise connections between the system components (β_{ij}) if these connections exist per the binary adjacency matrix of the floor plan ($A_{ij} = 1$).
- C_3 assesses the topological complexity of the floor plan by dividing the sum of the singular values of the binary adjacency matrix *E(A)* over the total number of system elements n. C3 is a complexity modifying factor that is inspired by the concept of graph energy, which has values less than 1 for centralized (star) system architecture and values greater than 2 for distributed system architecture.

The above metric can be used to calculate the overall complexity of the whole floor plan or the internal complexity of any of its volumetric modules. The internal complexity of a VM module based on its subgraph model to consider the VM's wall component complexity, their connection complexity, and internal topological complexity. The internal complexity of each VM module can then be used to contribute to the complexity of the whole floor plan by including it in the summed component complexity factor C_1. It should be noted that no internal complexity is computed for PW units because they merge wall segments as a single element, not modularizing them into an assembly.

ILLUSTRATIVE EXAMPLE

The proposed methodology is demonstrated using a small floor plan to allow the complexity assessment of multiple modulation strategies. As shown in Figure 3, the hypothetical floor plan was designed to allow for varied combinations of panelized walls and three topologies of VM units: M_A (single-room module), M_B (two-room module with one partition wall), and M_C (two-room module with two partition walls). The internal complexity is calculated for each VM unit topology, and it was found to be 8, 10.88, and 14.93, respectively. These internal values and the overall floor plan complexity were calculated based on the following input: 1) each wall segment has a component complexity of 1; and 2) the complexities of wall-wall, wall-VM, and VM-VM connections are 1, 2, and 4 respectively. Figure 3-b shows the segmented wall breakdown of the floor plan and its graph model representation. The overall complexity of the segmented wall approach was found to be 36.26 (C_1 = 11, C_2 = 17, C_3 =1.486). Figure 4 outlines the 10 modularization strategies considered in the analysis, which represent varying degrees of combinations between using each module topology and panelized walls.

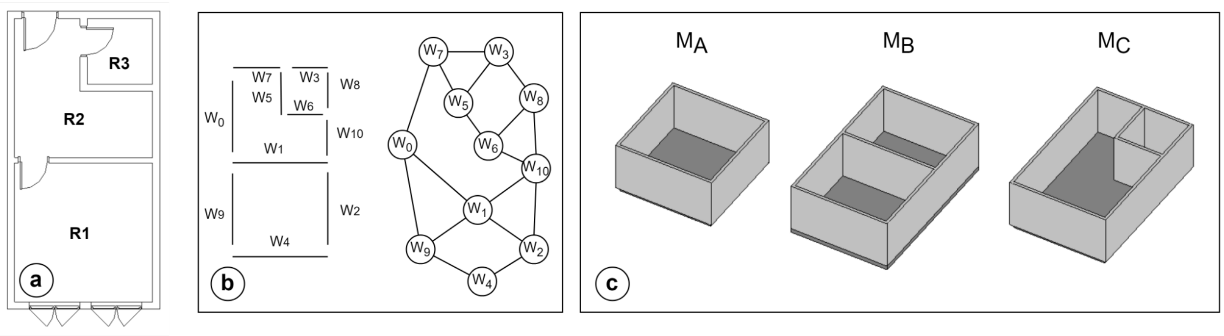

Figure 3. The illustrative example: a) the floor plan, b) the segment walls and their graph model, and c) the three topologies of VM units

The results provide initial insights on the impact of the modularization strategies on the overall complexity, element complexity, and integration complexity. Table 1 lists the resulting complexities of the analyzed modularization strategies. The fully panelized strategy (PW) resulted in the lowest overall complexity (18.6), which is 50% reduction from the initial segmented wall setup of the floor plan. The fully-modularized approach ($3M_A$) using three Modules M_A resulted in the highest complexity (31.54). The second lowest complexity (19.55) was achieved by grouping the whole floor plan in a single module (M_B), except for two walls (W_5 and W_6). The following general observations can be made:

- The careful increased use of panelization reduces the component-related complexity (C_1) due to the ability to merge wall segments and avoidance of wall duplication. Wall panelization is achieved by merging collinear wall segments, which reduces the number of elements without an increase in the wall complexity (i.e. the wall length has a negligible impact on the complexity). In addition, panelization eliminates the need for wall duplication between volumetric modules that are needed to maintain the integrity of each module during shipping and rigging.
- The increased use of volumetric modules can reduce the integration-related complexity, depending on their created connections and overall topology. Strategy $1M_B$ resulted in the lowest connection complexity (C_2 = 5), followed by strategy $1M_C$ (C_2 = 6), and strategy $3M_A$ (C_2 = 8). However, the complexity of integrating the offsite fabricated elements depends also on the topology of their connection. In this case, strategy 3MA had the lowest topology complexity (C_3 = 0.94) due to its simple star topology.

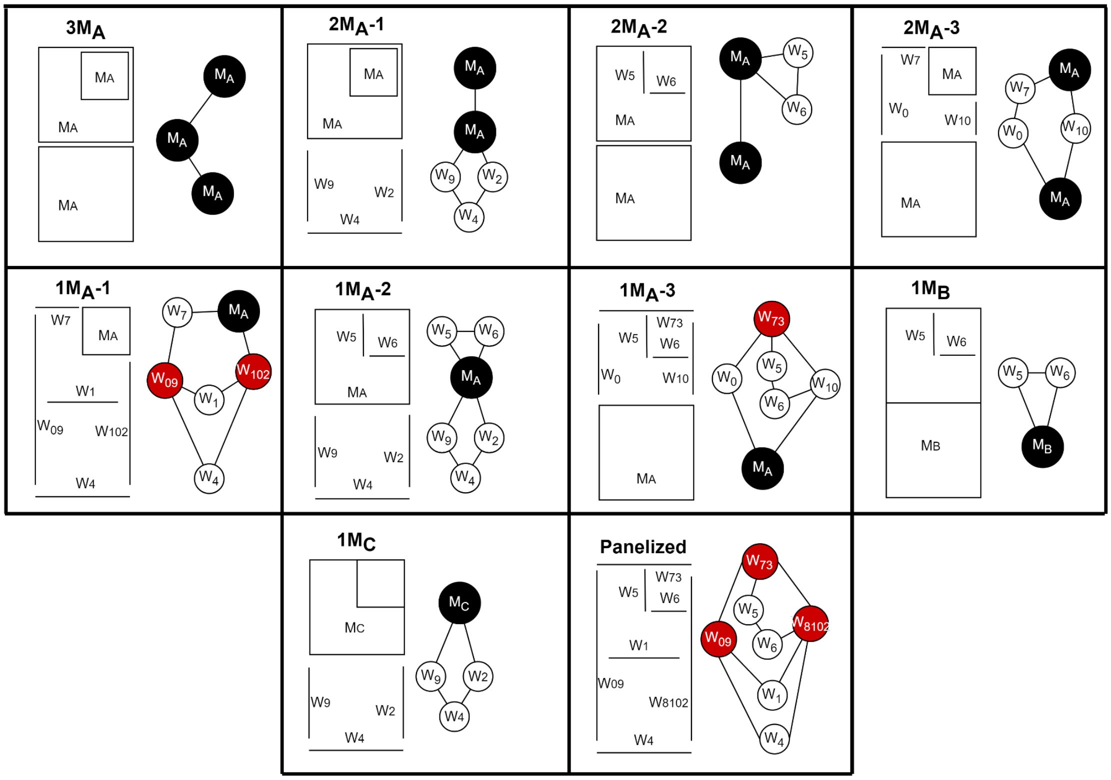

Figure 3. Modularization strategies for the hypothetical floor plan

Table 1. Complexity values of the analyzed modularization strategies

	3MA	2MA-1	2MA-2	2MA-3	1MA-1	1MA-2	1MA-3	1MB	1MC	PW
C1	24	19	18	19	13	13	13	12.88	17.93	7
C2	8	10	9	9	9	11	9	5	6	9
C3	0.94	1.12	1.24	1.29	1.26	1.26	1.28	1.333	1	1.24
C	31.54	30.19	29.16	30.65	24.35	26.82	24.48	19.55	23.93	18.16

CONCLUSION

This paper presents a complexity assessment methodology for building floor plan modularization, comprising three modules. First, floor plan data from BIM files is converted into a graph model using a wall-connection schema. Second, a modularization strategy sets binary values for wall connections, designating assembly locations, and applies novel graph operations to identify rooms, volumetric, and panelized modules.. Third, a complexity metric is applied to the modularized graph to assess the element, connection, topology, and overall complexities. The proposed methodology is a first attempt in the area of industrialized construction to provide a simple metric to assess the complexity of prefabrication approaches, which is indicative of the resulting risk of cascading changes and the required level of coordination.

The illustrative example showcased the dependency of the measured complexity on the modularization strategy and the extent of hybrid use of panelized walls and volumetric units. Panelized walls help to reduce the element complexity aspect of the building prefabrication due to the ability to merge collinear wall segments into larger panels and the avoidance of wall material redundancies needed when using volumetric modules. On the other hand, volumetric units reduce the integration-related complexity aspects of building prefabrication if the modularization is performed to reduce the connection and topologic complexities. As such, there is a need for a decision support system to explore the different modularization strategies and their impacts on the prefabrication complexity.

There are some limitations. The research focuses on demonstrating the theoretical methodology rather than developing a computational method. The empirical validation is confined to a hypothetical floor plan and only two VM topologies. Future research is recommended to focus on the creation of a computational method that integrates the generation of modularization strategies with complexity analysis. Additionally, testing the methodology against more complex floor plan and multiple-floor designs and expanding the range of VM topologies would improve its robustness and adaptability in a wider context, thus enhancing its effectiveness in optimizing modular construction practices.

REFERENCES

Aiello, G., G. La Scalia, and M. Enea. 2012. “A multi-objective genetic algorithm for the facility layout problem based upon slicing structure encoding.” *Expert Systems with Applications*, 39 (12): 10352–10358. https://doi.org/10.1016/j.eswa.2012.01.125.

Allaire, D., Q. He, J. Deyst, and K. Willcox. 2012. “An Information-Theoretic Metric of System Complexity With Application to Engineering System Design.” *Journal of Mechanical Design*, 134 (100906). https://doi.org/10.1115/1.4007587.

Almashaqbeh, M., and K. El-Rayes. 2021. “Optimizing the modularization of floor plans in modular construction projects.” *Journal of Building Engineering*, 39: 102316. https://doi.org/10.1016/j.jobe.2021.102316.

Almashaqbeh, M., and K. El-Rayes. 2022. “Multiobjective Model for Optimizing the Planning of Floor Plans, Finishing Level, and Transportation in Modular Construction.” *J. Archit. Eng.*, 28 (4): 04022029. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000563.

Baccarini, D. 1996. “The concept of project complexity—a review.” *International Journal of Project Management*, 14 (4): 201–204. https://doi.org/10.1016/0263-7863(95)00093-3.

Baldwin, C. Y., and K. B. Clark. 2000. *Design Rules: The Power of Modularity*. Cambridge, Mass: MIT Press.

Boafo, F. E., J.-H. Kim, and J.-T. Kim. 2016. “Performance of Modular Prefabricated Architecture: Case Study-Based Review and Future Pathways.” *Sustainability*, 8 (6): 558. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/su8060558.

Cao, J., D. F. Bucher, D. M. Hall, and M. Eggers. 2022. “A graph-based approach for module library development in industrialized construction.” *Computers in Industry*, 139: 103659. https://doi.org/10.1016/j.compind.2022.103659.

Costa, S., M. S. Carvalho, C. Pimentel, and C. Duarte. 2023. “A Systematic Literature Review and Conceptual Framework of Construction Industrialization.” *Journal of Construction Engineering and Management*, 149 (2): 03122013. American Society of Civil Engineers. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002410.

Ericsson, A., and G. Erixon. 1999. *Controlling design variants: modular product platforms*. Dearborn, Mich: Society of Manufacturing Engineers.

Feist, S., L. Sanhudo, V. Esteves, M. Pires, and A. A. Costa. 2022. “Semi-Supervised Clustering for Architectural Modularisation.” *Buildings*, 12 (3): 303. https://doi.org/10.3390/buildings12030303.

Ghannad, P., and Y.-C. Lee. 2023. “Optimizing Modularization of Residential Housing Designs for Rapid Postdisaster Mass Production of Housing.” *J. Constr. Eng. Manage.*, 149 (7): 04023046. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002390.

Gosling, J., M. Pero, M. Schoenwitz, D. Towill, and R. Cigolini. 2016. “Defining and Categorizing Modules in Building Projects: An International Perspective.” *J. Constr. Eng. Manage.*, 142 (11): 04016062. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001181.

Isaac, S., T. Bock, and Y. Stoliar. 2016. “A methodology for the optimal modularization of building design.” *Automation in Construction*, 65: 116–124. https://doi.org/10.1016/j.autcon.2015.12.017.

Jensen, P., T. Olofsson, M. Sandberg, and L. Malmgren. 2008. “Reducing complexity of customized prefabricated buildings through modularization and IT support.” 429–437. Universidad de Talca.

Kortler, S., M. Kreimeyer, and U. Lindemann. 2009. “A Planarity-Based Complexity Metric.” *DS 58-6: Proceedings of ICED 09, the 17th International Conference on Engineering Design, Vol. 6, Design Methods and Tools (pt. 2), Palo Alto, CA, USA, 24.-27.08.2009*, 31–42.

Murtaza, M. B., D. J. Fisher, and M. J. Skibniewski. 1993. “Knowledge-Based Approach to Modular Construction Decision Support.” *J. Constr. Eng. Manage.*, 119 (1): 115–130. https://doi.org/10.1061/(ASCE)0733-9364(1993)119:1(115).

Richard, R.-B. 2005. “Industrialised building systems: reproduction before automation and robotics.” *Automation in Construction*, 20th International Symposium on Automation and Robotics in Construction: The Future Site, 14 (4): 442–451. https://doi.org/10.1016/j.autcon.2004.09.009.

Said, H. M., T. Chalasani, and S. Logan. 2017. “Exterior prefabricated panelized walls platform optimization.” *Automation in Construction*, 76: 1–13. https://doi.org/10.1016/j.autcon.2017.01.002.

Salama, T., A. Salah, O. Moselhi, and M. Al-Hussein. 2017. “Near optimum selection of module configuration for efficient modular construction.” *Automation in Construction*, 83: 316–329. https://doi.org/10.1016/j.autcon.2017.03.008.

Salvador, F. 2007. “Toward a Product System Modularity Construct: Literature Review and Reconceptualization.” *IEEE Trans. Eng. Manage.*, 54 (2): 219–240. https://doi.org/10.1109/TEM.2007.893996.

Samarasinghe, T., T. Gunawardena, P. Mendis, M. Sofi, and L. Aye. 2019. “Dependency Structure Matrix and Hierarchical Clustering based algorithm for optimum module identification in MEP systems.” *Automation in Construction*, 104: 153–178. https://doi.org/10.1016/j.autcon.2019.03.021.

Schmidt, R., K. S. Vibaek, and S. Austin. 2014. “Evaluating the adaptability of an industrialized building using dependency structure matrices.” *Construction Management and Economics*, 32 (1–2): 160–182. https://doi.org/10.1080/01446193.2013.847274.

Sharafi, P., B. Samali, H. Ronagh, and M. Ghodrat. 2017. “Automated spatial design of multi-story modular buildings using a unified matrix method.” *Automation in Construction*, 82: 31–42. https://doi.org/10.1016/j.autcon.2017.06.025.

Sinha, K., H. Omer, and O. L. de Weck. 2013. “Structural complexity: Quantification, validation and its systemic implications for engineered complex systems.” *DS 75-4: Proceedings of the 19th International Conference on Engineering Design (ICED13), Design for Harmonies, Vol.4: Product, Service and Systems Design , Seoul, Korea, 19-22.08.2013*, 189–198.

Sinha, K., and O. L. de Weck. 2013. “A network-based structural complexity metric for engineered complex systems.” *2013 IEEE International Systems Conference (SysCon)*, 426–430.

Smith, R. E. 2010. *Prefab architecture: a guide to modular design and construction*. Hoboken, N.J: John Wiley & Sons.

Suárez, J. L., L. Gosselin, and N. Lehoux. 2023. “Optimizing Modularity of Prefabricated Residential Plumbing Systems for Construction in Remote Communities.” *J. Constr. Eng. Manage.*, 149 (1): 05022017. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002393.

Tidhar, N., Y. Li, K. S. Kristombu Baduge, P. Mendis, P. S. M. Thilakarathna, and E. R. K. Chandrathilaka. 2021. “A Slack approach to optimised modularisation of prefabricated structures using a multi-variable modularisation index.” *Structures*, 33: 1235–1251. https://doi.org/10.1016/j.istruc.2021.04.064.

Viana, D. D., I. D. Tommelein, and C. T. Formoso. 2017. “Using Modularity to Reduce Complexity of Industrialized Building Systems for Mass Customization.” *Energies*, 10 (10): 1622. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/en10101622.

Voordijk, H., B. Meijboom, and J. De Haan. 2006. “Modularity in supply chains: a multiple case study in the construction industry.” *International Journal of Operations & Production Management*, 26 (6): 600–618. https://doi.org/10.1108/01443570610666966.

Wee, T., M. Aurisicchio, and I. Starzyk. 2017. “Evaluating Modularisation Tools in Construction.” Taipei, Taiwan.

Williams, T. M. 1999. “The need for new paradigms for complex projects.” *International Journal of Project Management*, 17 (5): 269–273. https://doi.org/10.1016/S0263-7863(98)00047-7.