A Unified Framework for Integrating Design for Manufacturing and Assembly (DfMA) and Design for Deconstruction (DfD) in the Construction Industry

Cheryl Lyne C. Roxas[1,*], Rhem Leoric C. Dela Cruz[2], John Paul Q. De Pedro[2], and Breman M. Tamani[2], Nicanor R. Roxas Jr.[3]
[1] *Faculty, Department of Civil Engineering*
[2] *Research Assistant, Center for Engineering and Sustainable Development Research*
[3] *Faculty, Department of Manufacturing Engineering and Management*
**Corresponding Author: cheryl.capiz@dlsu.edu.ph*

Abstract: The escalating challenges in construction demand innovations to effectively tackle vital issues, such as inefficient processes, excessive costs, and heightened waste disposed of in landfills. Moreover, it is imperative to align current systems with the circular economy (CE) model to address resource scarcity and environmental degradation concerns. In recent years, design for X (DfX) approaches emerged as a potential solution to the ongoing challenges faced by various sectors. These methods have gained research and industry prominence due to their ability to optimize multiple product life cycle phases depending on the project objectives. In construction, notable design principles include design for manufacturing and assembly (DfMA) and design for deconstruction (DfD). However, there remains a gap in the body of knowledge about integrating these approaches. As such, this study proposes a framework that could assist practitioners in adopting such sustainable design methods. A literature review was performed to gather relevant principles and guidelines for creating the framework. Accordingly, the key priorities were identified, such as efficiency enhancement, cost reduction, and waste minimization. After identifying these parameters, the framework was developed according to a construction project's typical life cycle stages. The output of this research aids in the seamless adoption of DfMA and DfD strategies in construction projects. Future studies should employ the developed flowchart to validate its applicability further.

Key Words: circular economy, design for deconstruction, design for manufacturing and assembly, framework, sustainability

1. INTRODUCTION

Advancements in various disciplines constantly emerge to address contemporary challenges and improve the quality of individual life. Adopting these innovations directs nations toward economic prosperity and societal transformation. In this regard, current research efforts are centered on developing new or existing products and methods for achieving desired outcomes, such as efficient workflows and reduced expenditures. Design for X (DfX) approaches have gained prominence in reshaping conventional practices. These methods optimize a particular phase of the product lifecycle by incorporating relevant information and criteria in the final design. There are various types of DfX strategies. The application of these design principles depends on the objectives of a project. Regardless, implementing any technique ensures a more streamlined workflow across multiple sectors. Notably, these methods have brought tangible benefits to the construction industry.

Construction activities play a pivotal role in driving economic development. It generates vital infrastructures, such as bridges, buildings, dams, and roads, which accommodate regular operations. Due to rapid urbanization and population growth, there is currently a surge in demand for these facilities. However, several sustainability issues have become apparent as the number of erected structures in the built environment increases. Specifically, most construction processes result in adverse environmental impacts primarily associated with greenhouse gas emissions, energy consumption, wastes disposed of in landfills, and natural resources extracted from the Earth’s surface. Building construction uses 40% of raw materials, produces 40% of waste, and contributes 25% of carbon emissions worldwide (Oluleye et al., 2022). Additionally, numerous construction undertakings exhibit inefficient processes and excessive costs. Such problems affect all stakeholders involved. Hence, it is imperative to tackle these concerns effectively. Accordingly, research has been dedicated to exploring design principles to address these issues. Among these concepts are DfMA and DfD.

DfMA is a design approach that minimizes complexity, materials, labor, and operations in product manufacturing and assembly (Wasim et al., 2020). Its usage ensures system components can easily be fabricated and subsequently used to build the output. It originated from the manufacturing sector but has been widely utilized in construction. The benefits of implementing DfMA have been recognized, which include improved productivity, lowered costs, and reduced waste materials. Thus, utilizing DfMA strategies effectively addresses sustainability's environmental and economic dimensions.

In recent years, the circular economy (CE) concept has garnered heightened attention in research. It is a system that replaces conventional demolition procedures at a product’s end-of-life stage with sustainable practices, such as reducing, reusing, and recycling (Zisopoulos et al., 2022). This model significantly differs from the current linear economy (LE) structure, wherein products are demolished and sent to landfills. Adopting CE decreases resource extraction and waste generation. A prominent CE technique is DfD. Deconstruction refers to disassembling a product for future reuse or recycling (Rios et al., 2015). It is also known as “construction in reverse.” This approach ascertains that quality is preserved before a product is reintroduced into the supply chain. In DfD, deconstruction considerations are incorporated into the preconstruction phases. Like DfMA, it has been applied to building components and entire structures.

Employing DfMA and DfD is advantageous in construction. However, there is a lack of studies integrating these concepts. Many articles frequently reference these methods and categorize them under the umbrella term "DfX approaches." While these approaches can be effectively utilized separately, it is necessary to emphasize that these principles address distinct phases of a structure’s service life. Implementing DfMA does not tackle the end-of-life stage, and employing DfD does not thoroughly consider project execution. Therefore, the present study aims to generate a framework that integrates the principles outlined in DfMA and DfD studies. The findings of this research can furnish practitioners with guidelines for simultaneously or individually applying DfMA and DfD in a construction project.

2. METHODOLOGY

This study adheres to a systematic approach to creating the framework. The target objectives and scope were initially identified. Afterward, related literature was reviewed to determine relevant principles and guidelines. This review primarily extends the scope of a parallel study by Roxas et al. (2023) by concentrating on the framework development. Accordingly, the same set of studies were analyzed in this paper. Co-word analysis, a science mapping technique, was utilized for salient topics and their interconnections. VOSViewer was used for network visualization. This review identified the principles by evaluating the prevalent themes in DfMA and DfD research. Additionally, the guidelines were established by extracting the criteria for implementing these design approaches from the collected studies. The framework was generated after identifying these parameters.

3. RESULTS AND DISCUSSION

Numerous studies investigated the use of DfMA and DfD in construction. Fig. 1 illustrates the co-occurrence network of the author and index keywords in the papers gathered by Roxas et al. (2023). Co-occurring words appear at least twice in the articles’ keywords. As can be seen, the map is divided into five clusters distinguished by their respective colors: red (Cluster 1), blue (Cluster 2), green (Cluster 3), yellow (Cluster 4), and purple (Cluster 5).

Clusters 1 and 2 contain closely related words, such as “construction industry,” “design for manufacture and assembly,” “building information modeling,” “precast components,” “offsite construction,” “prefabrication,” “project management," and "productivity." Building information modeling (BIM) is the foremost technology integrated with DfMA. Research on the combined BIM and DfMA approach comprises the creation of a BIM component-based library (Abrishami & Martín-Durán, 2021), the development of a BIM-based DfMA framework that allows client participation (Bakhshi et al., 2022), and the generation of a BIM-enabled framework for building panelization (Liu et al., 2021). In these studies, BIM aided in connecting downstream and upstream activities, managing components, meeting client requirements, and expediting decision-making processes. Another widely explored concept is off-site construction (OSC), in which the construction process is shifted from the installation site to a controlled production plant (Jiang et al., 2018). Scholarly works on OSC include substituting reinforced concrete components with precast concrete (Hyun et al., 2022), the design of a prefabricated bamboo structure (Tan et al., 2020), and the design of prefabricated buildings (Yuan et al., 2018). These papers revealed reduced construction time and execution errors by applying DfMA. Overall, Cluster 1 studies elucidated the implementation of DfMA to enhance efficiency, whether by integrating it with OSC, BIM, or other technologies.

Cluster 3 centers on DfD and related terms like "recycling," "waste management," "reusable components," "concrete," "reinforced concrete," "concrete beams and girders," and "aggregates." Recycling and waste management efforts focused on the advancement of deconstructable concrete components. The feasibility of utilizing these parts in practical construction was determined by measuring their technical performance. Parallel studies explored beam-column joint designs for easy dismantling. Ding et al. (2020) concentrated on seismic performance, while Xiao et al. (2021) examined the effect of using recycled coarse aggregates. Both papers reported favorable results. Under seismic conditions, the beam-column joint exhibited ductile behavior. Additionally, specimens with recycled coarse aggregates exhibited durability when subjected to cyclic loading.

Studies investigated other disassemblable components, revealing varied performance according to the utilized metrics. In the work of Wang et al. (2020), a demountable composite beam made of clamping connectors and precast concrete planks demonstrated ductile characteristics with negligible yielding when subjected to full-service loading. In contrast, the DfD bolts attached to concrete blocks produced by Cai et al. (2019) exhibited inadequate behavior when exposed to cyclic compressive loads. As such, further explorations of these components should be conducted in future studies. These papers justify the need to choose suitable materials to ensure that the developed parts could effectively support widespread construction recycling, reuse, and waste management strategies.

Cluster 4 provides other essential words like "circular economy," "sustainable development," "sustainability," "reuse," and "end-of-life." Studies corroborated the impact of these design principles on environmental sustainability. Studies concerned with the environmental impact of applying DfMA centered on waste reduction.

Regarding DfD, studies utilized life cycle assessment (LCA) to assess the environmental impact. For instance, Xia et al. (2020) discovered that structures with DfD exhibited environmental benefits ranging from 1.8 to 2.8 times those without DfD. Another research by Eckelman et al. (2018) found that reusing DfD flooring systems could mitigate adverse environmental impacts by 60% to 70%. Aside from using LCA, environmental performance was evaluated according to ease of recycling and waste mitigation. Ortlepp et al. (2017) found that removing chemical bonds in building connections significantly enhances recyclability. Jayasinghe and Waldmann (2020) created a material and component bank to support deconstruction. The use of this product contributed to the effective construction and demolition waste (CDW) management of conventionally built structures. These studies underscored the critical role of waste reduction and collection of deconstruction data.

Cluster 5 predominantly focuses on timber. Besides concrete, timber is another material widely examined in research. Regarding DfMA, an example of a relevant study is the work of Wasim et al. (2020). In this paper, DfMA was applied to install a timber frame wall. Findings revealed a three-fold decrease in assembly time, significant cost savings, and reduced wastage. Concerning DfD, timber is associated with dry construction, enabling a structure's effective and practical disassembly. Nevertheless, applying these design methods to timber structures may stem from the need to broaden the range of available materials and practices. This observation corroborates the necessity of meticulously selecting appropriate materials and developing new materials emphasized in Cluster 3. For instance, Neve (2019) promoted the industry's extensive use of modular cross-laminated timber (CLT). Accordingly, Yazdi et al. (2021) and Bhandari et al. (2021) investigated the utilization of CLT in constructing structural walls and modular structures, respectively. However, research on this material is still in its infancy and must be extended in prospective studies. Nonetheless, such efforts to widen the pool of construction materials support choosing appropriate materials that seamlessly integrate with the design principles.

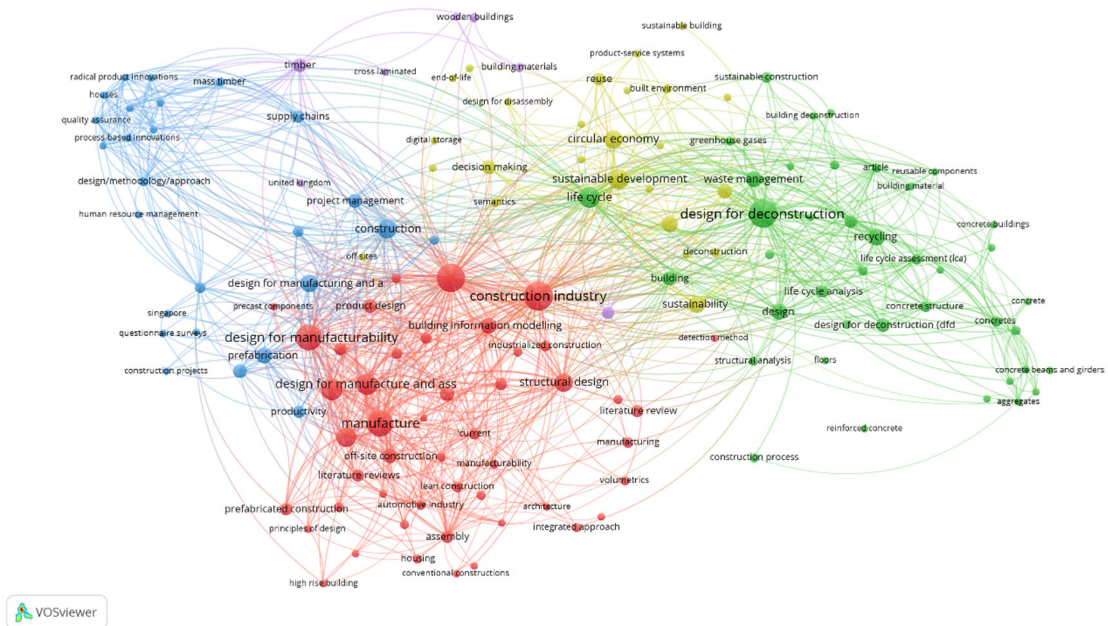

Fig. 1. Co-occurrence network of keywords

The review found the following priorities to be considered in the framework: efficiency optimization, cost reduction, and waste management for DfMA, as well as effective material selection, waste reduction, and deconstruction readiness for DfD. Thus, it was ensured that the guidelines employed aligned with these parameters.

The DfMA criteria developed by Boothroyd (2005) were considered, which include minimization of the number of parts, ease of handling, ease of insertion of parts, standardized parts, design for current process capabilities, and maintaining a margin for alternative design and assembly processes. These criteria consolidate additional guidelines offered by other studies.

DfD guidelines were collected in Roxas et al. (2023) and categorized in Fig. 2. These methods were divided into three groups: material selection, simplification, and deconstruction information collection. The material selection guidelines specify the types of materials that must be utilized. These components should be prefabricated, lightweight, reusable, environmentally friendly, and non-hazardous to ensure a quick deconstruction process and minimize the possibility of damage. Moreover, composite materials and secondary finishes must be avoided to reduce difficulties during disassembly. Finally, materials must be durable, and information should be recorded to ascertain recirculation in the supply chain.

The simplification guidelines focus on mitigating complexities in the system. Emphasis was placed on reducing and standardizing components, but contrary to the DfMA criteria, the simplification of connections was separated. Such connections must be demountable. Modular construction is also included. However, modular components are permissible if the structure cannot be modularized. Other essential techniques include employing dry construction, designing for accessibility, using an open building plan and structural grid, and incorporating interchangeable components. Dry construction typically uses components that could easily be dismantled. Moreover, accessibility to all building parts and technical installations is necessary for preserving the materials.

The deconstruction data collection guidelines are not directly associated with the structure's design.

However, it is critical to develop a deconstruction plan to guide the demolition contractor at the end-of-life phase. These approaches comprise the information and other requirements that must be stored and accomplished to support the deconstruction process.

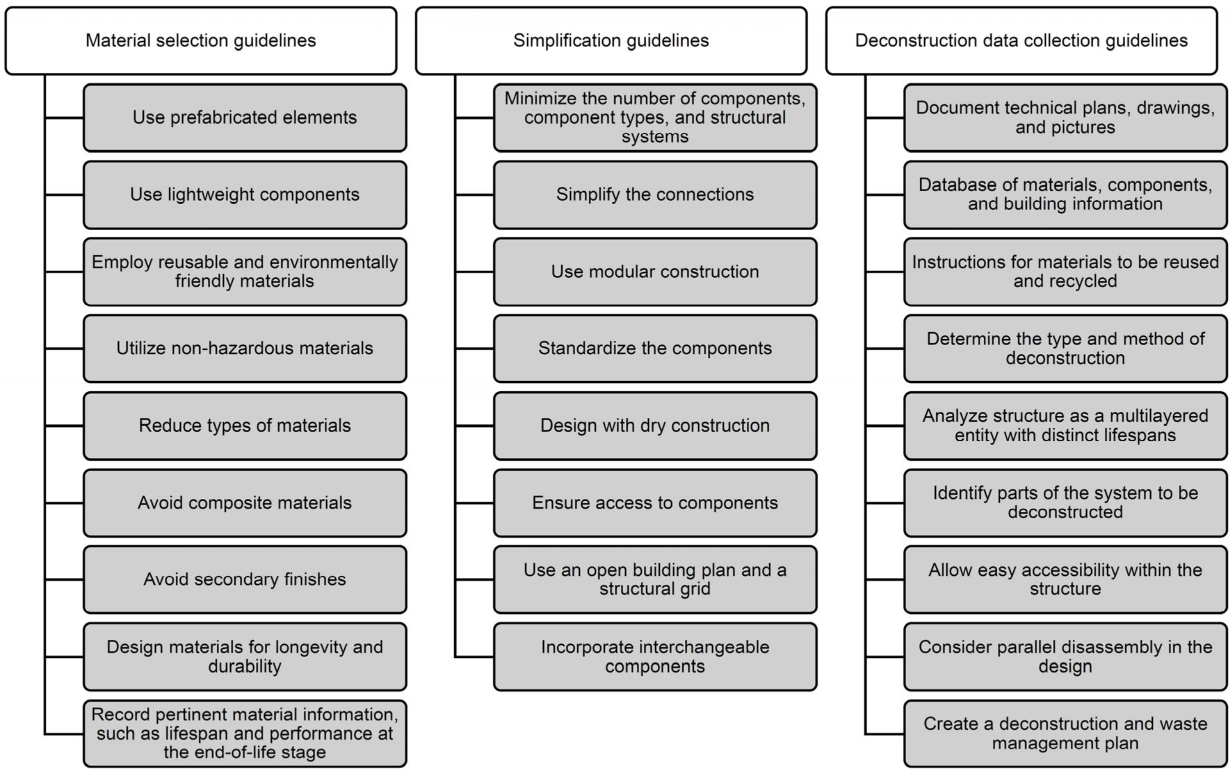

Fig. 2. DfD guidelines

Fig. 3 shows the generated framework for applying an integrated DfMA and DfD approach in construction projects. It is a process flowchart used to guide practitioners. It was also developed according to the typical life cycle of a project. In this framework, the objectives and requirements of a project are first identified and prepared. Afterward, the conceptual design and detailed design draft are accomplished. The established DfMA and DfD guidelines are incorporated during the design phase.

The flowchart initially asks the user if DfD will be applied. If yes, the designer will proceed with the DfD guidelines in Figure 4. This section has two outputs: the revised design with DfD and the comprehensive deconstruction plan. Upon accomplishing the revised design with DfD, the designer will determine if DfMA strategies will be employed. If the answer is affirmative, the designer will apply the DfMA guidelines presented. Consequently, a revised design with DfMA will be produced. However, it must be noted that the flowchart offers an option to individually apply DfMA or DfD or opt out of using both, depending on the project objectives. After revising the design, a thorough review will be conducted. If revisions are needed, the flowchart directs the designer to the detailed design draft level, which requires repeating the design process. However, if modifications are not necessary, the components can be fabricated, followed by the structure assembly. After completing the assembly process, the structure can be handed over to the client for use and maintenance. This phase is anticipated to last for a prolonged period. The original stakeholders may likely change during this time. In this regard, the comprehensive deconstruction plan will assist the demolition contractor. Using this plan, the structure can easily be disassembled, and the components can be recovered for future use.

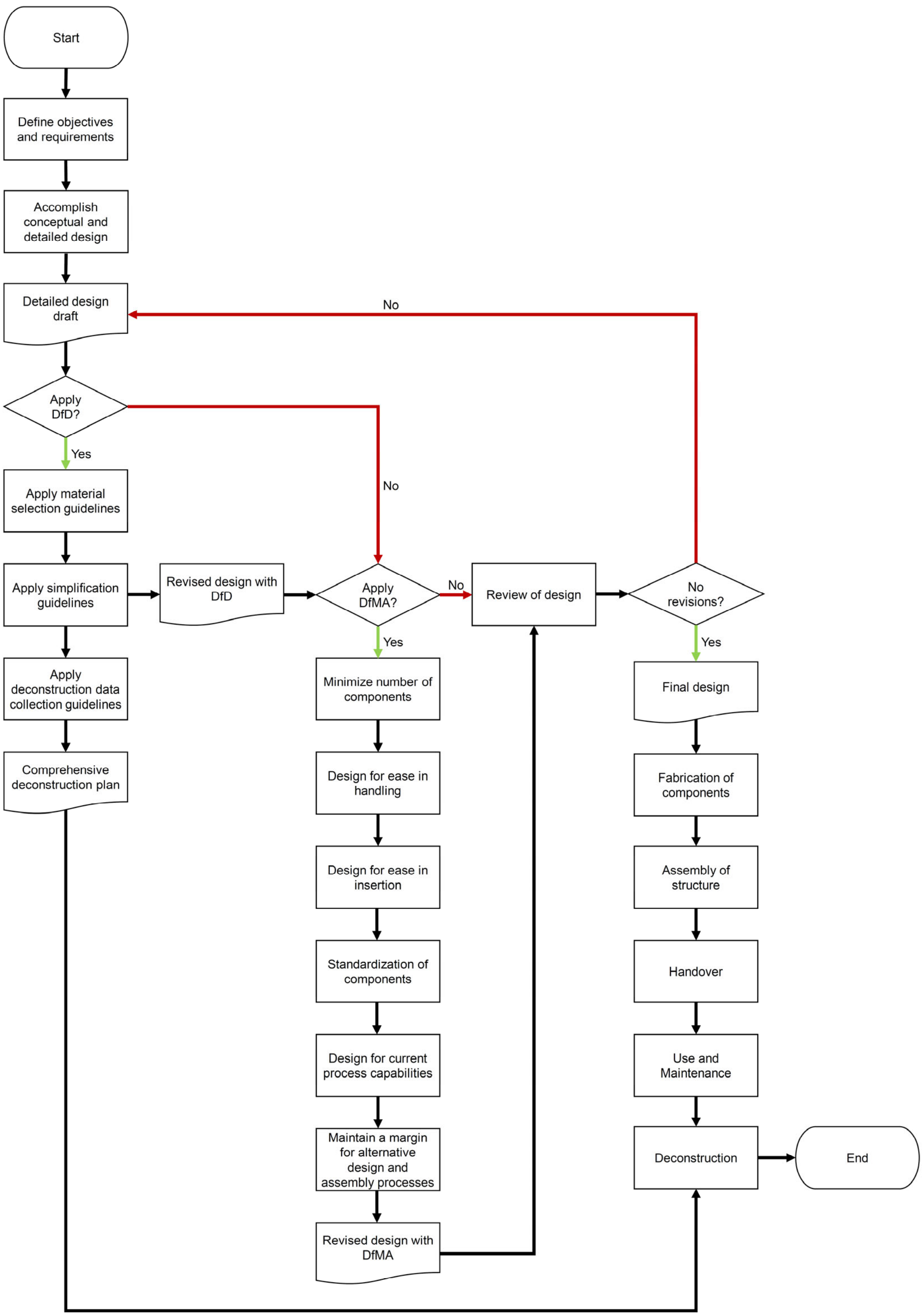

Fig. 3. Proposed framework

4. CONCLUSIONS

This study set out a process flowchart for enabling an integrated DfMA and DfD system in construction. A literature review was conducted to determine key priorities in the development of the framework. Accordingly, DfMA guidelines aimed at optimizing efficiency, reducing expenditures, and managing waste, as well as DfD guidelines directed toward effectively selecting materials, minimizing waste, and collecting deconstruction information, were gathered from various studies. The framework was created incorporating a construction project's typical life cycle stages. This scheme serves as a blueprint for assisting practitioners in implementing DfMA and DfD strategies. It facilitates responsible innovation by promoting sustainable design approaches considering the broader environmental and economic paradigm. Additionally, the techniques indicated in such concepts could significantly contribute to the targeted CE model.

Prospective investigations could expand the scope of this study. The framework's level of detail could be improved by soliciting the input of industry experts using methods such as interviews and surveys. Furthermore, the current flowchart must be verified through a case study involving its application on an actual construction project. Such undertaking would ascertain its applicability to real-world projects.

5. ACKNOWLEDGMENTS

This project is funded by the Department of Science and Technology (DOST) through the Science for Change Program (S4CP) – Collaborative Research and Development to Leverage Philippine Economy (CRADLE) and monitored by DOST Philippine Council for Industry, Energy, and Emerging Technology Research and Development (PCIEERD) with Project No. 8739. The authors want to acknowledge DOST, PCIEERD, the Department of Civil Engineering and Center for Engineering and Sustainable Development Research of De La Salle University, and Accutech Steel and Services, Inc. for supporting this paper.

6. REFERENCES

Abrishami, S., & Martín-Durán, R. (2021). Bim and dfma: A paradigm of new opportunities. Sustainability (Switzerland), 13(17). https://doi.org/10.3390/su13179591

Bakhshi, S., Chenaghlou, M. R., Pour Rahimian, F., Edwards, D. J., & Dawood, N. (2022). Integrated BIM and DfMA parametric and algorithmic design based collaboration for supporting client engagement within offsite construction. Automation in Construction, 133. https://doi.org/10.1016/j.autcon.2021.104015

Banks, C., Kotecha, R., Curtis, J., Dee, C., Pitt, N., & Papworth, R. (2018). Enhancing high-rise residential construction through design for manufacture and assembly - A UK case study. Proceedings of Institution of Civil Engineers: Management, Procurement and Law, 171(4), 164–174. https://doi.org/10.1680/jmapl.17.00027

Bhandari, S., Jahedi, S., Riggio, M., Muszynski, L., Luo, Z., & Polastri, A. (2021). CLT modular low-rise buildings: A DfMA approach for deployable structures using low-grade timber. World Conference on Timber Engineering 2021, WCTE 2021.

Boothroyd, G. (2005). Assembly Automation and Product Design. In Jurnal Ilmu Pendidikan (Vol. 7, Issue 2). CRC Press.

Cai, G., Xiong, F., Xu, Y., Larbi, A. S., Lu, Y., & Yoshizawa, M. (2019). A Demountable connection for low-rise precast concrete structures with DfD for construction sustainability-A preliminary test under cyclic loads. Sustainability (Switzerland), 11(13). https://doi.org/10.3390/su11133696

Ding, T., Xiao, J., Chen, E., & Khan, A.-U.-R. (2020). Experimental Study of the Seismic Performance of Concrete Beam-Column Frame Joints with DfD Connections. Journal of Structural Engineering (United States), 146(4). https://doi.org/10.1061/(ASCE)ST.1943-541X.0002576

Eckelman, M. J., Brown, C., Troup, L. N., Wang, L., Webster, M. D., & Hajjar, J. F. (2018). Life cycle energy and environmental benefits of novel design-for-deconstruction structural systems in steel buildings. Building and Environment, 143, 421–430. https://doi.org/10.1016/j.buildenv.2018.07.017

Hyun, H., Kim, H.-G., & Kim, J.-S. (2022). Integrated Off-Site Construction Design Process including DfMA Considerations. Sustainability (Switzerland), 14(7). https://doi.org/10.3390/su14074084

Jayasinghe, L. B., & Waldmann, D. (2020). Development of a BIM-based web tool as a material and component bank for a sustainable construction industry. Sustainability

(Switzerland), 12(5), 1–15. https://doi.org/10.3390/su12051766

Jiang, R., Mao, C., Hou, L., Wu, C., & Tan, J. (2018). A SWOT analysis for promoting off-site construction under the backdrop of China's new urbanisation. Journal of Cleaner Production, 173, 225–234. https://doi.org/10.1016/J.JCLEPRO.2017.06.147

Liu, H., Zhang, Y., Lei, Z., Li, H. X., & Han, S. (2021). Design for Manufacturing and Assembly: A BIM-Enabled Generative Framework for Building Panelization Design. Advances in Civil Engineering, 2021. https://doi.org/10.1155/2021/5554551

Neve, O. (2019). Modular CLT - Time to swallow the offsite pill. 20th Congress of IABSE, New York City 2019: The Evolving Metropolis - Report, 642–650.

Oluleye, B. I., Chan, D. W. M., Saka, A. B., & Olawumi, T. O. (2022). Circular economy research on building construction and demolition waste: A review of current trends and future research directions. Journal of Cleaner Production, 357. https://doi.org/10.1016/J.JCLEPRO.2022.131927

Ortlepp, S., Masou, R., & Ortlepp, R. (2017). Green construction methods of buildings capable for disassembly to support circular economy. Challenges for Technology Innovation: An Agenda for the Future - Proceedings of the International Conference on Sustainable Smart Manufacturing, S2M 2016, 21–26.

Rios, F. C., Chong, W. K., & Grau, D. (2015). Design for Disassembly and Deconstruction - Challenges and Opportunities. Procedia Engineering, 118, 1296–1304. https://doi.org/10.1016/J.PROENG.2015.08.485

Roxas, C. L. C., Bautista, C. R., Dela Cruz, O. G., Dela Cruz, R. L. C., De Pedro, J. P. Q., Dungca, J. R., Lejano, B. A., & Ongpeng, J. M. C. (2023). Design for Manufacturing and Assembly (DfMA) and Design for Deconstruction (DfD) in the Construction Industry: Challenges, Trends and Developments. Buildings, 13(5). https://doi.org/10.3390/buildings13051164

Tan, T., Lu, W., Li, C., Chen, K., & Tan, G. (2020). Implementation of Design for Manufacture and Assembly (DfMA) Principles in Construction: A Case Study. Construction Research Congress 2020: Project Management and Controls, Materials, and Contracts - Selected Papers from the Construction Research Congress 2020, 907–915.

Wang, L., Webster, M. D., & Hajjar, J. F. (2020). Design for Deconstruction Using Sustainable Composite Beams with Precast Concrete Planks and Clamping Connectors. Journal of Structural Engineering (United States), 146(8). https://doi.org/10.1061/(ASCE)ST.1943-541X.0002659

Wasim, M., Han, T. M., Huang, H., Madiyev, M., & Ngo, T. D. (2020). An approach for sustainable, cost-effective and optimised material design for the prefabricated non-structural components of residential buildings. Journal of Building Engineering, 32. https://doi.org/10.1016/j.jobe.2020.101474

Xia, B., Ding, T., & Xiao, J. (2020). Life cycle assessment of concrete structures with reuse and recycling strategies: A novel framework and case study. Waste Management, 105, 268–278. https://doi.org/10.1016/j.wasman.2020.02.015

Xiao, J., Chen, Z., Ding, T., & Xia, B. (2021). Effect of recycled aggregate concrete on the seismic behavior of DfD beam-column joints under cyclic loading. Advances in Structural Engineering, 24(8), 1709–1723. https://doi.org/10.1177/1369433220982729

Yazdi, A. J., Fini, A. A. F., & Forsythe, P. (2021). Mass-customisation of cross-laminated timber wall systems at early design stages. Automation in Construction, 132. https://doi.org/10.1016/J.AUTCON.2021.103938

Yuan, Z., Sun, C., & Wang, Y. (2018). Design for Manufacture and Assembly-oriented parametric design of prefabricated buildings. Automation in Construction, 88, 13–22. https://doi.org/10.1016/j.autcon.2017.12.021

Zisopoulos, F. K., Schraven, D. F. J., & de Jong, M. (2022). How robust is the circular economy in Europe? An ascendency analysis with Eurostat data between 2010 and 2018. Resources, Conservation and Recycling, 178, 106032. https://doi.org/10.1016/J.RESCONREC.2021.106032