CEES 2023 | 2nd International Conference on
Construction, Energy, Environment & Sustainability
27-30 June 2023, Funchal - Portugal

LIFE CYCLE ASSESSMENT FOR PREFABRICATED BUILDINGS: A STATE OF THE ART FOR ENHANCING CONSTRUCTION CIRCULARITY

Ana C. M. Barbosa [1]
Bruno A. F. Figueiredo [1]
Paulo J. S. Cruz [1]

[1] University of Minho, School of Architecture, Art and Design, Guimaraes | Portugal
Corresponding author: a84079@alunos.uminho.pt

Keywords

Circular Architecture; Life Cycle Assessment in Buildings; Prefabricated Construction; Design for Disassembly

Abstract

The construction sector is partly responsible for the high rise in waste production and environmental problems like air and water pollution, global warming, and biodiversity loss [1]. Designing buildings with a more circular approach that considers the deconstruction process alongside construction can help reduce waste and emissions in the Architecture, Engineering, and Construction (AEC) [2]. Prefabricated construction methods can also facilitate the adoption of circular principles [3] by increasing building efficiency and adequacy while mitigating the lack of skilled handwork and meeting tight deadlines [4]. However, to ensure circularity, materials and components used in prefabrication must be sustainable and designed for disassembly and reuse [5]. Life Cycle Assessment (LCA) is a methodology used to evaluate a building's life cycle holistically and identify opportunities for waste reduction and resource efficiency [6]. LCA methods can also inform the design process and help identify optimal end-of-life scenarios for materials and products in a circular economy framework [7,8,9]. Adopting circular economy principles and using LCA can help the construction sector minimize waste, maximize resource efficiency, and reduce the environmental impact of buildings and infrastructure [10-20]. This paper aimed to do a state of the art about the LCA in prefabricated buildings to enhance circularity in AEC.

1. INTRODUCTION

In recent years, the construction sector has reached historic records for CO2 emissions. The building sector is currently responsible for 50 % of primary raw material consumption globally and at least 40 % of all greenhouse gas emissions [21,22]. In parallel, in the past six years, the global economy consumed an additional half a trillion tonnes of virgin materials, namely minerals, ores, fossil fuels and biomass. These enormous volumes of materials—by and large wasted after use— are climbing year on year. Ultimately, waste is connected to most environmental problems, from biodiversity loss, to global warming and air and water pollution [1]. The building sector is currently responsible for producing approximately 30 percent of global waste [23]. The need to adopt notions of reuse and reduction of emissions and waste is a primary concern in the Architecture, Engineering and Construction (AEC) industry [2]. The current practices in the deconstruction of existing buildings have encountered multiple technical obstacles that hinder the successful recovery and reuse of materials and components. These barriers mainly originate from the conventional construction practices that perceive the assembly of materials and components as a unidirectional process aimed at creating a final building [24]. This linear approach to the built environment severely limits the options available at the end-of-life stage when a building has completed its service life. Instead, a more cyclical or closed-loop perspective of the built environment and its materials should be adopted. This approach recognizes the necessity of considering the deconstruction process along with the construction process during the project's design phase, which can be achieved by designing for disassembly [25]. Adopting prefabricated construction methods has numerous advantages [26], as it can also allow a better practice of circular principles in the building environment [3], in comparison to conventional building techniques. Regarding the lack of qualified handwork and the necessity of fulfilling the timelines burden in conventional buildings, prefabrication aims to increase the building's efficiency and adequacy [4]. However, to ensure that prefabrication is a circular approach, the materials and components used in the process must be sustainable and designed for disassembly and reuse. This means that materials must be selected for their ability to be easily separated and recycled at the end of their useful life [5].

2. PREFABRICATED CONSTRUCTION

Prefabricated, offsite, or modular construction [27], means the practice of manufacturing the components of a building or structure in factory circumstances and then transporting and assembling them onsite [28]. Prefabrication has been seen as a response to material waste, and it can be disassembled as easily as they were assembled and reused as industrial nutrients [29]. Prefabricated buildings have various sustainable benefits, such as fewer emissions, cost savings from construction, materials and manpower reductions [13].

Prefabrication can be understood at different levels [29, 30, 31, 32]. Considering four types of categorizations – Linear, Panel, Modular and Hybrid [33], prefabrication can be divided into four categories with each category based on its level of prefabrication: (1) the linear system in parts, with assembly in situ, is produced in large quantities and in specialized factories, delivered separately in the site, implying a high number of connections at the shipyard, (2) the panel system that consists in parts, with assembly in situ, involving some more elaborate components, which may already constitute the different layers of a constructive element (wall or slab), produced in large quantities and in specialized factories, delivered separately in the site, also implying some connections at the shipyard, (3) the modular factory-made three-dimensional system, that implies that all spaces and all components of the building are entirely made, assembled and finished in the factory as 3D structural modules, requiring only simple connections with the infrastructure, and (4) the hybrid system that combines the advantages of the linear system, in order to avoid the disadvantages of the modular system. The simplest elements are produced in the factory, such as slabs, walls and some infrastructure, the more complex parts of the building are elaborated in the shipyard. When choosing and implementing a prefabricated system, it's important to first meet each project's demands, as each of the categories has its own benefits and limitations and none is universal [31].

3. CIRCULAR ECONOMY IN AEC

As the building sector has the highest share in resource consumption, emissions and waste generation of all industries [34], the transition towards a CE in the built environment is vital to create a more sustainable society. The built environment can be made more circular by integrating CE principles in building components [8]. The CE concepts of reduction, reuse, and recyclability of materials and components were already successfully applied to a number of products, from electronic goods to clothing, but to a lesser extent for buildings and building components [3]. Because of the actual intrinsic linear form of construction [24], the AEC's industry transition to a circular economy aims to adopt easily assemble and disassemble dry-built architectural strategies and their executive design according to a life cycle thinking approach, with end-of-life scenarios [35]. The biological circular principles are different in a technical approach [21], so in order to implement circularity in AEC, technical cycles must be considered separately to avoid compromising the circularity potential of nutrients, goods and products and their corresponding mechanisms (see figure 1).

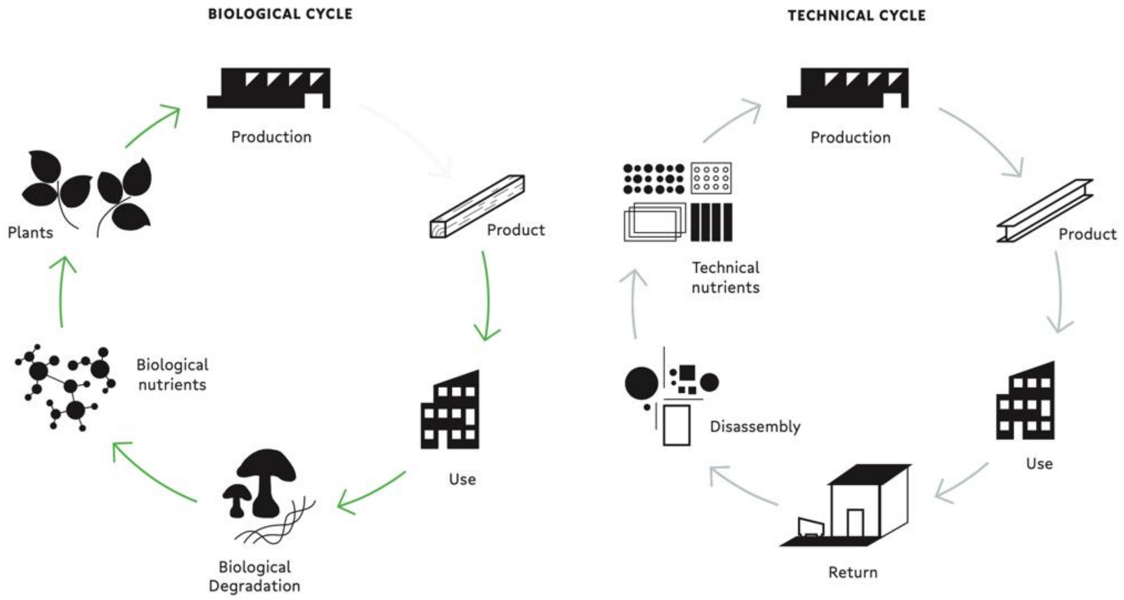

Figure 1. Differentiation between biological and technical cycles [21].

4. LCA AND CIRCULARITY

In order to evaluate the environmental impacts of buildings and construction methods, the Life Cycle Assessment (LCA) is a methodology that can assess a building's life-cycle holistically throughout its entire life cycle, identifying opportunities to reduce the environmental impact and waste production of buildings [6]. Life Cycle Assessment (LCA), it has in recent years become an increasingly important method for measuring and comparing the ecological impact of products and the built environment. A product life cycle can be considered in different phases: the production (raw material extraction, manufacturing, construction, installation, transportation), the use phase (operation and maintenance, including repair and replacements) and disposal (demolition, transportation, landfill or incineration). LCA examines and quantifies the different impacts on the natural environment over the various phases of the life cycle to provide a reliable basis for assessment and comparison. Aspects of reuse and recycling diverge from the conventional linear "cradle to grave" model, and as such can only be calculated as a potential. LCA methods can certainly also be used to map closed material cycles but it is, unfortunately, difficult to predict – and even more difficult to guarantee – what will actually happen to a product at the end of its service life as currently there is no legal obligation to adopt circular economy principles. [21]. Studies show an overall tendency to see building processes as linear rather than circular. As many LCA approaches only consider Cradle-to-Gate approaches, according to ISO 14044 (an international standard for environmental management and life cycle assessment). The understanding in the construction industry is not yet circular, as the LCA's standards (which are also the standards that many want to use for S-LCA) are linear [9]. LCA can be used to inform the design process and identify opportunities for the reuse and recycling of materials in a circular economy framework. For example, LCA can be used to evaluate the environmental impact of using recycled materials in construction, and to determine the optimal end-of-life scenarios for materials and products [7,8,9]. By using LCA in a circular economy approach, the construction sector can optimize the use of resources, minimize waste and reduce the environmental impact of buildings and infrastructure. [10-20]. The implementation of circular economy (CE) is still in the early stage for the built environment. The vague definitions, inadequate assessment methods and insufficient standard practices of CE discourage the transition process from a linear to a circular paradigm in the built environment. Application of LCA in CE can achieve this transition for the built environment [7]. Circular economy principles aim to minimize waste and maximize resource efficiency throughout the life cycle of a product, material, or building. By using LCA, the construction sector can identify the environmental impact of materials and products throughout their entire life cycle and identify opportunities to reduce waste and improve resource efficiency [5]. If an LCA study accounts for the important circular principles, it will stimulate circularity throughout the whole life cycle of a building solution, e.g., encourage the use of existing over new materials, stimulate multiple uses of materials, and reward reuse and high-quality recycling at the end of life [6]. Using prefabricated methods involves a selective deconstruction plan and reversible connection design or ease dismantling with reversible joints such as bolted, screwed and nailed connections, comprehending the design for disassembly purposes [7].

5. LCA IN PREFABRICATED BUILDINGS

The use of prefabricated methods in the AEC industry is demonstrating a better performance, compared with conventional methods. A selection of ten studies that assessed different phases of LCA in prefabricated buildings were analysed in order to help in the inference of a state of art in the LCA of prefabricated buildings. In addition to identifying the projects and authors of the studies, table 1 also indicates the type of structures and the indicators for the assessment, the LCA phases and the softwares that were employed in the LCA.

One of the most notable studies was conducted by Pons (2014), which involves an assessment of the sustainability of various types of prefabricated systems, with emphasis on the necessity of establishing a specific framework for evaluating prefabricated buildings. By adjusting the selection of systems, this type of assessment is relevant for comparing different prefabricated solutions.

In the elaboration of LCA in prefabricated buildings there is a predisposition to evaluate the life cycle in a more comprehensive way, in a cradle to grave perspective [4, 10, 11, 18, 20, 27]. The implementation of circularity principles in the LCA includes the end-of-life modules, where the scenarios may cover component recycling or reuse, for implementation in other buildings [36].

Table 1. State of the art on LCA of prefabricated buildings.

Author	Year	Building type	Location	Type of Structure	Indicators	LCA Phase	Softwares
Pons [18]	2014	School	Spain	Concrete, steel and wood industrialized systems	Economic: Construction and Assembly Cost; Cost derivation probability; Maintenance Cost; Environmental: water consumption; Co2 emissions; Solid waste; Energy consumption; Social: Neither adaptable nor disassemble building percentage; Derivation of neither adaptable nor disassemble building percentage; Labor risk of accidents during building and assembly; Users'risk of accidents during building enlargements;	Cradle to grave	MIVES, Simplified LCA
Cao et al. [4]	2015	Residential	China	Concrete systems	Resource Depletion; Ecosystem Damage and Health Damage;	Cradle to grave	BEPAS & CEPAS, BHIAS
Hong et al. [11]	2016	n.a.	China	Building components	Embodied Energy;	Cradle to grave	eBalance 4.7, CLCD
Honic et al. [36]	2019	Residential	Austria	Concrete and CLT	GWP (Global Warming Potential), AP (Acidification Potential) and PEI (Primary Energy Intensity), Embodied Energy	Cradle to cradle	BIM, Eco2Soft
Kamali et al. [15]	2019	Single family house	Canada	Wood-frame	Global warming potential; Acidification potential; Human health effect; Eutrophication potential; Smog potential; Ozone depletion potential; Fossil fuel consumption; Eco-toxicity effect	Cradle to gate	Athena Impact Estimator for Buildings
Balasbaneh & Ramli [10]	2020	Single family house	Malaysia	Concrete, steel	Non-renewable energy; Respiratory inorganics; Land occupation; Mineral extraction; Electricity and fossil fuel consumption; CO2 emissions; Global warming potential; Life cycle cost;	cradle to grave	BEES, Impact 2002
Wang et al. [27]	2020	Pubic	Japan	Prefabricated construction; cast in situ construction	Climate warming; Acidification, Health damage; Carbon emissions; Cost;	Cradle to grave	AIJ-LCA & LCW ver. 4.04
Ji et al. [12]	2020	Appartment building	China	Cast in situ concrete; precast concrete	Global warming; Ozone consumption; Ionizing radiation; Fine particle formation; Photochemical ozone formation; Human toxicity (cancer); Human toxicity (non-cancer); Water consumption; Freshwater ecotoxicity; Freshwater eutrophication; Terrestrial ecotoxicity; Terrestrial acidification; Marine ecotoxicity; Ecosystems damage ozone formation; Land occupation;	Cradle to gate	BIM, Ecoinvest 3..5 database, ReCiPe 2016
Tavares et al. [19]	2021	Single family house	Portugal	Light Steel Frame, Wood Frame, Brick masonry	Abiotic depletion (AD), Abiotic depletion (fossil fuels) (ADFF), Global warming (GW), Ozone layer depletion (OD), Photochemical oxidation (PO), Acidification (AC), Eutrophication (EU) (from CML 2001 baseline), and Non-renewable energy (NRE)	Cradle to grave	Sima Pro V8.0, Ecoinvent
Xu & Liu [38]	2021	Residential	China	Cast in situ concrete; precast concrete	Greenhouse gas emissions; fine particle emissions; acid gas emissions; energy resource consumption; consumption of mineral resources; monetization	Cradle to gate	ReCiPe2016

Most LCA's compare traditional or conventional construction with prefabricated construction [4, 11, 12, 15, 19, 27, 38], concluding that prefabricated construction has reduced consumption of materials, waste and energy, compared with the traditional and the conventional construction methods.

Within the prefabricated methods, those containing wood have a better environmental performance, a better absorption of CO2 as well as a greater potential for recycling [36]. It can be concluded that within prefabricated buildings, those containing prefabricated wood have better results in LCA [15, 18, 19, 27, 36].

6. CONCLUSION

Considering the analysis of the case studies and bibliographic references, this study has reached several conclusions. Adopting prefabricated methods in the current AEC has shown various benefits in alternatives to conventional construction. In comparison to conventional construction methods, modular prefabrication has been shown to provide significant sustainable advantages in terms of construction waste reduction, aesthetic versatility, reduced water usage, generated pollution, material savings, and the ability to reuse components. These advantages make prefabricated buildings a key component in the optimization of the construction industry. By implementing the identified strategies in prefabricated building construction, it is possible to establish a circular economy within the construction sector. The adoption of these strategies can lead to greater sustainability and efficiency in construction practices, ultimately benefiting both the industry and the environment.

The effective implementation of off-site construction requires the adoption of a new design system and standardization. In this regard, the concept of 'Design for Manufacturing and Assembly (DfMA)' has emerged as a crucial approach to ensure the success of off-site construction. However, there is a shortage of research on the integration of DfMA into off-site construction practices. In order to expand the implementation of circular construction, it is imperative to ensure economic feasibility. This can be achieved by reducing construction timelines, reusing materials in multiple design cycles, and minimizing labour-related risks and costs. To facilitate this shift towards a manufacturing-oriented approach, the development of standardized prefabricated components is necessary. This will enable the creation of a more efficient and sustainable construction industry, with a greater emphasis on the circular economy. The implementation of life cycle assessment (LCA) in circular economy practices for the built environment presents several benefits that contribute to the transition towards a sustainable and circular future. First, it strengthens the connection between circular economy and sustainable development. Second, it improves the comprehensiveness of circular economy assessments. Lastly, it reduces the environmental impact of circular economy practices. These advantages demonstrate the significance of LCA in promoting circular economy principles and practices. Hence, it can be inferred that LCA will continue to play a crucial role in implementing a circular economy in the built environment.

To achieve a more comprehensive assessment of the environmental impact of circular versus linear building elements, it is imperative to develop LCA studies that are in accordance with the methodological framework of EN 15804/15978 standards. Such studies can effectively incorporate critical circular principles and consider characteristic life cycle scenarios, thereby enabling a more rigorous evaluation of the environmental implications of circular economy practices in the built environment. This can be an essential step in promoting sustainable and circular practices in the built environment, developing circular principles and considering characteristic life cycle scenarios are important first steps to determining the environmental impact of circular versus linear building in a more robust way.

Acknowledgements

The authors wish to express their sincere gratitude to the Multiannual Funding of the Landscape, Heritage and Territory Laboratory (Lab2PT), under the Investigation Scholarship Lab2PT/UIDB-04509/14, financed by national funds (PIDDAC) through the Portuguese Foundation for Science and Technology (FCT) and Minister of Science, Technology and Higher Education (MCTES), that supported this initiative. Appreciation is also extended to all the members of the research team for their invaluable contributions.

References

[1] Circle Economy. (2022). “The Circularity Gap Report 2022”, (pp. 1-64, Rep.). Amsterdam. Circle Economy.

[2] United Nations Environment Programme, 2022. “2022 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector”. Nairobi.

[3] Minunno, R., O’Grady, T., Morrison, G., Gruner, R. & Colling, M., 2018. "Strategies for Applying the Circular Economy to Prefabricated Buildings" Buildings 8, no. 9: 125. https://doi.org/10.3390/buildings8090125.

[4] Cao, X., Li, X., Zhu, Y., & Zhang, Z., 2015. “A Comparative Study Of Environmental Performance Between Prefabricated And Traditional Residential Buildings In China”. Journal of Cleaner Production, 109, 131– 143. https://doi.org/10.1016/j.jclepro.2015.04.120.

[5] Dams, B., Maskell, D., Shea, D., Allen, S., Driesser, M., Kretschmann, T., Walker, P. & Emmitt, S., 2021. “A circular construction evaluation framework to promote designing for disassembly and adaptability”. Journal of Cleaner Production, Volume 316, 128122, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2021.128122.

[6] Van Gulck, L., Wastiels, L. & Steeman, M., 2022. “How to evaluate circularity through an LCA study based on the standards EN 15804 and EN 15978”. Int J Life Cycle Assess 27, 1249–1266. https://doi.org/10.1007/s11367-022-02099-w.

[7] Lei, H., Li, L., Yang, W., Bian, Y., Li, C., 2021. “An analytical review on application of life cycle assessment in circular economy for built environment.” Journal of Building Engineering, Volume 44, 103374, ISSN 2352-7102. https://doi.org/10.1016/j.jobe.2021.103374.

[8] Van Stijn, A., Malabi E., Jansen W., & Meijer, A., 2021. “A Circular Economy Life Cycle Assessment (CE-LCA) model for building components.” Resources, Conservation and Recycling, 174, [105683]. https://doi.org/10.1016/j.resconrec.2021.105683.

[9] V.G. Larsen, Tollin N., Sattrup P., Birkved M. & Holmboe T., 2022. “What Are The Challenges In Assessing Circular Economy For The Built Environment? A Literature Review On Integrating LCA, LCC And S-LCA In Life Cycle Sustainability Assessment, LCSA.” Journal of Building Engineering. https://doi.org/10.1016/j.jobe.2022.104203.

[10] Balasbaneh, A.T.; Ramli, M.Z., 2020. “A comparative life cycle assessment (LCA) of concrete and steel-prefabricated prefinished volumetric construction structures in Malaysia”. Environ Sci Pollut Res 27, 43186–43201. https://doi.org/10.1007/s11356-020-10141-3.

[11] Hong, J., Shen, G. Q., Mao, C., Li, Z., & Li, K., 2016. “Life-cycle energy analysis of prefabricated building components: An input–output-based hybrid model”. Journal of Cleaner Production, 112, 2198–2207. https://doi.org/10.1016/j.jclepro.2015.10.030.

[12] Ji, Y., Qi, K., Qi, Y., Li, Y., Li, H.X., Lei, Z. and Liu, Y., 2020. "BIM-based life-cycle environmental assessment of prefabricated buildings", Engineering, Construction and Architectural Management, Vol. 27 No. 8, pp. 1703-1725. https://doi.org/10.1108/ECAM-01-2020-0017.

[13] Jiang, Y., Zhao, D., Wang D., and Xing Y., 2019. "Sustainable Performance of Buildings through Modular Prefabrication in the Construction Phase: A Comparative Study" Sustainability 11, no. 20: 5658. https://doi.org/10.3390/su11205658

[14] Jin, R., Hong, J., & Zuo, J., 2020. “Environmental performance of off-site constructed facilities: A critical review.” Energy and Buildings, 207, 109567. https://doi.org/10.1016/j.enbuild.2019.109567

[15] Kamali, M., Hewage, K., & Sadiq, R., 2019. “Conventional Versus Modular Construction Methods: A Comparative Cradle-To-Gate LCA For Residential Buildings.” Energy and Buildings, 204. https://doi.org/10.1016/j.enbuild.2019.109479

[16] Kamali, M., & Hewage, K., 2016. “Life Cycle Performance Of Modular Buildings: A Critical Review.” Renewable and Sustainable Energy Reviews, 62, 1171–1183. https://doi.org/10.1016/j.rser.2016.05.031

[17] Moradibistouni, M., Vale, B., & Isaacs, N., 2019. “Evaluating Sustainability Of Prefabrication Methods In Comparison With Traditional Methods.” Smart Innovation, Systems and Technologies, 131, 228–237. https://doi.org/10.1007/978-3-030-04293-6_23.

[18] Pons, O., 2014. “Assessing The Sustainability Of Prefabricated Buildings.” In Eco-efficient Construction and Building Materials (pp. 434–456). Elsevier. https://doi.org/10.1533/9780857097729.3.434.

[19] Tavares, V., Soares, N., Raposo, N., Marques, P., & Freire, F., 2021. “Prefabricated Versus Conventional Construction: Comparing Life-Cycle Impacts Of Alternative Structural Materials.” Journal of Building Engineering, 41. https://doi.org/10.1016/j.jobe.2021.102705.

[20] Tavares, V., Gregory, J., Kirchain, R., & Freire, F., 2021. “What Is The Potential For Prefabricated Buildings To Decrease Costs And Contribute To Meeting EU Environmental Targets?” Building and Environment, 206, 108382. https://doi.org/10.1016/j.buildenv.2021.108382.

[21] Heisel, F., Hebel, D. E., & Webster, K., 2022. “Circular Construction and Circular Economy.” Birkhäuser.

[22] International Energy Agency, 2023. “CO2 Emissions in 2022”, IEA, Paris. https://www.iea.org/reports/co2-emissions-in-2022, License: CC BY 4.0.

[23] OECD, 2019. “Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences.” OECD Publishing, Paris, https://doi.org/10.1787/9789264307452-en.

[24] Ellen MacArthur Foundation, 2013. “Towards the Circular economy: Economic and Business Rationale for an Accelerated Transition”. Ellen MacArthur Foundation, Cowes.

[25] Crowther, P., 2009. “Designing for Disassembly”. Technology, design and process innovation in the built environment, (pp. 224–237). Abingdon: Taylor & Francis.

[26] Gibb, A.G., 1999. “Off-Site Fabrication: Prefabrication, Pre-Assembly and Modularisation”; John Wiley & Sons: Hoboken,NJ, USA.

[27] Wang, H., Zhang, Y., Gao W., & Kuroki S., 2020. "Life Cycle Environmental and Cost Performance of Prefabricated Buildings" *Sustainability* 12, no. 7: 2609. https://doi.org/10.3390/su12072609

[28] Chauhan, K., Peltokorpi, A., Lavikka, R., and Seppänen, O., 2019. “Deciding Between Prefabrication and On-Site Construction: A Choosing-by-Advantage Approach.” Proc. 27th Annual Conference of the International. Group for Lean Construction (IGLC), Pasquire C. and Hamzeh F.R. (ed.), Dublin, Ireland, pp. 749-758. DOI: https://doi.org/10.24928/2019/0158.

[29] Smith, R. E., 2010. “Prefab Architecture: A Guide To Modular Design And Construction”. John Wiley & Sons, Inc. New Jersey.

[30] Knaack, U., Chung-Klatte, S., & Hasselbach, R., 2012. “Prefabricated Systems: Principles of Construction.” Birkhäuser.

[31] Smith, R. E., & Quale, J. D., 2017. “Offsite Architecture: Constructing the Future.” Routledge. Oxon.

[32] Staib, D., & Rosenthal., 2008. “Components and Systems: Modular Construction.” Birkhäuser.

[33] Barbosa, Ana. 2023. “A Pré-fabricação Como Método Construtivo para uma Arquitetura Sustentável”. Tese de Mestrado. Guimarães.

[34] Ness, D.A., Xing, K., 2017. “Toward a resource-efficient built environment: a literature review and conceptual model.” J. Ind. Ecol. 21, 572–592. https://doi.org/10.1111/ jiec.12586.

[35] Palumbo, E; Camerin, F; Panozzo, C. & Rossetti, M., 2021. “La gestione del fine vita come strumento di progetto: il caso di un involucro a secco in legno” journal article In TECHNE. Retrieved from http://hdl.handle.net/10446/211695.

[36] Honic, M., Kovacic, I., Rechberger, H., 2019. “Improving the recycling potential of buildings through Material Passports (MP): An Austrian case study”. Journal of Cleaner Production, Volume 217, Pages 787-797, ISSN 0959-6526. https://doi.org/10.1016/j.jclepro.2019.01.212.

[37] Jin, R., Gao, S., Cheshmehzangi, A., & Aboagye-Nimo, E., 2018. “A Holistic Review Of Off-Site Construction Literature Published Between 2008 And 2018.” Journal of Cleaner Production, 202, 1202–1219. https://doi.org/10.1016/j.jclepro.2018.08.195

[38] Xu, M. & Liu, Y., 2021. “Environmental impact assessment of Materialization Stage of prefabricated buildings based on LCA and WTP”. IOP Conference Series: Earth and Environmental Science, Volume 634. 2nd International Conference on Civil Engineering, Environment Resources and Energy Materials. 18-20 September 2020, Changsha, China.