Development of a Multi-life cycle assessment framework for temporary modular housing

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Abstract
In recent years, temporary modular housing (TMH) has been widely built worldwide to satisfy the housing requirements of vulnerable groups. Although the environmental and economic benefit of TMH relocation is potentially exciting, little is known about the environmental and economic impacts of TMH that are evaluated across its whole life cycle. This study proposes a new framework to assess TMH's environmental and economic impacts over several life cycles, which was created based on the concept of multi-life cycle assessment (MLCA) and multi-life cycle costing (MLCC). Besides, to better understand the comprehensive performances of TMH deconstruction, a single index will be computed to uniform the economic and environmental impacts. The proposed framework consists of three modules: the input module, the assessing module, and the output module. The input module is used to manage the inventory and other pertinent data. The scope and method of assessment are provided by the assessment module. Finally, the evaluation results and a sustainability index will be given in the output module. This research contributed to producing a new evaluation guideline for TMH that explains how modular units can be better built to achieve multi-life cycle environmental and economic sustainability.

Keywords
multi-life cycle assessment, multi-life cycle costing, temporary modular housing, circular economy.

1. Introduction

The building sector, a large contributor to the global economy, greatly affects sustainable development by increasing resource consumption and waste generation. A building significantly impacts the environment, economy, and society throughout its life cycle, from the extraction of raw materials to the end of life. Globally, there is a growing demand for sustainable buildings due to population expansion and resource scarcity. In recent years, temporary modular housing (TMH) has been an appropriate solution to satisfy sustainable demands. This type of building is becoming increasingly popular in many places due to its rapidity and economic feasibility. TMH can be moved and reused several times due to its modular designs, undergoing multiple life cycles. By decreasing the use of virgin resources, minimizing demolition waste, and preserving economic and environmental value, which implements the circular economy (Yang et al., 2022).

Most of the existing sustainability assessment methodologies place a greater emphasis on the single life cycle. Researchers from the TU Delft and other European universities have made the first steps toward developing methodologies for assessing the environmental impact of building components over the multi-life cycle environmental impact and multi-life cycle economic impact in the context of circular construction. For instance, van Stijn et al. (2021, 2022) and Wouterszoon Jansen et al. (2020) assess several kitchen design solutions' environmental and economic impacts over the course of a multi-life cycle. Also, Cascione et al. (2022) evaluated the environmental performance of bio-based wall panels. Although the environmental and economic gains of TMH relocation are potentially exciting little is known about: how the environmental and economic impacts of TMH are assessed from the multi-life cycle point of view. Therefore, this study will further complete the multi-life cycle assessment (MLCA) and multi-life cycle costing (MLCC) methods and propose a new framework to assist assessment and comparison of the multi-life cycle environmental and economic impacts of TMH. The study's results will include recommendations for improving the modular unit design to achieve multi-life cycle environmental and economic sustainability.

This research will distinguish itself from the others by (i) including building services in the multi-life cycle impact analysis, an area that lacks prior research attention; (ii) developing a new approach to improve the evaluation efficiency of the multi-life cycle impact analysis; and (iii) developing an evaluation guideline for TMH to attain its multi-life cycle sustainability.

2. MLCA framework.

This study's proposed framework was derived from the logical evaluation framework for sustainable building. It consists of three modules: an input module, an assessment module, and an output module. The critical elements collected from a comprehensive analysis are incorporated into various modules, as shown in Fig. 1. The input module defines the goal and scope and provides a life cycle inventory for sustainability assessment. The assessment module quantifies the environmental and economic impacts based on the normalized methods. The output module provides the sustainable index and evaluation outcomes.

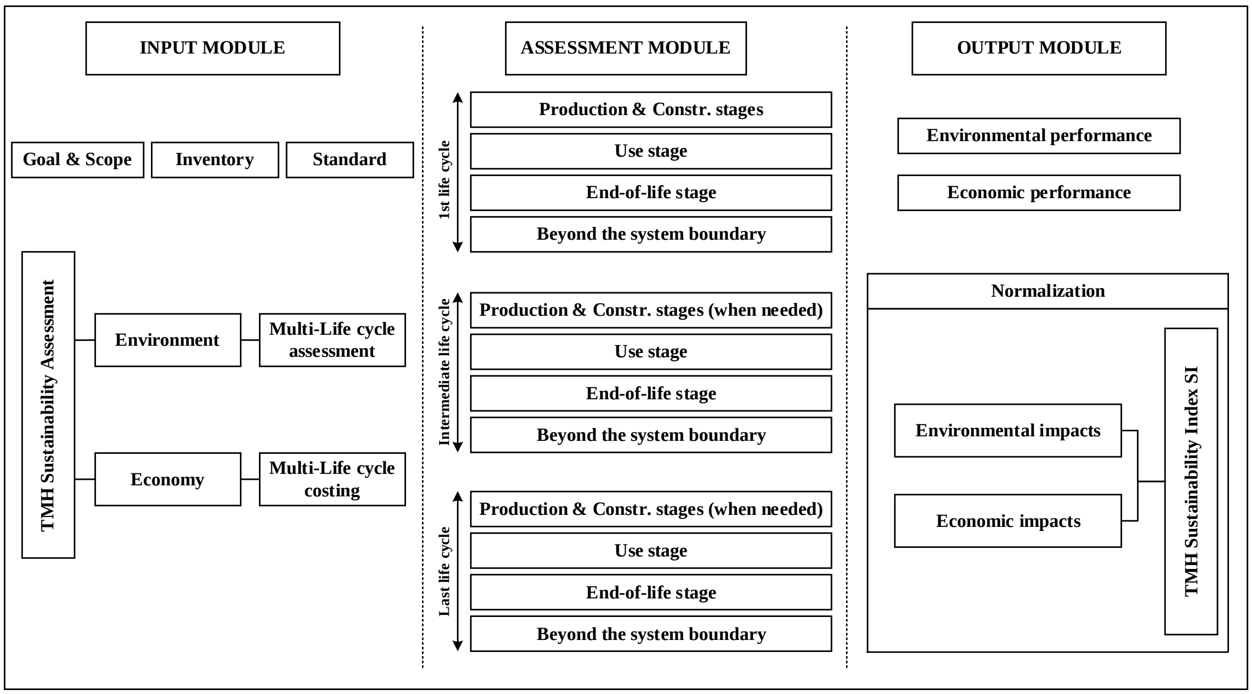

Fig. 1. Framework for TMH sustainability assessment.

2.1 Input module

The input module manages the input information, including data collecting and processing, and provides the goal-inventory-standard hierarchy. The goal is to quantify TMH's environmental and economic impacts throughout its multi-life cycle, from the initial to the end. When developing the framework based on the three pillars concept, only the environmental and economic impacts are considered. There are numerous environmental impact categories that differ between countries and assessment standards. The present study evaluates the environmental performance with the global warming potential (100a), since embodied carbon is typically used as the accounting unit of environmental performance. The life cycle cost is chosen as the economic performance criterion, and among the many costs involved in the life cycle of TMH, initial investment cost, maintenance cost, disassembly cost, and disposal cost are taken into account. The life cycle inventory includes geometric data, unit impact factors, and project documents. Geometric data is typically extracted from 2D drawings and 3D models; impact factors include unit cost and emission factor, which can be obtained from professional databases and standard datasets; and project information is obtained from contractors and suppliers.

2.2 Assessment module

According to Europe Norm 15978 (2011), the life cycle stage of a building (component) - and system boundary of the LCA - is divided into four Modules: A (production and construction), B (usage), C (end-of-life), and D. (benefits and loads beyond the system boundary). Based on the standard framework, the life cycle stages of TMH per cycle are depicted in Figure 2. To avoid duplicate calculations, the sub-processes involved in each life cycle step should be distinguished. In the initial life cycle, for example, Module A includes production, transportation, and installation. Module A in the intermediate lifespan includes the re-assembly of reusable modular components as well as the manufacture of new modular units as needed. Module B is the usage of modular units, which will encompass repair and maintenance while excluding energy and water use for operation (Minunno et al., 2020). The proposed MLCA and MLCC techniques will concentrate on the environmental and economic implications inside and outside the evaluated modular units over numerous life cycles (van Stijn et al., 2021). Modular units, for example, can be repaired and reused within the same system or recycled as secondary materials utilized elsewhere.

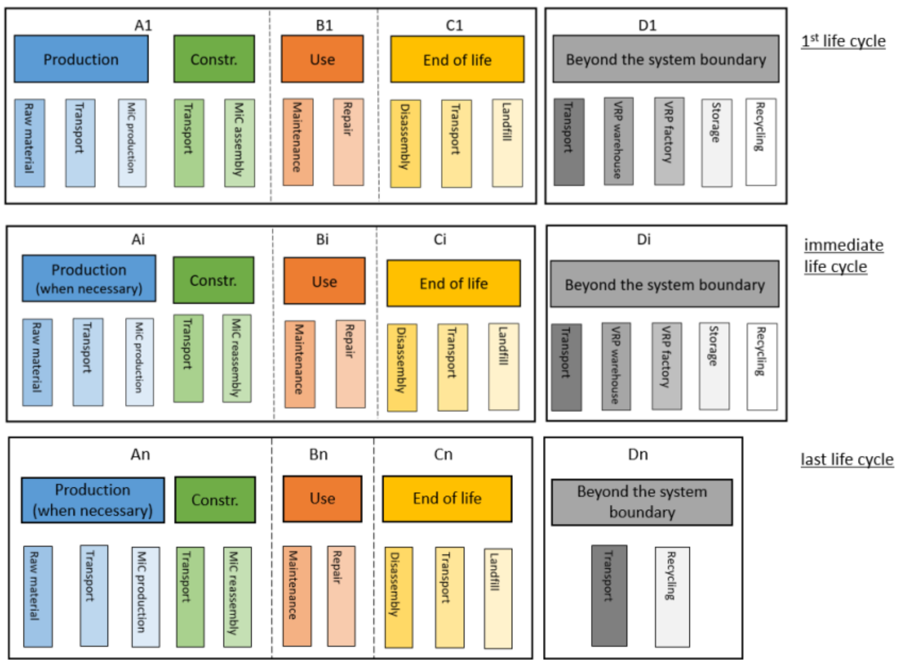

Figure 2 Life cycle stage and system boundaries

2.3 Output module

The output module quantifies the environmental and economic impacts of the TMH over its multi-cycle. Because of the intricacy of multiple factors, solely computing performance is meaningless. As a result, appropriate weights were allocated to each criterion, and the results were aggregated into a single index using the data normalization process, yielding the 'Sustainability Index.' This process could help prevent contradictory conclusions arising from the economic and environmental analysis (Silvestre et al., 2013).

3. Multi-life cycle assessment

MLCA calculations will be developed based on previous standards and research (de Wolf et al., 2020; PAS 2050: 2011, 2012; van Stijn et al., 2021) by (a) dividing the processes into sub-processes, (b) expanding the system boundary to multiple life cycles, (c) allocating the environmental loads and gains between cycles, and (d) accounting for material degradation in future life cycles. The sum of the environmental impacts of structural systems and building services throughout several life cycles will be used to assess the total environmental impact of a modular unit. The environmental benefits of relocation and reuse will be ascribed to the life cycle after that. The following equations show a simplified mathematical description of the proposed MLCA framework. Equation 1 illustrates the carbon emissions produced by the first life cycle, which combines the impacts of production, on-site assembly, repair, disposal, and recycling.

$$En_1 = En_{P1} + En_{O1} + En_{U1} + En_{D1} + En_{Rec1} \quad \textbf{(1)}$$

Where: In the first life cycle. En_{P1} is the total environmental load of production; En_{O1} is the total environmental load of on-site assembly; En_{U1} is the total environmental load of repair; En_{D1} is the total environmental load of disposal; En_{Rec1} is the net environmental impact of recycling.

As to the intermediate life cycle, the carbon emissions incorporate modular reuse, on-site re-assembly, repair, disposal, and recycling, as depicted in Equation 2. In the intermediate stage, the components' reusability levels will be considered in modular reuse En_{rusi}. The reusability of modular unit components will be decided by (i) material lifespan and (ii) material quality loss, and this will be considered in the environmental impacts of modular reuse. The technical lifespan or functional lifespan of a substance determines its lifespan. Some obsolete materials, such as fireproofing boards, will be replaced by new ones as their technological lifespans approach. Some deteriorating materials, such as beam-column connectors, may require removal from whole modular units. Besides, the incompatible modular design with the new site layout may impact the functional lifespan. As a result of this effect, incompatible modular modules may be discarded.

$$En_i = En_{rus,i} + En_{Oi} + En_{Ui} + En_{Di} + En_{rec,i} \quad \textbf{(2)}$$

Where: In the intermediate life cycles. En_{rusi} is the total environmental load of modular reuse; En_{Oi} is the total environmental load of on-site assembly; En_{Ui} is the total environmental load of repair; En_{Di} is the total environmental load of disposal; En_{Reci} is the net environmental impact of recycling.

In the last life cycle, all the materials are recovered, recycled, reused, or landfilled. The total emissions are shown in Equation 3, which combines the impacts of modular reuse, on-site re-assembly, repair, disposal, and recycling.

$$En_l = En_{rus,l} + En_{Ol} + En_{Ul} + En_{Dl} + En_{rec,l} \quad \textbf{(3)}$$

Where: In the last life cycle. En_{Pl} is the total environmental load of production; En_{Ol} is the total environmental load of on-site assembly; En_{Ul} is the total environmental load of repair; En_{Dl} is the total environmental load of disposal; En_{Recl} is the net environmental impact of recycling.

4. Multi-life cycle costing

The sum of structural systems and building services expenses throughout multiple life cycles will be used to calculate the total economic impact. The economic benefits and costs of relocation and reuse will be attributed to the next life cycle. Throughout the return on investment period, time value and discount rates will be examined for multiple life cycles (Wouterszoon Jansen et al., 2020). Economic factors like the cost of carbon and life cycle will be added to building sustainability assessments for TMH. It is technically impossible to achieve 100% material recycling or relocation of TMH. In this study, TMH deconstruction refers to relocation, recycling, and disposal. Deconstruction expenses, value-added, carbon emissions, and carbon footprint savings will be utilized to determine economic viability. More specifically, the value gained from relocation and the resale value of recycled materials will be subtracted from the total costs associated with disposal, recycling, and relocation, which includes transportation and handling costs, to determine the economic sustainability of TMH deconstruction. Equation 4 depicts the overall cost generated by the first life cycle, which includes costs for production, on-site assembly, repair, and disposal. The resale value of recycled materials will be deducted from the total costs in the initial cycle.

$$Ec_1 = Ec_{P1} + Ec_{O1} + Ec_{U1} + Ec_{D1} - Ec_{Rec1} \quad \textbf{(4)}$$

Where: Ec_{p1} is the total cost of production; Ec_{o1} is the total cost of on-site assembly; Ec_{U1} is the total cost of repair; Ec_{D1} is the total cost of disposal; En_{Rec1} is the gained value produced from material recycling.

Time is an important consideration in any cost model or economic framework. If the relationship of time-value is neglected, cost reduction, regardless of when it occurs, would seem to have higher cost alternatives. As a result, all costs in the MLCC framework should be calculated at the present value (PV) because stakeholders use different discount rates defined for each stakeholder. In the current study, most housing units could be kept reusing during the intermediate life cycle. The future costing will be converted to the PV. The total cost of each intermediate cycle could be computed by Equation 5, which includes the expenses of replacing broken housing units, re-assembling modules, repair and maintenance, and disposal. The value acquired through resale material will also be subtracted from the total cost.

$$Ec_i = \frac{(Ec_{rusi} + Ec_{rei} + Ec_{Ui} + Ec_{Di} - Ec_{Reci})}{(1+i)^t} \quad \textbf{(5)}$$

Where: Ec_{rusi} is the cost of replacement of broken housing module; Ec_{o1} is the cost of re-assembly; Ec_{Ui} is the total cost of repair and maintenance; Ec_{Di} is the cost of disposal; En_{Reci} is the gained value produced from material recycling. i represent the discount rate, and t indicates the time in years.

All materials and modular housing will be deconstructed and disposed of at the end of the life cycle. Similarly, the final life cycle's overall cost can be evaluated using Equation 6, which incorporates the expenses of replacing broken housing units, re-assembling housing modules, repair and maintenance, and disposal.

$$Ec_l = \frac{(Ec_{rusl} + Ec_{rel} + Ec_{Ul} + Ec_{Dl} - Ec_{Recl})}{(1+i)^t} \quad \textbf{(6)}$$

Where: Ec_{rusl} is the cost of replacement of broken housing module; Ec_{ol} is the cost of re-assembly; Ec_{Ul} is the total cost of repair and maintenance; Ec_{Dl} is the cost of disposal; En_{Recl} is the gained value produced from material recycling. i represent the discount rate, and t indicates the time in years.

5. Sustainability index

In order to create a single and comparable number, deconstruction's environmental costs and benefits will be turned into an economic unit. This research used a shadow price method, which unites all category indicators into a single sustainability index. Carbon costs will be calculated using a predetermined carbon value. These factors are related to the cost of carbon emissions that the public pays for, such as the loss of property due to the rise of sea level. This procedure may help in avoiding contradicting outcomes from economic and environmental assessments. The integrated sustainability index SI is calculated below (Equation 7).

$$\text{SI} = Ec_{total} + En_{total} \times u_{cp} \quad \textbf{(7)}$$

Where: Ec_{total} is the cost of the whole TMB life cycle, En_{total} is the total carbon emissions, u_{cp} is the unit price of carbon emissions.

6. Conclusion

The need for TMH is quickly becoming a trend as building stakeholders become more aware of the advantages of sustainable construction. The research first updates and improves the existing LCA and LCC methodology that overcome multiple life cycle challenges. Although still in the conceptual stage, implementing the proposed framework will support multi-aspect evaluation for TMH across its whole life cycle and assist in achieving a higher level of TMH circularity. With the help of this innovative method, professionals will be able to monitor the long-term environmental and economic impacts of modular housing throughout multiple life cycles. In the future, we can Incorporate a larger range of sustainability standards, including some for social sustainability indicators, which will expand the framework's functionality. The suggested MLCA and MLCC frameworks can also be tested on various buildings to ensure their robustness and validity. By doing so, the proposed MLCA and MLCC methods may help the global development of LCA and LCC standards by incorporating important methodological aspects concerning multiple life cycles. This study will promote regional and international standard and practice reforms in the building sector to promote sustainable multiple life cycle management.

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