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Life Cycle Assessment of a Structural Insulated Panel Modular House in New Zealand

Aflah Alamsah Dani [1], Ran Feng [2,3,*], Zhiyuan Fang [1] and Krishanu Roy [1,*]

[1] School of Engineering, University of Waikato, Hamilton 3240, New Zealand; ad413@students.waikato.ac.nz (A.A.D.); arthur.fang@waikato.ac.nz (Z.F.)
[2] School of Civil and Environmental Engineering, Harbin Institute of Technology, Shenzhen 518055, China
[3] Guangdong Provincial Key Laboratory of Intelligent and Resilient Structures for Civil Engineering, Harbin Institute of Technology, Shenzhen 518055, China
* Correspondence: fengran@hit.edu.cn (R.F.); krishanu.roy@waikato.ac.nz (K.R.)

Abstract: Innovative solutions are essential to meet the increasing demand for housing in New Zealand. These innovations must also be sustainable, given the significant contribution of the building and construction sectors to global carbon emissions (25–40%) and, specifically, to New Zealand's gross carbon emissions (20%). This research aims to analyse the environmental impacts of a structural insulated panel (SIP) modular house and evaluate this innovative approach as a sustainable solution to the current housing issue. A life cycle assessment (LCA) was conducted using the New Zealand-specific tool LCAQuick V3.6. The analysis considered seven environmental impact indicators, namely, global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), photochemical ozone creation potential (POCP), abiotic depletion potential for elements (ADPE), and abiotic depletion potential for fossil fuels (ADPF), with a cradle-to-cradle system boundary. Focusing on the embodied carbon of the SIP modular house, the study revealed that the whole-of-life embodied carbon was 347.15 kg CO_2 eq/m^2, including Module D, and the upfront carbon was 285.08 kg CO_2 eq/m^2. The production stage (Modules A1–A3) was identified as the most significant source of carbon emissions due to substantial energy consumption in activities such as sourcing raw materials, transportation, and final product manufacturing. Specifically, the study found that SIP wall and roof panels were the most significant contributors to the house's overall embodied carbon, with SIP roof panels contributing 25% and SIP wall panels contributing 19%, collectively accounting for 44%. Hence, the study underscored the SIP modular house as a promising sustainable solution to the housing crisis while emphasising the inclusion of operational carbon in further research to fully understand its potential.

Keywords: life cycle assessment (LCA); structural insulated panels (SIPs); modular house; embodied carbon emissions; New Zealand

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Academic Editor: Apple L.S. Chan

Received: 21 November 2024
Revised: 25 December 2024
Accepted: 4 January 2025
Published: 6 January 2025

Citation: Dani, A.A.; Feng, R.; Fang, Z.; Roy, K. Life Cycle Assessment of a Structural Insulated Panel Modular House in New Zealand. *Buildings* **2025**, *15*, 146. https://doi.org/10.3390/buildings15010146

1. Introduction

Recent studies in the building and construction (B&C) sector highlight the increasing significance of sustainable housing trends. Incorporating sustainable practices into affordable housing can enhance energy efficiency, minimise resource waste, and create healthier living spaces [1]. The B&C sector accounts for 37% of global carbon emissions [2] and contributes 20% of New Zealand's total carbon emissions [3]. Throughout its life cycle, from construction to demolition, a building demands considerable energy [4]. Environmental performance is now a key design factor in construction, with a focus on sustainable methods and materials to reduce greenhouse gas emissions. In New Zealand, both government and industry are working to lower emissions, targeting reductions in embodied carbon and operational emissions [5]. Therefore, adopting a sustainable housing strategy can be one of the solutions to the climate change issue, not only minimising carbon emissions from the industry but also addressing some housing challenges such as overcrowding, poor accessibility, substandard housing, high costs, and a lack of financial support [6,7]. Changes in population, particularly the increase in the number of households, lead to an increased demand for housing [8]. According to the United Nations [9], the primary cause of the housing crisis is the disparity between the supply and demand of housing, which has resulted in a marked rise in homelessness over the past ten years. Anenberg and Ringo [10] found that approximately 93% of the reduction in the monthly supply of homes for sale could be attributed to increased demand. This underscores the need for an innovative approach to addressing the housing crisis, as conventional construction methods are increasingly inadequate to meet the growing demand while also being sustainable to meet the carbon reduction target.

Modular housing presents a viable solution to the housing crisis and has gained popularity over the past decade due to its advantages over traditional construction methods. Modular construction involves the off-site construction of structural parts, followed by their transportation to the construction site for assembly. This approach provides advantages, such as faster construction time, safer manufacturing processes, improved quality control, and reduced environmental impacts compared to conventional on-site construction methods [11]. A study conducted by Subramanya et al. [12] highlights the benefits of modular construction, showing an average 40% reduction in project completion time and 80% fewer incidents due to the minimalistic on-site construction approach. There are several types of modular construction, including the structural insulated panel (SIP) system. SIPs are composite materials consisting of a foam insulation core sandwiched between two structural facings, typically oriented strand board (OSB) [13,14]. The development of SIPs has been driven by the demand for enhanced thermal performance and structural efficiency in building construction [15]. SIPs provide enhanced insulation, minimise cold bridging, and comply with building regulations [13]. They are energy-efficient and easy to install, and they offer greater strength and soundproofing compared to conventional construction methods [14].

Life cycle assessment (LCA) is one of the environmental impact evaluation methods that can be used for construction products and buildings, supporting comparison and improvement [16]. The ISO 14040:2006 standard [17] provides a general approach to LCA, covering stages such as defining the goal and scope, compiling the Life Cycle Inventory (LCI), conducting the Life Cycle Impact Assessment (LCIA), interpreting data, and reporting results. An example of building LCA was conducted by Asif et al. [18] for housing in Scotland, highlighting concrete, timber, and ceramic tiles as the three most energy-intensive materials. Another building LCA study of a single-family timber house in Sweden was performed in 2019 by Petrovic et al. [19]; the study revealed that the building emitted 6 kg CO_2 eq/m^2 per year over a 100-year lifespan within a cradle-to-grave system boundary, which corresponds to 600 kg CO_2 eq/m^2 of gross floor area. In New Zealand, several LCA studies on buildings and building products have been conducted [20–22]. Dani et al. [23] performed a comparative LCA of light timber and light steel-framed houses in Auckland, New Zealand, revealing that over a 90-year lifespan, the total embodied carbon was 347.4 kg CO_2 eq/m^2 for the light timber house and 465.3 kg CO_2 eq/m^2 for the light steel-framed house. An LCA study by Quale et al. [24] compared modular and site-built residential constructions, looking at the cradle-to-gate system boundary. The study discovered that modular home construction generally has less of an impact on the environment than traditional on-site construction [24]. Studies have shown that various factors influence a house's environmental performance, including design options, construction materials, operational patterns, and heating systems [25]. However, it should be noted that there are challenges remaining with the LCA methodology, where the results of the assessment are highly influenced by the selection of calculation tools, databases, and methods [26].

Initiatives have been introduced to reduce carbon emissions, necessitating a methodical approach. Modular construction has become a sustainable practice that can boost the housing supply due to its efficiency in construction time and reduced environmental impacts. LCA is one of the most widely recognised methodologies for comprehensively assessing the environmental performance of products, including but not limited to SIP modular houses. Design choices and material selections are critical factors that significantly impact a building's performance, and LCA serves as a valuable tool for quantifying their direct contributions to the overall environmental footprint. The literature consistently highlights the application of LCA as a reliable approach to evaluating the environmental impacts of buildings. However, there remains a gap in comprehensive research assessing the environmental performance of SIPs in modular houses over the entire life cycle of the building. Analysing the environmental performance of SIP modular houses using the Life Cycle Assessment (LCA) method is crucial for understanding their overall impact from production through to end of life. This assessment evaluates whether SIP modular houses offer net environmental benefits and highlights opportunities to reduce their environmental footprint. Additionally, conducting an LCA helps ensure compliance with green regulations and initiatives while promoting innovation in climate-resilient construction practices. Therefore, an LCA study is necessary to fill this gap and explore the potential of SIP modular houses as a solution to the housing crisis in New Zealand. The primary goal of this research is to evaluate the environmental performance of the SIP modular construction system. To achieve this, an LCA is conducted, providing a thorough analysis of the environmental impact of the modular house. The findings are expected to assist the construction industry in understanding the potential environmental impacts, particularly the global warming potential (GWP), associated with using SIPs. Therefore, three research objectives are outlined to achieve the main goal of the study, which are as follows: (1) to analyse the environmental impacts of a modular building that was built using SIPs; (2) to perform a hotspot analysis of the modular building's whole-of-life embodied carbon emissions; and (3) to evaluate the contribution of SIPs to the environmental impacts of the modular building.

2. Materials and Methods

To achieve the objectives of this study, an LCA was carried out in accordance with the ISO 14040:2006 standard [17], which provides the methodological framework for LCA. The process commenced with defining the assessment's goal and scope, including the system boundary and functional unit. This was followed by the life cycle inventory phase, during which both foreground and background data were gathered. The subsequent life cycle impact assessment involved selecting an impact assessment method. Finally, an interpretation analysis was performed to derive the outcomes of the assessment. The research workflow for this study is illustrated in Figure 1.

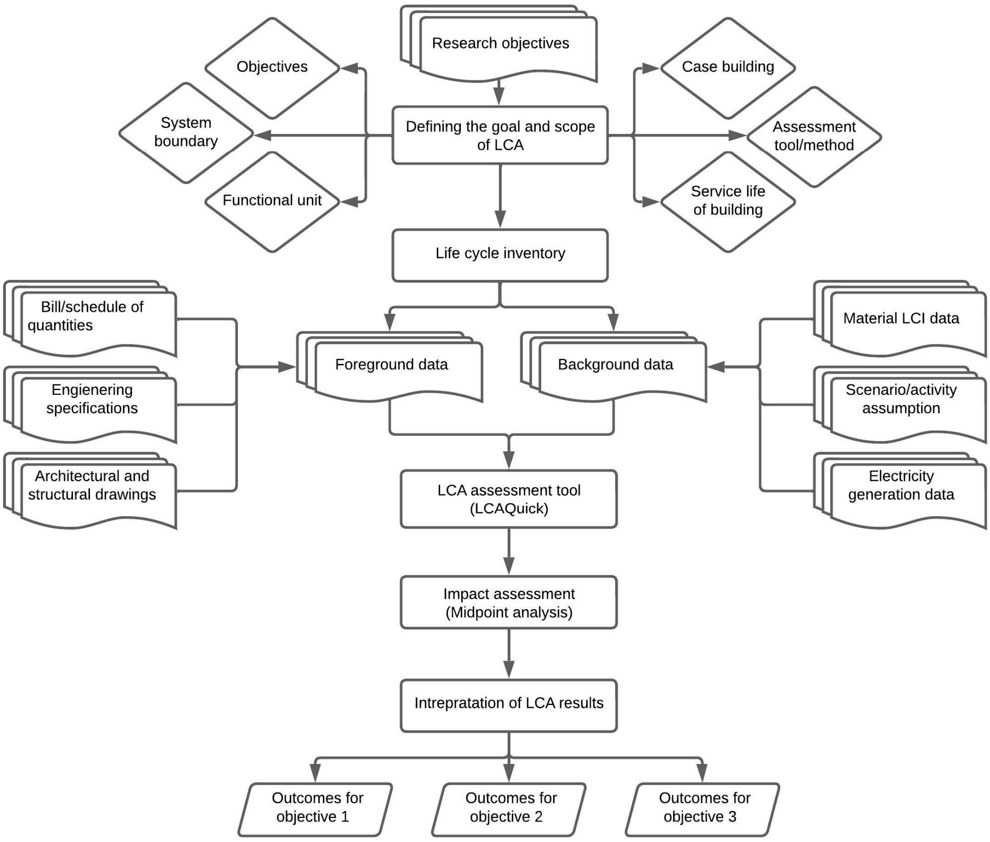

Figure 1. Research workflow.

2.1. Goal and Scope of LCA

2.1.1. Goal Definition

The increasing need for LCAs in buildings is highlighted by the rising carbon footprints observed both globally and nationally in recent decades. As reported by Stats NZ [27], residential buildings were the largest contributors to pollution among gross fixed capital assets, representing 28% of the total. This situation has led numerous countries to conduct environmental assessments of these assets to mitigate rising carbon emissions. The goal of this LCA was to examine the potential environmental impacts of a SIP modular house in New Zealand. Specifically, this assessment was conducted to analyse the possible ecological effects (e.g., global warming potential) generated by using SIPs as exterior wall and roof systems in a building in Auckland, New Zealand. The results were intended to assist the industry in identifying the potential environmental impacts of SIP modular houses in the country and analysing the contribution of SIPs to the overall embodied carbon emissions of the modular house, thereby addressing existing knowledge gaps.

2.1.2. Scope Definition

The scope of the building elements assessed in the study was based on the mandatory components specified in the Whole-of-Life Embodied Carbon Assessment: Technical Methodology guideline [28]. Consequently, elements not included in the guideline or classified as voluntary, such as water, drainage, electrical services, fixtures, fittings, furniture, decks, and stairs, were excluded from the assessment. Therefore, the study focused on the following categories of building elements: (1) substructure, including foundations and floors; (2) superstructure; (3) external envelope; (4) internal finishes; and (5) non-structural internal elements.

This LCA was conducted using a cradle-to-cradle system boundary approach, which accounts for the potential carbon offsets associated with the building materials. This system boundary was chosen to assess the environmental impacts of the case study building throughout its entire life cycle. This approach aligns with the principles of the circular economy and sustainability, focusing on minimising waste and carbon emissions. It also promotes recycling or upcycling at the end of life, contributing to the development of a more sustainable and positive community. The cradle-to-cradle system boundary includes modules A1 (raw material supply) through C4 (disposal) and also considers the benefits and loads beyond the system (module D). Figure 2 depicts the building life cycle stages assessed in this study, highlighted in green.

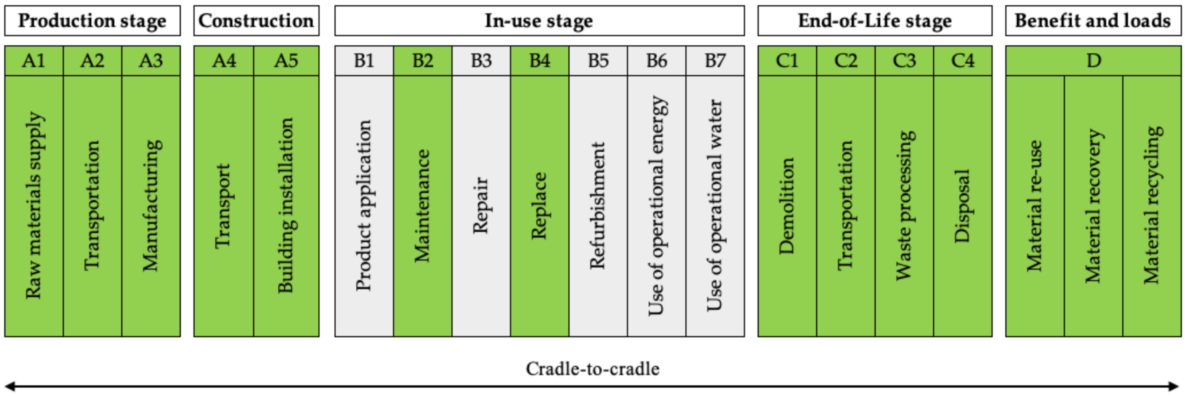

Figure 2. The selected system boundary in this study.

The functional unit was defined as one square metre of the modular SIP house's gross floor area (GFA) over the building's service life. The building was assumed to have a 50-year building service life, following the guidelines of the Whole-of-Life Embodied Carbon Assessment: Technical Methodology [28]. Products with service lives shorter than the project's lifespan were assumed to be replaced at intervals corresponding to their service lives. However, the operational energy and water use stages of the building were excluded from the functional unit. Therefore, the unit of the assessment results was the environmental impact unit per square metre (e.g., kg CO_2 eq/m^2).

Several assumptions guided the LCA conducted in this study. These premises were used to support the assessment process and help define unspecified, unidentified, or unmeasured data inputs. It is important to note that assumptions in LCA research can potentially affect and influence the findings and conclusions of the assessment [29]. The study assumed that biogenic carbon sequestration was not included in the assessment, based on the NZGBC's Green Star NZ Embodied Carbon Methodology [30]. Although this sequestration value was excluded from the overall results, it was reported separately.

Regarding building materials, the study assumed that materials outside the building's dripline were excluded from the analysis. The HVAC system was also excluded because the focus was on building elements within the study's scope. Structural connections, such as the individual screws, nails, other fastening elements, and minor fittings, were considered significant and subject to the cut-off criteria outlined in EN 15978:2011 [31]; thus, they were excluded from the study.

The accuracy of such an LCA relies heavily on the reliability and quality of the data in the BRANZ database [32]. Outdated or incomplete data can introduce uncertainty in the results. This study used New Zealand-specific geographic data, applying local carbon coefficients and energy consumption figures. As a result, the findings should be interpreted with caution when comparing them to buildings outside the study's scope, as they are highly dependent on geographic location and specific building materials and processes.

2.2. Life Cycle Inventory (LCI)

According to ISO 14040:2006 [17], LCI analysis is a step in LCA that involves collecting and estimating a product's inputs and outputs across its life cycle. This step necessitates gathering all the necessary information to conduct the LCA study. The LCI process involves two types of data: foreground data (primary) and background data (secondary). The foreground system refers to the specific processes within a system that the decision maker controls, such as building quantity data. On the other hand, the background system involves processes that are part of it but are not directly influenced by the decisions analysed in the study, such as raw material extraction, the production of construction products, and the generation of water and electricity [33].

A modular house located in Auckland, New Zealand, was chosen as the case building in this study. It was a one-story, detached residential building that was built with SIPs as the main structural material in its exterior walls and roof systems. The scope of construction work for the building was a new build, and no demolition of existing buildings occurred in this project. The GFA of the modular house was 88 m^2, and this value excluded the deck area. Figure 3 presents a 3D view model of the house, while Figure 4 shows the floor plan.

(**a**) (**b**)

Figure 3. A 3D view model of the SIP modular house: (**a**) front view; and (**b**) back view.

The building information data (foreground data), such as the architectural drawings and bill of quantities (BOQ), were collected from the local construction company. However, not all building elements' quantities were recorded in the BOQ; therefore, a manual calculation of the building quantity data was performed by referring to the architectural drawings and engineering specification documents. For example, in quantifying the detail materials for the SIPs (i.e., wall and roof systems), the technical documents from the SIP supplier were referred to [34], such as Figure 5. Table 1 presents the primary data for this LCA study, specifically the starting data on the building materials.

Background data include inventory information on processes, materials, and energy flows not directly linked to the specific product or system being evaluated, allowing LCA studies to account for upstream and downstream impacts across the entire product or process life cycle [35,36]. Environmental Product Declarations (EPDs) and online open-access LCA databases typically source these data for building LCAs, playing a crucial role in promoting the use of LCA in the construction industry [37]. The BRANZ CO2NSTRUCT database [33] served as the source of background data for this study's LCA of the SIP modular house.

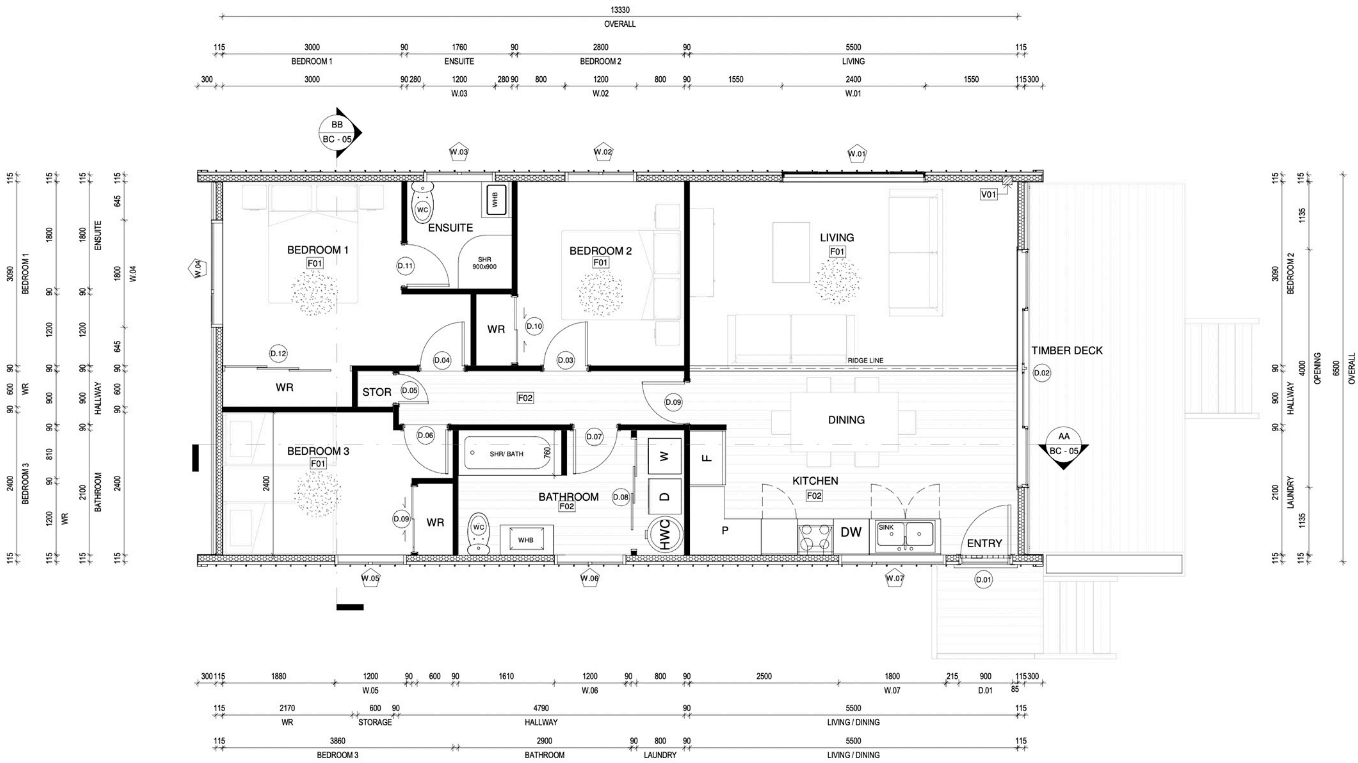

Figure 4. A house plan of the SIP modular house.

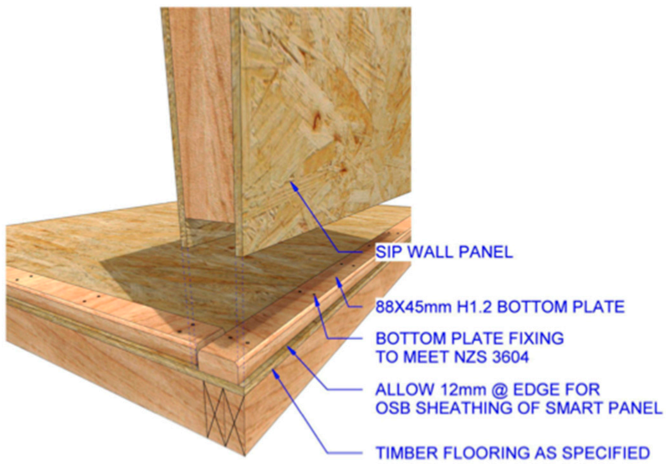

Figure 5. SIP wall panel connection to floor [29].

Table 1. Building material data of the case study building.

Building Element	Material Description	Unit	Quantity
Foundation	Reinforced concrete, 25 MPa, in situ, inc. 100 kg/m^3 steel reinforcement (OPC)	m^3	0.41
	Softwood timber H4, structural applications (timber post)	m^3	0.13
Floor system	Softwood timber H3.1, structural applications	m^3	4.73
	Plywood floor	m^3	1.49
	Membrane (DPM), polyethylene under slab, vapour barrier	m^2	78.5

Table 1. *Cont.*

Building Element	Material Description	Unit	Quantity
Floor finishes	Carpet tile	m^2	55.5
	Direct-pressure laminate, flooring	m^2	23
Wall frame	Stud wall system, steel, primary (galvanised finish, coating class Z275), 0.75 BMT	m^2	95
Wall finishes	Plasterboard (GIB® standard 10 mm)	m^3	1.51
	Plasterboard (GIB aqualine® 10 mm)	m^3	0.39
	Paint, water-borne, walls (2 coats/m^2)	m^2	151.42
Exterior wall cladding	Composite timber exterior cladding	m^2	55
	Steel wall cladding 0.55 mm BMT	m^2	80
Wall SIP systems	Wall SIP, 115 mm thick, R4.5	m^2	135
	Softwood timber H1.2, framing applications	m^3	0.13
	Engineered wood, LVL (Nelson Pine, NZ)	m^3	0.15
	Softwood timber H3.1, framing applications	m^3	0.46
	Membrane, building wrap, polyethylene (PE)	m^2	135
Windows/doors	Window/door, IGU, double glazing	m^3	0.19
	Window/door frame (aluminium)	m^3	0.04
Interior doors	Door, interior, MDF, unpainted	m^2	19.56
	Paint, water-based acrylic primer/undercoat (1 coat/m^2)	m^2	19.56
	Window/door frame (PVC-U)	m^3	0.31
Roof systems	Roof SIP, 215 mm thick, R9.4	m^2	106
	Engineered wood, LVL (Nelson Pine, NZ)	m^3	0.07
	Steel roof cladding, 0.55 mm BMT	m^2	106
	Aluminium, flashing, flat sheet, 0.9 mm BMT	m^2	21.52
	Aluminium, profile sheet metal (for box gutter), 0.9 mm BMT	m^2	9.75
	Softwood timber H1.2, framing applications	m^3	0.43

2.3. Impact Assessment Method and Tool

Impact categories help evaluate a wide range of effects and make LCA results more understandable and comparable. The selection of impact categories may vary depending on the specific goals and scope of the LCA study. Impact assessment in LCA has two approaches: midpoints and endpoints (damage-oriented) [38,39]. Midpoints are points along the cause–effect chain of an impact category (e.g., global warming potential), while endpoints focus on the final outcomes, such as human health and ecosystems [40,41]. Aligning with the goal of the LCA study, the midpoint impact method was chosen, and EN 15978:2011 [31] and EN 15804+A1:2013 [42] were followed in defining the environmental impact indicators for the assessment. This selection was based on the accessibility of the impact assessment method in the LCA tool and the availability of compatible data. Table 2 shows the environmental impact indicators that were assessed in this study.

Table 2. The selected environmental impact indicators.

Impact Categories	Units
Global warming potential (GWP)	kg CO_2 eq
Stratospheric ozone depletion potential (ODP)	kg CFC 11 eq
Acidification potential of land and water (AP)	kg SO_2 eq
Eutrophication potential (EP)	kg $PO_4{}^{3-}$ eq
Photochemical ozone creation potential (POCP)	kg C_2H_2 eq
Abiotic depletion potential for elements (ADPE)	kg Sb eq
Abiotic depletion potential for fossil fuels (ADPF)	MJ (NCV)

The environmental impact assessment was conducted using an NZ-based LCA tool named LCAQuick V3.6. This tool was a simplified spreadsheet model capable of calculating the potential environmental impact of a building design [43]. In this context, LCAQuick quantified the environmental impacts, including the whole-of-life embodied carbon, of the SIP modular house. In addition, in deriving the climate change value, the biogenic carbon sequestration (GWP-biogenic) was excluded from the assessment.

3. Results and Discussion

3.1. Overall Environmental Impacts Results

The case study evaluated seven environmental impact indicators for the SIP modular house, following the guidelines outlined in EN 15978:2011 [31] and EN 15804+A1:2013 [42]. The study concentrated on the environmental aspects of sustainability, identifying the intermediate environmental impacts of the building under study. The modular house is located in Auckland, New Zealand, with a GFA of 88 m^2. The results were derived from the LCA tool used, LCAQuick V3.6, based on the foreground data that were input into the tool. Table 3 displays the assessment results according to the functional unit of the assessment, which is one square metre of the gross floor area of the SIP modular house over a 50-year building service life (i.e., kg CO_2 eq/m^2). Focusing on climate change (i.e., global warming potential), the total emission from the house is 347 kg of CO_2 eq/m^2. This value was derived from the GWP-fossil (i.e., carbon emissions from non-biogenic sources) and GWP-luluc (i.e., carbon emissions and removals from land use and land-use change).

Table 3. Summary of environmental impact assessment results.

Impact Categories	Units	Total per m^2 of GFA
Global warming potential (GWP)	kg CO_2 eq.	3.47×10^2
Stratospheric ozone depletion potential (ODP)	kg CFC 11 eq.	1.59×10^{-5}
Acidification potential of land and water (AP)	kg SO_2 eq.	1.69
Eutrophication potential (EP)	kg $PO_4{}^{3-}$ eq.	4.39×10^{-1}
Photochemical ozone creation potential (POCP)	kg C_2H_2 eq.	6.60×10^{-1}
Abiotic depletion potential for elements (ADPE)	kg Sb eq.	4.55×10^{-3}
Abiotic depletion potential for fossil fuels (ADPF)	MJ (NCV)	5.31×10^3

To validate the assessment results, a comparison was made with a similar study to determine if the calculated values, particularly the GWP result, fell within an acceptable range. A study by Moradibistouni et al. [44] was selected for the validation of results due to the similar nature of the assessment, where they conducted a life cycle assessment

(LCA) of a foam polyurethane SIP house. Over a 50-year building service life, their study found that the oriented strand board (OSB) SIP house emitted 9.1 kg CO_2 eq/m^2/yr, or 455 kg CO_2 eq/m^2 when adjusted to the same declared unit. These results were found to be slightly higher than the GWP emissions from the SIP modular house in this study. It is noteworthy that Moradibistouni et al. [44] included the conditioning energy as part of the operational emissions of the SIP house, whereas this study did not account for any operational emissions.

3.2. Environmental Impacts of Life Cycle Stages

Table 4 shows the environmental impacts of each life cycle stage for the case study modular house, while Figure 6 illustrates their contribution to the total results in a percentage-stacked bar chart format. Across all environmental impact indicators, the production stage was identified as the hotspot for the case study building, contributing at least 50% to the total environmental impact [45]. The contributions of the production stage to each impact indicator were as follows: 75% of GWP, 71% of ODP, 70% of AP, 50% of EP, 85% of POCP, 50% of ADPE, and 81% of ADPF.

Table 4. Breakdown of the environmental impacts of each building life cycle stage.

Impact Category	Unit per m^2 of GFA	Building Life Cycle Stage				
		A1–A3	A4–A5	B2, B4	C1–C4	D
GWP	kg CO_2 eq.	2.61×10^{2}	2.40×10^{1}	7.58×10^{1}	3.28×10^{1}	-4.66×10^{1}
ODP	kg CFC 11 eq.	1.12×10^{-5}	2.68×10^{-6}	1.68×10^{-6}	9.98×10^{-7}	-6.95×10^{-7}
AP	kg SO_2 eq.	1.19	1.22×10^{-1}	4.01×10^{-1}	6.81×10^{-2}	-9.31×10^{-2}
EP	kg $PO_4{}^{3-}$ eq.	2.18×10^{-1}	2.29×10^{-2}	1.17×10^{-1}	9.66×10^{-2}	-1.60×10^{-2}
POCP	kg C_2H_2 eq.	5.65×10^{-1}	5.33×10^{-2}	5.77×10^{-2}	7.37×10^{-3}	-2.36×10^{-2}
ADPE	kg Sb eq.	2.27×10^{-3}	4.53×10^{-5}	1.60×10^{-3}	1.11×10^{-5}	6.21×10^{-4}
ADPF	MJ (NCV)	4.30×10^{3}	3.08×10^{2}	1.03×10^{3}	1.52×10^{2}	-4.68×10^{2}

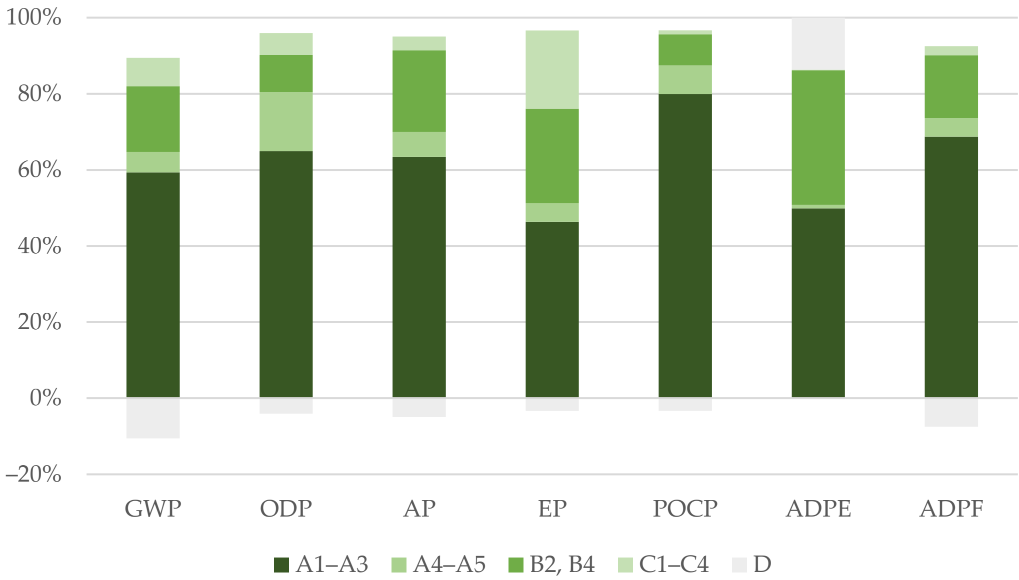

Figure 6. Percentage contributions to environmental impacts by each building life cycle stage.

Examining the global warming potential (GWP) impacts, there is an increase in global temperatures attributed to the heightened production of greenhouse gases. These emissions result from intensive human activities, including fossil fuel combustion, deforestation, and land-use changes [18]. The construction of buildings has a significant environmental effect, mainly because of the carbon emissions linked to it [46]. The production stage (Modules A1–A3) includes the processes of sourcing raw materials, transporting them, and producing the final product. These activities contribute to the emission of carbon and require significant energy consumption. Converting natural resources into building materials requires a considerable amount of energy, mostly derived from fossil fuels, and leads to large-scale emission of pollutants [47].

Additionally, the construction stage (Modules A4–A5) contributes 7% of the environmental impact of building development. The installation waste resulting from the product's vulnerabilities must be accounted for in the LCA, based on the bill of quantities or drawings for this stage [48]. However, the construction phase has a relatively minor impact on the overall environmental footprint compared to other stages of the building life cycle.

3.3. Whole-of-Life Embodied Carbon Analysis

Further analysis considered the embodied carbon of the case study building. Carbon emissions from buildings can be classified into two categories: embodied carbon and operational carbon. Embodied carbon refers to the greenhouse gas emissions that are produced during the manufacturing and upkeep of building materials. On the other hand, operational carbon refers to the emissions that are released while the structure is being used [49]. This study not only calculated the whole-of-life embodied carbon from Modules A–D, based on the system boundary, but also calculated the upfront carbon emissions and the whole-of-life embodied carbon, excluding potential benefits and loads beyond the system boundary (Module D). According to NZGBC [30], upfront carbon is carbon emissions arising from the production of materials, their transportation to the construction site, and the construction of the building(s) prior to their occupancy (Modules A1–A5). Figure 7 shows the embodied carbon analysis results of the building.

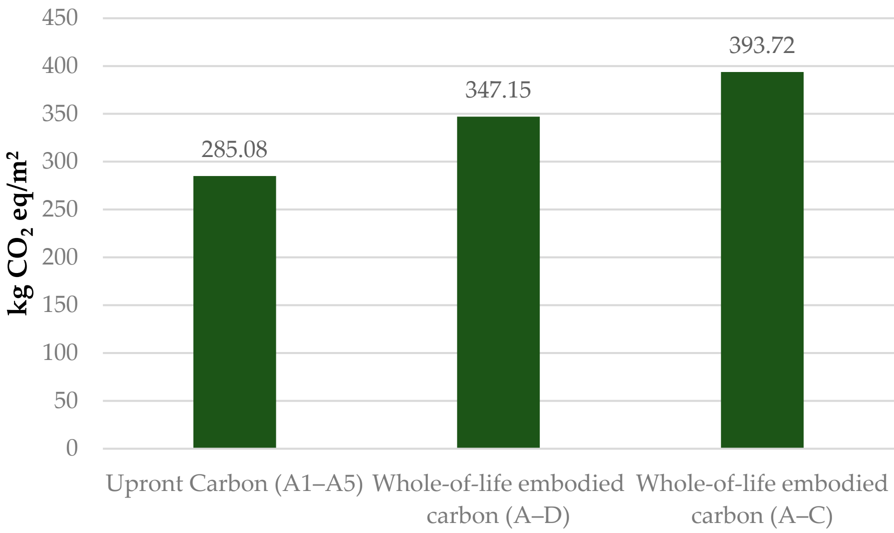

Figure 7. Embodied carbon analysis of the SIP modular house.

The study found that the whole-of-life embodied carbon of the house was 393.72 kg CO_2 eq/m^2 when excluding potential benefits and loads after the end-of-life stages (Module D) and 347.15 kg CO_2 eq/m^2 when including Module D. These values did not account for the biogenic carbon sequestration of the bio-based materials used in the building, such as timber products. However, the study separately calculated the potential biogenic sequestration and found it to be −178.35 kg CO_2 eq/m^2 for the modular house.

Furthermore, the study revealed that the upfront carbon of the SIP modular house was 285.08 kg CO_2 eq/m^2. This value represents the "today emissions", which encompass those produced during the production and construction stages up until the building is ready for occupancy or operational use, also known as "Year 0" of the building. Figure 8 illustrates the emissions released today in contrast to emissions released in the future, following the Whole-of-Life Embodied Carbon Assessment: Technical Methodology guideline [28]. It was evident that Module A released more embodied carbon than any of the other stages. However, the comparison of carbon emissions across each stage may vary when operational carbon is included in the assessment. Additionally, the study's GWP results were compared with those of a typical new detached house in New Zealand [50] to validate the findings within the same geographical context. Chandrakumar et al. [50] reported that a typical new detached house in New Zealand emits 16 kg CO_2 eq/m^2/year, or 800 kg CO_2 eq/m^2 over a 50-year lifespan when adjusted to the same functional unit as this study. In contrast, global studies show a broader range of 10–90 kg CO_2 eq/m^2/year, or 500–25,000 kg CO_2 eq/m^2 over the same timeframe. The notable discrepancies between this study's results and other benchmark values in the literature can be attributed to the following: (1) the inclusion of operational carbon emissions in some studies; (2) differences in structural systems, with benchmarks often based on conventional systems; and (3) variations in geographical boundaries, as LCA outcomes are sensitive to regional factors. Thus, given the lower embodied carbon of the case study buildings compared to the benchmark, this study concludes that the SIP modular house holds significant potential as a sustainable housing solution in terms of environmental sustainability.

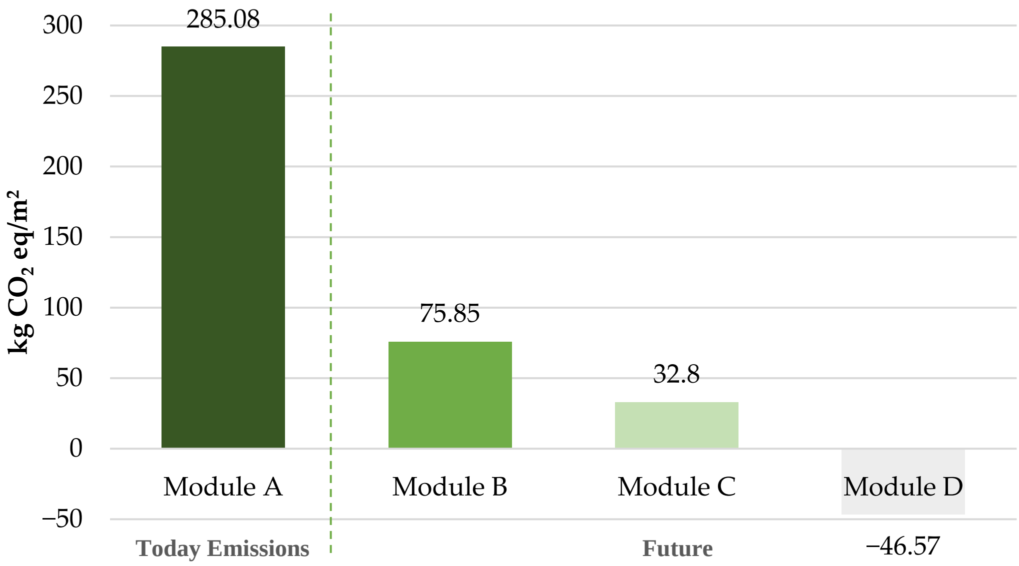

Figure 8. Embodied carbon analysis for each module of the SIP modular house.

3.4. Building Materials' Embodied Carbon Analysis

The case study building was constructed using a variety of materials. The main construction system employed SIPs for the walls and roof. The foundation system used timber posts with concrete footings, and the flooring system was designed with timber floor joists. Additionally, a cold-formed steel frame system was used for the interior walls, and a timber ridge beam and roof purlins were used to support the SIP roof panel.

The choice and quantity of building materials significantly impacted the embodied carbon produced during the early stages of the building's life cycle. To understand the factors contributing to the GWP results of the building, it is essential to evaluate the environmental performance of the materials used. The embodied carbon of the building materials was derived from the LCA tool, where the material templates from the software and Environmental Product Declaration(s) were used in the tool to calculate the emissions. Table 5 displays the embodied carbon results for all the building materials used in the case study building, considering the whole life cycle of the materials, while Figure 9 illustrates their contributions to the total embodied carbon of the house.

Table 5. Building materials' embodied carbon results.

Material Description	kg CO_2 eq/m^2
Roof SIP, 215 mm thick, R9.4	8.68×10^1
Wall SIP, 115 mm thick, R4.5	6.57×10^1
Window/door frame (PVC-U)	3.60×10^1
Steel roof cladding, 0.55 mm BMT	2.92×10^1
Softwood timber H3.1, structural applications (timber post)	2.18×10^1
Steel wall cladding 0.55 mm BMT	2.16×10^1
Window/door, IGU, double glazing	1.14×10^1
Plywood floor	1.08×10^1
Carpet tile	1.08×10^1
Composite timber exterior cladding	1.02×10^1
Plasterboard (GIB® standard 10 mm)	7.70
Paint, water-borne, walls (2 coats/m^2)	6.24
Window/door frame (aluminium)	3.88
Aluminum, flashing, flat sheet, 0.9 mm BMT	3.70
Reinforced concrete, 25 MPa, in situ, inc. 100 kg/m^3 steel reinforcement (OPC)	3.45
Door, interior, MDF, unpainted	2.92
Aluminium, profile sheet metal (for box gutter), 0.9 mm BMT	2.91
Softwood timber H1.2, framing applications	2.70
Softwood timber H3.1, framing applications	2.47
Membrane, building wrap, polyethylene (PE)	2.19
Plasterboard (GIB aqualine® 10 mm)	2.10
Membrane (DPM), polyethylene underslab, vapour barrier	1.27
Engineered wood, LVL (Nelson Pine, NZ)	7.59×10^{-1}
Softwood timber H4, structural applications	5.41×10^{-1}
Paint, water-based acrylic primer/undercoat (1 coat/m^2)	4.59×10^{-2}
Stud wall system, steel, primary (galvanised finish, coating class Z275), 0.75 BMT	2.51×10^{-3}
Direct-pressure laminate, flooring	-6.06×10^{-2}

The study revealed that the SIPs used for the roof and walls contributed the most to the embodied carbon of the modular house. The roof SIPs had an embodied carbon content of 86.8 kg CO_2 eq/m^2, accounting for 25% of the overall GWP results. The wall SIPs followed, contributing 19% to the building's total GWP with 65.7 kg CO_2 eq/m^2. According to the hotspot analysis rule outlined by Zampori et al. [45], the roof and wall SIPs, along with the PVC-U window and door frames, were identified as the primary hotspots in terms of building materials, collectively accounting for over 50% of the GWP results.

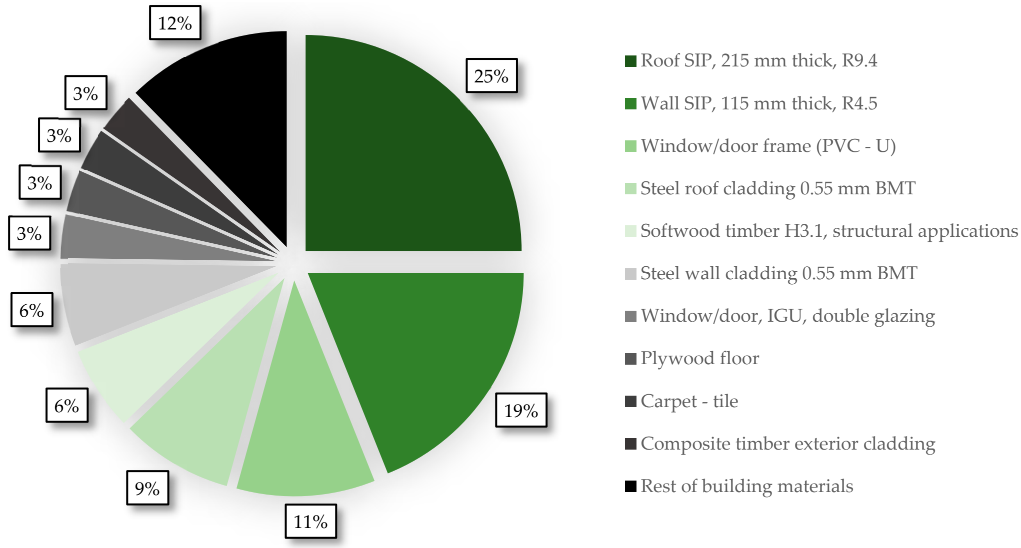

Figure 9. Top 10 building materials' contributions to the overall GWP results.

The production stage of the SIPs was identified as a major contributor to their embodied carbon, accounting for over 90% of the total embodied carbon for both the roof and wall panels, with no potential carbon offset in Module D. According to the Environmental Product Declaration (EPD) for SIPs [51], the manufacturing process involves seven key activities: (1) cutting the strand board, (2) forming the panel cassette, (3) foaming the panel in the press, (4) breaking out the panel, (5) conducting a quality check, (6) wrapping and stacking the panels, and (7) dispatching the panels from the factory. The modelling process assumed that at the end of their lives, the SIPs would be disposed of in a landfill [44], resulting in no potential benefits or carbon offsets after the end-of-life stage. In addition, Moradibistouni et al. [44] found that the polyurethane foam (PUR) used in SIPs was responsible for the majority of CO_2 emissions, making up 83% of the total embodied carbon emissions from the panels. The significant amount of energy and CO_2 emissions associated with polyurethane foam is due to its large use volume and the fact that it has higher energy and CO_2 coefficients than other insulating materials [51].

4. Conclusions and Recommendations

The research highlighted the significance of conducting LCA for residential buildings in New Zealand. This approach aimed to overcome the housing crisis by offering and exemplifying an environmentally sustainable housing solution. Therefore, this study conducted an LCA on an example SIP modular house to evaluate its potential as a viable solution to the current issue, while aligning with both national and global sustainable development goals and the target of net-zero carbon emissions.

LCAQuick V3.6, a New Zealand-based life cycle assessment tool, was used to calculate the environmental impacts of the modular house. The standards EN 15978:2011 and EN 15804+A1:2013 were referenced to define the environmental impact indicators for the assessment. The system boundary selected for this study was cradle-to-cradle, encompassing the production stage (Modules A1–A3) through to the end-of-life stage (Modules C1–C4) and including Module D. This approach was used to analyse the environmental impacts of the modular house during its 50-year service life. The study found that the total global warming potential (GWP) of the modular house was 347 kg CO_2 eq/m^2. To achieve the first research objective, additional impact indicators such as ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), photochemical ozone creation potential (POCP), abiotic depletion potential for elements (ADPE), and abiotic depletion potential for fossil fuels (ADPF) were evaluated. The results indicated that the case building accounted for 1.59×10^{-5} kg CFC 11 eq, 1.69 kg SO_2 eq, 0.44 kg $PO_4{}^{3-}$ eq, 0.66 kg C_2H_2 eq, 4.55×10^{-3} kg Sb eq, and 5.31×10^3 MJ (NCV).

To fulfil research objectives 2 and 3, a detailed embodied carbon analysis was conducted. The study identified the production stage (Module A1–A3) as the primary hotspot for whole-of-life embodied carbon across the building's life cycle stages. This is due to the significant energy required to convert natural resources into building materials, which are primarily sourced from fossil fuels, resulting in substantial pollutant emissions. Analysing the contribution of building materials to the modular house's overall embodied carbon, the study found that the SIP roof and wall panels, along with the PVC-U window and door frames, were the major hotspots of the module house, collectively accounting for over 50% of the GWP results. Focusing on SIPs' contribution to the overall results, the study revealed that the SIPs were the most significant contributors, with the roof SIPs contributing 25% and the wall SIPs contributing 19%, totalling 44% collectively.

Additionally, this study offers several recommendations for practical applications in the construction industry and for future research. First, SIP modular houses present a significant opportunity to address the housing crisis while also demonstrating lower embodied carbon emissions throughout their building life cycle stages. Second, SIPs in modular houses contribute the most to the overall embodied carbon of the house. Efforts are needed to reduce the embodied carbon from SIPs used in the country, particularly focusing on the use of PUR insulation materials. Third, the study recommends including operational carbon emissions in the scope of future research. By incorporating operational energy and water usage and considering the thermal modelling of modular houses with SIPs, more comprehensive LCA results can be presented, helping the industry better understand the system's environmental performance. Finally, the study suggests conducting a comparative LCA study to compare SIPs with other structural systems, such as light steel and timber frames. This comparative study will provide clearer insights into the sustainability of SIP systems, specifically regarding their environmental impacts and embodied carbon. Additionally, future studies should incorporate uncertainty analysis to evaluate the degree of uncertainty in the LCA results of SIP modular houses. This approach would help quantify variations arising from the availability and reliability of databases, assumptions made, and methodological choices. This will enable future research to more effectively anticipate potential errors in the overall LCA results of SIP modular houses, including the embodied carbon in their building materials.

Author Contributions: Conceptualization, A.A.D. and K.R.; methodology, A.A.D. and K.R.; software, A.A.D.; validation, A.A.D. and K.R.; formal analysis, A.A.D.; investigation, A.A.D.; resources, K.R.; writing—original draft preparation, A.A.D.; writing—review and editing, R.F., Z.F., and K.R.; visualization, A.A.D. and Z.F.; supervision, K.R.; project administration, K.R.; funding acquisition, R.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (grant number 52178131), the International Science and Technology Cooperation Subject for the Guangdong Science and Technology Planning Project (grant number 2023A0505050089), and the Natural Science Foundation of Guangdong Province (grant number 2024A1515012190).

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

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