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Evaluating the Circular Economy Potential of Modular Construction in Developing Economies—A Life Cycle Assessment

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Abstract: Circular economy (CE) is an emergent concept that promotes resource circularity in multiple product systems. Modular construction (MC), an evolving construction technique, which includes an off-site manufacturing environment, increasingly supports CE strategies such as reuse due to the elevated potential for design for disassembly (DfD). Design-stage environmental assessments are paramount in aiding the early decision making of modular construction projects to successfully plan and implement DfD strategies. Research on synergising modular construction, circular economy and environmental sustainability is rare in developing economies. Thus, the current study aims to conduct a design-stage life cycle assessment of a DfD and linear versions of a modular building unit in Sri Lanka to evaluate the potential environmental benefits. The life cycle assessment results highlight that the DfD strategy has the lowest environmental impacts in all categories, with a 63% reduction in global warming potential and an approximately 90% reduction in terms of human toxicity compared to the linear version. Further, it showed the elevated potential of reuse compared to recycling practices in improving the environmental performance. Sensitivity assessment revealed that steel was the most sensitive to the change in reuse percentage among main building materials. The analysis outcomes highlight the importance of long-term thinking, architectural design creativity and industrial and technology development to uptake the CE-driven MC in the Sri Lankan context. Finally, strategies are proposed to support the CE approach in MC in developing regions. Both quantitative and qualitative outcomes provide a basis for construction industry stakeholders, academia, and policy makers to explore further and promote modular construction practices to enhance the circularity of building materials and components in developing regions.

Keywords: circular economy; modular construction; life cycle assessment; reuse and recycle; design for disassembly; design stage; off-site manufacturing

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Citation: Jayawardana, J.; Sandanayake, M.; Kulatunga, A.K.; Jayasinghe, J.A.S.C.; Zhang, G.; Osadith, S.A.U. Evaluating the Circular Economy Potential of Modular Construction in Developing Economies—A Life Cycle Assessment. *Sustainability* **2023**, *15*, 16336. https://doi.org/10.3390/su152316336

Academic Editor: Aliakbar Kamari

Received: 13 October 2023
Revised: 13 November 2023
Accepted: 23 November 2023
Published: 27 November 2023

1. Introduction

Construction, an industry with never-ending growth and scalability, is responsible for significant consumption of global natural resources and massive waste generation worldwide [1]. The global architectural, engineering and construction (AEC) industry is keen on exploring and adopting sustainable methods of construction to address the existing environmental issues. Modular construction (MC), a modern method of construction, is increasingly recognised by the AEC industry as a viable alternative to conventional construction [2]. MC manufactures modular components in an off-site production facility and then transports, erects, and assembles them on the final construction site to build the desired construction outcome [3]. Faster delivery, cost competitiveness, improved productivity and environmental savings are some of the well-recognised advantages of MC over in situ construction [4–6]. The increased capability for quality controlling and monitoring in the modular unit production process elevates the material consumption efficiencies and reduces waste generation [7,8].

MC is centred on a controlled manufacturing environment that raises the opportunity for using circular economy (CE) strategies. Applying CE strategies such as reduce, reuse, and recycle can potentially increase material efficiencies, thus reducing the end-of-life (EoL) waste created [9]. The CE concept still has a slow momentum in the global context [10]. For example, even though Europe is a pioneer of the CE philosophy, the European construction industry with high recycling rates is only 30% circular. Moreover, only approximately 19% of construction materials in new buildings are derived from recycled or renewable sources [11]. A transformation from a conventional linear to a circular model presents significant challenges for the global construction sector, considering the already established infrastructure and business networks [12]. The industry requires a considerable effort to the transition, which could fit in a long-term philosophy. Design for disassembly (DfD), is one such approach the building industry can apply to realise the circularity of building materials [9,12]. DfD needs a thoroughly planned design stage and construction phase to yield the expected life cycle sustainability performance.

The adoption of modular construction technologies in developing regions such as South Asia is slow compared to developed and industrialised economies [13]. Furthermore, there is limited research evaluating the environmental sustainability of MC practices using methodologies such as life cycle assessment (LCA) in the South Asian context [3]. Thus, research approaches such as case study-based LCAs on MC integrated with DfD and CE strategies can enrich the research and development initiatives in these countries. Moreover, the potential of MC to support the CE phenomenon needs to be investigated to promote MC adoption in the developing economy construction sector. Thus, the current study aims to conduct a LCA to estimate and compare the environmental impacts of a design-stage modular building unit considering different EoL strategies. Two versions (DfD vs. linear) of the case study modular unit will demonstrate the LCA considering Sri Lankan conditions. The research will attempt to showcase the distinctive capability of modular construction to elevate material circularity and compare CE practices (reuse vs. recycle) in terms of environmental savings. The outcomes of the current study have the potential to contribute to research and developments in developing regions associating sustainability, modular construction practices and circular economy.

2. Background and Research Significance

2.1. Global Context of Modular Construction

The manufacturing industry is evolving consistently, creating technological capabilities that evaluate, monitor, and improve the holistic production processes and overall sustainability. The built environment, one of the significant and essential industries globally, has seen diverse challenges from traditional ways of building. As one of the PFC techniques, MC has increasingly been recognised as a manufacturing-centred construction technology, which has a high potential to use the strengths of manufacturing systems and technologies. MC offers a range of benefits, from reduced construction times and enhanced work efficiency to sustainability savings in GHG emissions and waste generation [14–16]. Moreover, portability and quick fixing ability are distinct capabilities of MC that reinforce the competitiveness over conventional construction [17,18]. The potential for designing for disassembly and reuse is one of the unique possibilities of using MC, consequently reducing the demolition waste [9]. The potential that MC possesses to enhance the circularity of the construction process is becoming increasingly evident. However, even with the well-documented benefits of modular construction compared to traditional construction, the application of these technologies is less globally. Notably, adoption in low socioeconomic countries such as Sri Lanka is significantly behind other developed and industrialised countries [3]. Some key impediments to applying MC technologies are high initial capital establishment costs, transportation constraints (module dimensions, road conditions and regulations and logistic costs), and a lack of experienced and skilled engineers, designers, labourers, and technical experts [19–21].

2.2. Modular Construction in Sri Lanka

In the present context, only a few construction companies use prefabrication in construction projects in Sri Lanka. Among them, the main focus is still on building elements, such as non-volumetric wall panels and infrastructure-based bridge components [5]. The application of modular technologies under prefabrication is still slow in Sri Lanka compared to other developed and industrialised economies [22]. Under a modular construction space, container-based modules and steel-framed building units are the main modular products currently in Sri Lanka [5]. The use of timber technologies such as cross-laminated timber (CLT) and glued laminated timber (Glulam) is yet to be achieved in the modular construction stage of Sri Lanka. Concrete-based modular units were introduced into the market in 2022 by one construction organisation, with a sample first volumetric modular building completed in the same year [23]. However, even with recent advancements, modular construction has yet to reach a considerable share of the Sri Lankan construction market [22]. On top of that, the novel technology and innovation transfer to overall construction work is significantly lower compared to contemporary progress in developed and industrialised countries.

2.3. The Importance of Circular Economy in Building Construction

CE is an evolving phenomenon that promotes the cyclical use of resources that extends the resource life and minimises waste generation [10,24]. CE is still a vague concept that does not have a singular definition. However, Moraga et al. [10] presented that CE differs from the linear economy by designing extended-life goods and products and closing the post-consumer stage and raw material extraction. Generally, CE strategies are identified by 3Rs: reduce, reuse, and recycle. Nonetheless, the 9Rs: rethink, refuse, reduce, reuse, repair, refurbish, remanufacture, recycle, and recover are growing traction as a more comprehensive CE strategy approach [25]. The CE strategies were successfully employed in various products, from clothing to electronic goods. However, the application to building and building components is not comprehensively explored [26]. Building construction consumes approximately 40% of global natural resources throughout the life cycle and generates approximately 35–40% of global solid waste [27,28]. Thus, the building industry must take prompt action to employ CE strategies to reduce virgin material usage and waste produced.

Traditional construction methods show more barriers to CE integration compared to MC [29,30]. MC possesses distinctive benefits such as manufacturing in a controlled environment, engaging a specialised skilled workforce, easiness in quality monitoring, and highly engineered fabrication, creating better mechanisms for DfD [31–33]. According to an explorative study from Australia, MC presents a set of unique capabilities compared to traditional construction. Tracking materials and components within their supply chain, integrating lean production practices during the off-site manufacturing stage and designing adaptable elements to minimise the waste due to modifications in the use phase of buildings are such crucial possibilities [9]. Moreover, Pan and Zhang [34] stated that the circularity and sustainability of urban developments could be enhanced by building temporary modular facilities for DfD and reassembly.

2.4. Circular Economy in Modular Construction

CE is a relatively novel economic concept, and MC is a modern construction technology still adopted in lesser proportions. Case study research focusing collectively on these two aspects is rare in the literature relating to developing economies. Table 1 presents a set of selected studies that have researched this domain using qualitative and quantitative approaches. Notably, the first three studies [9,26,35] have extensively highlighted the potential of MC for applying CE strategies and reducing waste at the EoL stage. The primary challenges in using CE strategies in modular construction are the long life cycle of buildings, supply chain complexity and uncertainties, individuality and composite materials of building units, and lack of profitability and demand [35]. The research on integrating CE with sustainability assessments such as LCA is not much presented in the current state-of-the-art literature in developing regions such as South Asia.

Table 1 shows that case study-based LCAs were conducted on a prototype modular building manufactured in Australia [9] and modular housing units developed using containers in China [36]. None of the previous studies conducted sustainability assessments in the design stage of modular buildings in South Asian countries such as Sri Lanka that focused on elaborating and demonstrating the potential of CE strategies in MC. Thus, it forms a research opportunity to carry out early decision-making stage LCAs to compare variants of CE strategies that can motivate the DfD technique in modular construction focusing on Sri Lanka. Design-stage assessments create substantial value to support the hypotheses from the relevant literature. Software platforms such as SimaPro and openLCA can aid in comprehensive design-stage assessment of environmental impacts related to MC.

Table 1. Selected studies that have focused collectively on CE in MC.

Study	Research Design *						Study Purpose	Key Research Highlights
	SLS	QA	SBR	LCA	ES	CS		
[26]	✓	✓					A conceptual framework is developed to identify barriers and propose strategies to adopt CE in modular construction	Modular buildings are key to material savings, waste reduction, and reuse of components
[35]	✓		✓				Analysed the contemporary challenges and barriers to adopting CE in MC and proposed a strategy roadmap	15 guidelines are proposed to overcome the obstacles to CE adoption in MC
[9]	✓			✓		✓	Comparative environmental assessment of a DfD modular building and conventional construction approach	Compared to recycling, DfD offsets greenhouse gas emissions by 88% and also benefits other tested environmental impacts
[36]				✓	✓	✓	Compare the environmental impacts of four designs of a transportable, modular housing unit	Shows that the potential reuse of the building structure provides significant environmental benefits
[24]						✓	Novel virtual reality (VR)-based approach to advanced learnings and experiences of the CE in the modular construction	Provides a visual link between the building information modelling, bill of quantities and resiliency of the selected materials
[37]	✓		✓				Investigates the critical success factors for implementing circular MC projects in Hong Kong	Revealed the vitality of the planning and design stages for achieving circularity in MC projects
[25]		✓	✓				Investigates the integration of CE principles in MC to enhance the sustainability	30 strategies are proposed to mitigate obstacles in adopting CE principles to solve the sustainability issues in MC

* SLS—systematic literature survey, QA—qualitative analysis, SBR—survey-based research (questionnaire surveys, interviews), LCA—life cycle assessment, ES—energy simulation, and CS—case study-based research.

2.5. Research Significance

Design-stage sustainability assessments are crucial in decision making at all life cycle stages of building projects. Design-stage sustainability assessments of MC practices are seldom performed in the relevant literature pertaining to developing economy context, particularly in South Asia. Moreover, countries such as Sri Lanka do not have published LCAs investigating the effect of DfD-driven CE approaches in MC life cycle sustainability. Hence, the current study conducted an LCA to predict and estimate the environmental impacts of a modular building unit in Sri Lanka, considering two main versions. The first version is designed for disassembly, and the second version (linear) is not designed for disassembly; hence, it will be demolished at the end-of-life cycle. DfD makes it possible to salvage and reuse some structural and non-structural components of the modular building unit. Conversely, in the linear version, this CE strategy is not viable. Moreover, this study conducted a sensitivity assessment to investigate the variations in environmental impacts with the change in the reuse capability of primary building materials that can be salvageable.

The outcomes of these analyses can contribute to several aspects. First, the current LCA analysis was conducted at the design stage. The complicated nature and hardships of conducting sustainability assessment at a pre-implementation stage are visible throughout this study. Comprehensive decision making and participation of stakeholders at different stages of the life cycle of modular units is needed to conduct a more accurate and complete LCA. Secondly, this study quantifies the environmental impacts of the modular unit at different EoL CE strategies. The potential savings of recycling and reuse strategies will be compared under the DfD and linear models. Thirdly, the outcomes and implications can be used by Sri Lankan modular construction-related stakeholders such as academia, researchers, and policy makers. Material circularity and material reuse in multiple product systems are crucial considerations from the current study. Finally, the proposed strategies can be implemented to uptake the diffusion of CE philosophy into modular construction techniques.

3. Research Methodology

The LCA approach has been adopted effectively in the construction sector for over 20 years to conduct systematic and comprehensive environmental assessments [13]. According to the ISO 14040 series, ISO 14040:2006 describes the principles and framework for LCA, including the four main stages of LCA (goal and scope, life cycle inventory analysis, life cycle impact assessment, and interpretation) [38]. The current study follows the process-based attributional LCA to quantify the environmental impacts of the modular case study building in the design stage, as shown in Figure 1.

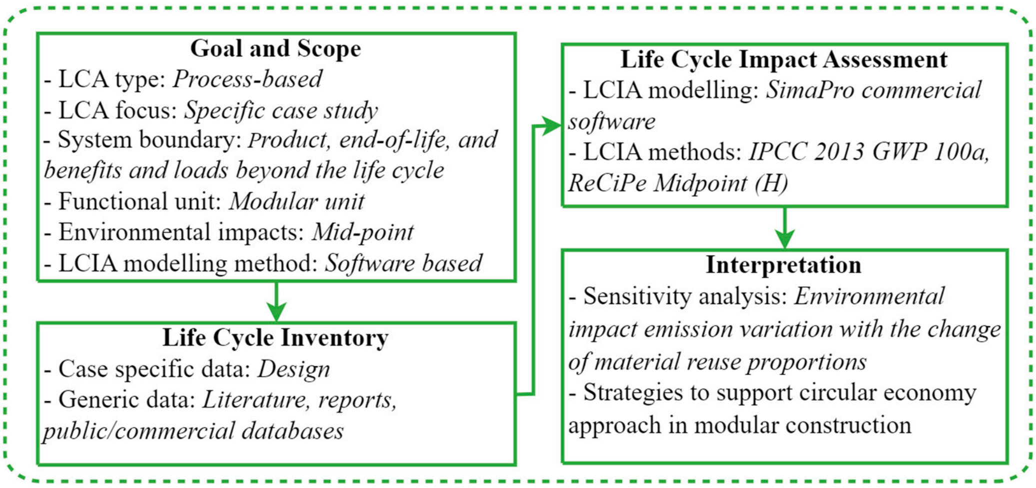


Figure 1. Research methodology of this study.

3.1. Goal and Scope

The main goal of this study is to calculate and compare the environmental impact of a design-stage modular building considering the application of different circular economy strategies at the end-of-life stage. Thus, this research aims to quantify the potential savings from employing the circular economy strategy such as DfD reuse. The system boundary includes the product stage, end-of-life stage, and benefits and loads beyond the life cycle, omitting the construction stage, use phase and the deconstructed element transportation (see Figure 2). The whole construction (off-site and on-site) and operation phases are excluded, considering this LCA is performed at a point where some of the decisions related to construction and use stages were not comprehensively taken. Thus, due to a considerable number of ambiguities and speculations, these two phases were eliminated to avoid larger margins of errors. All module joints and most wall and ceiling connections can be manufactured by avoiding adhesive bonding and welding for easy and feasible disassembling. Similar to the construction and use phases, the comprehensive process details are not decided for the end-of-life cycle stage of the modular unit. However, general scenarios applicable to Sri Lankan conditions were used. For example, under waste processing, machines for handling in sorting plants, electricity demand for sorting plants, and energy for dismantling are considered. It is assumed that the recycling scenario demolishes the building with skid-steer loaders. Moreover, it is considered that the sorting plants can build waste by pre-sorting mixed waste, crushing and manual sorting. In the reuse scenario, it is assumed that the dismantling is performed entirely manually. The functional unit of the LCA analysis is set as one modular building unit.

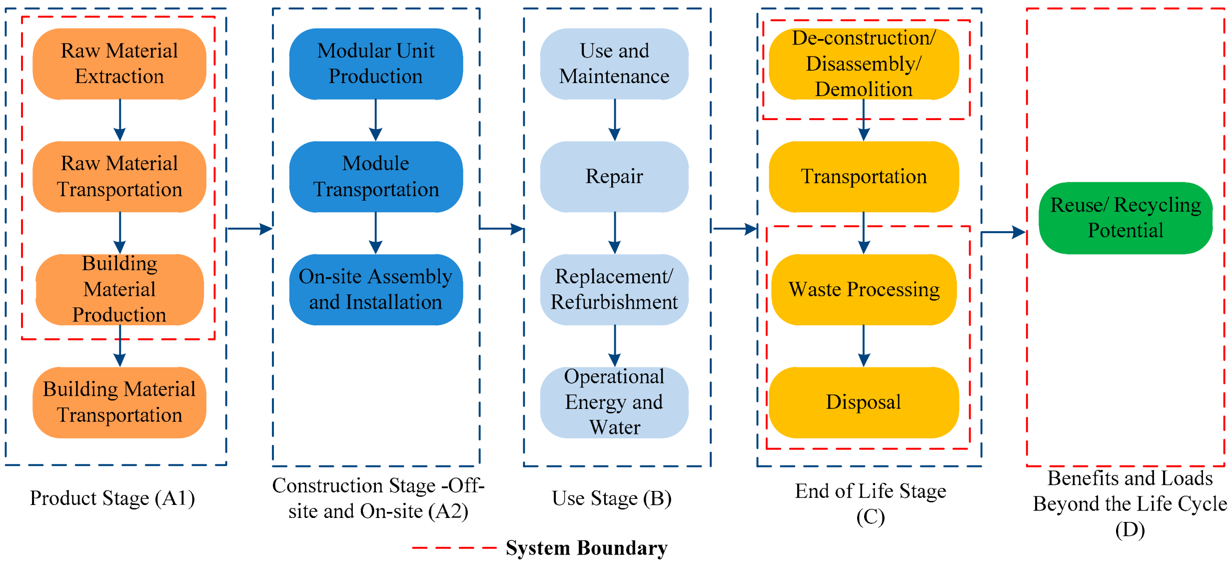


Figure 2. System boundary of this study.

3.2. Life Cycle Inventory

The life cycle inventory (LCI) analysis was conducted to quantify the primary inputs of the modular case building. A bill of materials was prepared at the design stage by estimating the input building materials required to fabricate the modular unit. Moreover, the Ecoinvent 3.3 database is used as the primary secondary data source in this analysis. The LCI complies with the chosen system boundary and the functional unit of this study. A cut-off allocation on a weight basis was used in the LCI analysis. The main building materials within a cumulative weight of approximately 95% of the modular building unit were selected for the analysis. Thus, cut-off criteria excluded building materials with low cumulative weights, such as fittings and mineral wool. The manufacturing processes at the product stage (A1) are acquired from the LCI databases in SimaPro. The operations were selected to represent the Sri Lankan conditions. One of the practical problems is the unavailability of specific processes for Sri Lankan requirements. Thus, here, processes related to South Asia, Asia or the rest of the world were used in the modelling. Reuse and Disposal scenario functions available in SimaPro were used to create waste scenarios. Product stage and EoL scenarios were assembled under Calculation setups under the impact assessment in SimaPro. A waste scenario in SimaPro can be made by inputting a waste treatment process from the Waste Treatment section. Moreover, for the building materials with units m^3 and m^2, SimaPro demands the values as weight inputs in the EoL modelling. Thus, in these cases, for example, the volume of plywood boards was converted to kilograms using the average density of the plywood. Similarly, for a building material with the unit m^2, the component's density and thickness were used. For example, the thickness of a glass sheet in a window is considered when calculating the weight of the glass.

3.3. Life Cycle Impact Assessment

The life cycle impact assessment (LCIA) phase quantifies the environmental impacts mainly by characterisation approach and supplementary by normalisation and weighting methods. The LCIA was conducted in SimaPro 8.3.0.0 software (Ph.D. Version). The present study has employed IPCC 2013 GWP 100a V1.03 and ReCiPe Midpoint (H) V1.13 as the primary methods for the LCIA. The selection of the ReCiPe method can be justified under impact category coverage, characterisation model, normalisation and weight factors and geographical boundary compared to CML 2001, Eco-indicator 99 and TRACI 2.1. CML 2001 method does not cover the particulate matter formation, the Eco-indicator 99 method does not contain the photochemical oxidation impact category, and TRACI 2.1 does not have the ionising radiation and land use impacts. Conversely, the ReCiPe method covers all these impacts, including acidification, climate change, resource depletion, ecotoxicity, eutrophication, human toxicity, and ozone layer depletion. Moreover, ReCiPe is the only method that supports all midpoint and endpoint characterisation approaches and normalisation and weighting factors. Furthermore, more importantly, it covers both Europe and the Global level, where only the CML 2001 method covers similar geographical boundaries. However, it does not have an endpoint characterisation model and weighting factors. For selecting the midpoint impact categories, a cumulative approach is used. The normalised impact values were ranked from highest to lowest, and then the impacts that added to a total of approximately 95% were selected for the impact assessment and further interpretation. Table 2 shows the chosen 12 impact categories with their corresponding normalisation factors.

The following equations can represent the quantitative formulations of characterisation and normalisation [39].

$$C_i = \sum_s CF_{i,s} \times IV_s \tag{1}$$

where C_i is the characterised score of the impact category i and $CF_{i,s}$ is the characterisation factor of i^{th} impact category and s^{th} substance. Moreover, IV_s is the inventory score of s^{th} substance. Characterisation factor of i^{th} impact category and s^{th} substance can be calculated from the following equation.

$$CF_{i,s} = \frac{CIV_{s/re}}{CIV_{rs/w}} \tag{2}$$

where $CIV_{s/re}$ is the category indicator score of s^{th} substance or re^{th} region and $CIV_{rs/w}$ is the category indicator score of the reference substance (rs) or the emission-weighted world average (w).

The normalised value of each impact category can be calculated from the following equation.

$$N_i = C_i \times NF_i \tag{3}$$

where N_i is the normalised score of the impact category i and NF_i is the normalisation factor of i^{th} impact category.

Table 2. Midpoint normalisation factors.

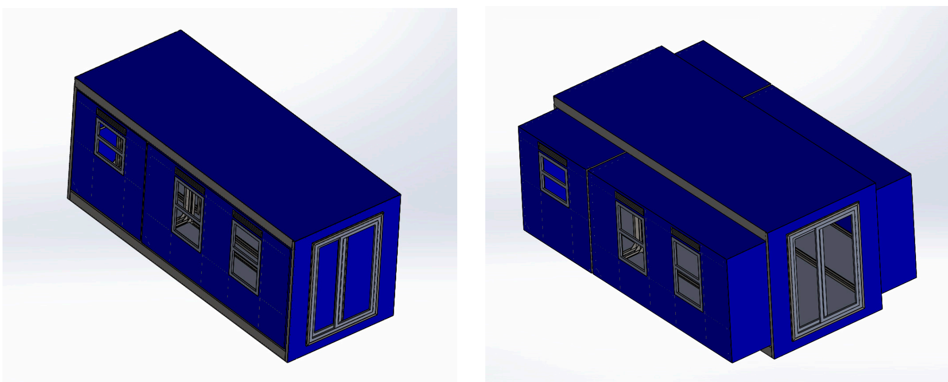
Impact Category	Unit	Value	Reference
Global warming potential/Climate change (GWP)	kg CO_2 eq	6.89×10^3	[40,41]
Terrestrial acidification (TA)	kg SO_2 eq	3.82×10^1	
Freshwater eutrophication (FE)	kg P eq	2.90×10^{-1}	
Human toxicity (HT)	kg 1,4-DB eq	3.26×10^2	
Photochemical oxidant formation (POF)	kg NMVOC	5.67×10^1	
Particulate matter formation (PMF)	kg PM_{10} eq	1.41×10^1	
Terrestrial ecotoxicity (TET)	kg 1,4-DB eq	5.93	
Freshwater ecotoxicity (FET)	kg 1,4-DB eq	4.30	
Marine ecotoxicity (MET)	kg 1,4-DB eq	2.46	
Agricultural land occupation (ALO)	m^2a	5.42×10^3	
Metal depletion (MD)	kg Fe eq	4.45×10^2	
Fossil depletion (FD)	kg oil eq	1.29×10^3	

3.4. Sensitivity Analysis

Salvaging building materials/components for 100% reusing can vary with the practical circumstances. Even though the modular units are designed for DfD, the technology used and worker skills employed for disassembling will influence the success of this process. Hence, considering these factors, a sensitivity assessment is carried out to investigate how these uncertainties can cause a change in environmental emissions. Six of the twelve midpoint impact categories were mainly selected for the sensitivity analysis considering the end-of-life significance and simplicity.

4. Case Study

The case building is designed as an expandable and contractable (Figure 3) modular unit with five main compartments. The central compartment will be fixed, and the other four can move for extensibility. The guider and rack and pinion mechanism realise the movements of the two large units and two small compartments with the central chamber. Figure 4 depicts a cross-section of the modular unit. The case study design-stage building unit will be manufactured as a treatment unit for infectious diseases (such as COVID-19). Moreover, the unit can be used in medical-related applications and emergencies. The central unit, combined with extended large compartments, is the main working space of the building. At the same time, one small chamber can be utilised as a kitchen and the other smaller unit as a washroom.



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

Figure 3. (**a**) Contracted state and (**b**) expanded state of the modular building unit.

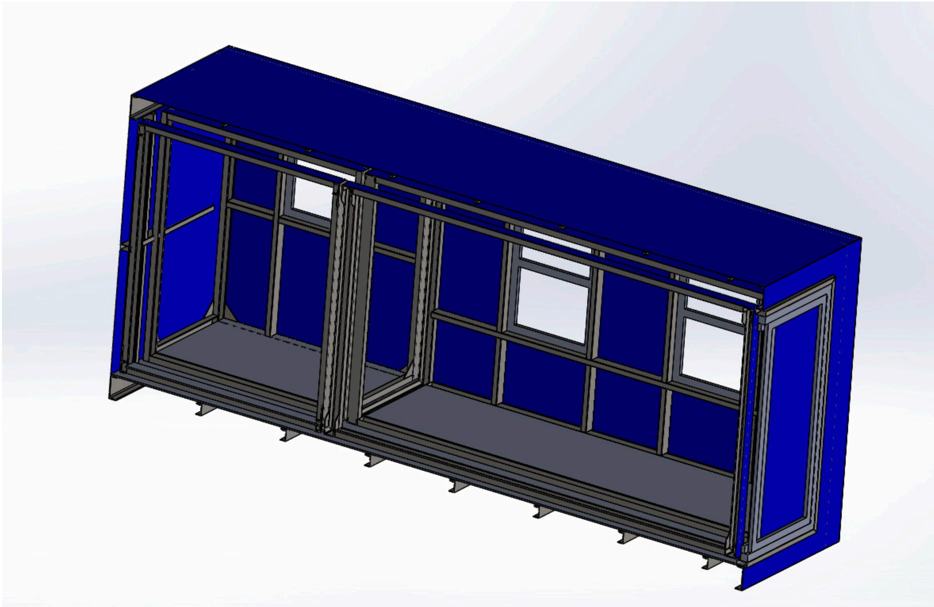


Figure 4. Cross-section of the modular building unit.

Ground floor area of the modular building is 28.22 m^2. The dimensions (width × height × length) of the central compartment are 2440 mm × 2600 mm × 6100 mm, the side compartment (large) is 1120 mm × 2250 mm × 3970 mm, and the side compartment (small) is 1120 mm × 2250 mm × 1985 mm. Moreover, the expected lifespan of the modular building is ten years. Table 3 describes the building elements, and Table 4 shows the estimated input material quantities of this modular building. The material quantities are estimated using mass calculation with SOLIDWORKS and manually using the defined specifications.

Table 3. Description of design-stage case study modular building unit.

Building Element	Description
Framing	Mild steel C sections; box bars as intermediate beams to support window and door framing; 100 mm × 100 mm webs for joining; cast iron corner posts
External walls	Galvanized mild steel plates
Internal walls and ceiling	Gypsum boards
Floor	Plywood boards
Roof	Galvanized mild steel plates
Insulation	Mineral wool
Doors and windows	Mild steel framing; one sliding double door (2100 × 1800 mm) with aluminium profile and glass; 4 single doors (2100 × 900 mm) with aluminium profile and glass; 2 windows (1500 × 2100) with aluminium profile, louvre, and glass; 2 windows (900 × 600) with aluminium profile, louvre, and glass
Painting and finishing	External walls with one coat of cataloy, one coat of primer, and two coats of enamel paint

The main decision related to selecting materials is directed at the framing of the modular building. In the Sri Lankan context, timber framing is not yet visible in the main stage of modular construction projects. Lack of policies and design and construction codes, lack of awareness among construction professionals and the general public and lack of research data on these novel technologies and timber classification are the main challenges in adopting timber-based technologies in the Sri Lankan construction industry [42]. Sri Lankan media outlets have emphasised the benefits of using timber systems such as CLT and Glulam and conveyed the need for the government and Sri Lanka's housing authorities to apply these in housing projects initiated with the central business district (Colombo) [43]. Thus, considering the technical feasibility and other practical considerations of using timber frames in Sri Lankan projects are not identified and demonstrated adequately, the modular building in the current study will be constructed using steel framing. As highlighted in Section 2.2, steel-based modular units are marginally popular compared to timber or concrete-based modules in the Sri Lankan context. The materials for the walls, floor and roof are chosen based on the regional availabilities of the materials and cost demands of the project.

Table 4. Life cycle inventory, main material quantities.

Material/Component	Description	Unit	Quantity
Mild steel	Main structure framing, doors and windows framing, external walls, roof	kg	3865
Cast iron	Corner posts	kg	180
Gypsum boards	Internal walls and ceiling	kg	1327
Plywood boards	Floor	m^3	0.104
Glass	Doors and windows	m^2	13.98
Aluminium	Door and window profiles, window louvres	m^2	8.58
Paint, primer, thinner	Painting and finishing	kg	30

5. Results and Discussion

The current section presents the LCIA results derived from SimaPro modelling for DfD and linear versions of the modular building case study. In the DfD version, the modular building is designed for disassembly, thus enabling the salvage of structural steel and cast-iron components, including exterior wall panels and aluminium framed windows and doors. However, the salvaging of 100% of reusable components may not be possible in practical conditions. For example, scrap material generated from disassembly activities such as using tools and machinery and damages caused by handling and transport [44]. Hence, a sensitivity assessment was conducted to investigate the variation in environmental emissions with the change in reuse percentages of steel, cast iron, aluminium, and glass. In the linear version, where the modular building is not designed for disassembly, the primary building materials will be recycled except for plywood, which is landfilled. All environmental savings from the CE strategies are discounted to the current product system to showcase the merits of the material circularity and circular economy applications.

5.1. Life Cycle Impact Assessment

5.1.1. Product Stage (A1)

Steel is the primary building material that totals approximately 70% of the modular unit (main structure framing, doors, windows framing, external walls, roof). Its environmental impact is above 60% for most impact categories, except for terrestrial ecotoxicity and agricultural land occupation (see Table 5). Steel accounts for approximately 95% of the metal depletion, the highest contribution to any impact category by steel material. At the outset, this result was derived considering steel represents the majority of total metal inputs used in the modular unit. Notably, total steel usage affects approximately 85% of particulate matter formation, 84% of photochemical oxidant formation and 81% of climate change. Steel and iron production encompasses complicated processes, including the oxygen blast furnace process, which generates significant air emissions such as greenhouse gases (GHGs) [45,46]. Thus, the efficient and next-product system use of steel as a building material is crucial to support sustainable construction in the developing economy context.

Table 5. Midpoint impacts of the product stage (A1).

Impact Category	Unit	Steel	Gypsum Board	Cast Iron	Plywood	Aluminum	Glass	Coatings *	Total
Global warming potential	kg CO_2 eq	6848.58	232.46	307.61	45.40	729.54	83.26	162.23	8409.07
Terrestrial acidification	kg SO_2 eq	24.86	1.31	1.26	0.30	3.48	0.71	0.81	32.74
Freshwater eutrophication	kg P eq	0.24	0.01	0.01	0.00	0.02	0.00	0.01	0.30
Human toxicity	kg 1,4-DB eq	572.30	16.43	247.39	5.59	52.00	2.70	11.11	907.54
Photochemical oxidant formation	kg NMVOC	29.35	0.86	1.32	0.32	2.01	0.40	0.68	34.94
Particulate matter formation	kg PM_{10} eq	26.13	1.16	1.21	0.22	1.57	0.23	0.39	30.91
Terrestrial ecotoxicity	kg 1,4-DB eq	0.26	0.15	0.07	0.01	0.02	0.00	0.23	0.75
Freshwater ecotoxicity	kg 1,4-DB eq	1.86	0.24	0.22	0.06	0.12	0.08	0.49	3.07
Marine ecotoxicity	kg 1,4-DB eq	4.56	0.25	0.60	0.06	0.20	0.04	0.44	6.14
Agricultural land occupation	m^2a	49.03	155.38	4.09	447.40	3.81	3.19	20.55	683.44
Metal depletion	kg Fe eq	4293.20	17.21	154.80	0.34	4.01	1.50	2.89	4473.95
Fossil depletion	kg oil eq	1363.40	67.03	71.83	15.46	147.06	21.30	54.29	1740.37

* Paint, primer and thinner.

Gypsum boards are the second building material in terms of the contribution to the total weight of the modular unit (approximately 24%). However, compared to cast iron (the third weightiest building material), the impacts are lesser in gypsum boards. Gypsum boards contribute approximately 23% and 21% to agricultural land occupation and terrestrial ecotoxicity, respectively. Cast iron showed a higher impact in human toxicity (27%) and marine ecotoxicity (10%). Notably, plywood was the highest contributor to the agricultural land occupation (~65%). The requirement of a larger land area to manufacture the final product of timber, causes the former observation. Moreover, although the aluminium weight percentage is lower than other materials, it showed considerable intensities in terrestrial acidification (~11%) and climate change (~9%).

5.1.2. DfD Version

Steel, cast iron, aluminium and glass are salvageable; hence, it was assumed they could be reused entirely in the base case. However, sensitivity analysis will consider a set of reuse percentages of these building materials to represent different practical scenarios. Furthermore, gypsum boards are recycled, and plywood is landfilled in the DfD version. The negative impacts from the disposal of building materials are accounted for in the end-of-life cycle stage (C) of the modular unit. At the same time, the positive impacts from reusing and recycling (D) are discounted from the current product system to estimate the overall environmental performance of the modular building unit under the selected system boundary. Table 6 shows the environmental impact of the A1, C and D life cycle stages of the DfD version for the 12 midpoint impact categories. Reusing steel, cast iron, aluminium and glass creates positive benefits to the next product system. Conversely, the disposal of gypsum boards (recycling) and plywood (landfilling) causes a negative environmental load on the current product system. Metal depletion is the most profited impact category due to the adoption of CE strategies at the disposal stage of the modular building. The percentage of the total impact value of metal depletion after discounting benefits with the product stage is approximately 0.5%. The former was followed by human toxicity with a total to A1 ratio of 3.84% and climate change with 5.62%. Prominently, as the highest contributor to most impact categories, the reuse of steel resulted in positive achievements. The total to A1 ratio is highest in agricultural land occupation, which is approximately 91%. This has resulted due to the landfilling of plywood; thus, the positive benefits of reusing or recycling could not be afforded in this context. Terrestrial ecotoxicity has a total to A1 ratio of approximately 53% due to the inapplicability of CE strategies on paint as a building material. Paint production emits various chemicals to the terrestrial ecosystems, which cause higher negative environmental loads [47,48].

Table 6. Midpoint impact values of the modular unit for the DfD version.

Impact Category	Unit	A1	C		D				Total
			Gypsum Board	Plywood	Steel	Cast Iron	Aluminum	Glass	
Global warming potential	kg CO_2 eq	8409.07	4.10	2.96	−6843.26	−307.61	−709.64	−83.26	472.36
Terrestrial acidification	kg SO_2 eq	32.74	0.03	0.00	−24.84	−1.26	−3.39	−0.71	2.58
Freshwater eutrophication	kg P eq	0.30	0.00	0.00	−0.24	−0.01	−0.02	0.00	0.03
Human toxicity	kg 1,4-DB eq	907.54	0.04	0.02	−571.86	−247.39	−50.81	−2.70	34.84
Photochemical oxidant formation	kg NMVOC	34.94	0.06	0.00	−29.33	−1.32	−1.95	−0.40	2.00
Particulate matter formation	kg PM_{10} eq	30.91	0.12	0.00	−26.11	−1.21	−1.51	−0.23	1.97
Terrestrial ecotoxicity	kg 1,4-DB eq	0.75	0.00	0.00	−0.26	−0.07	−0.02	0.00	0.40
Freshwater ecotoxicity	kg 1,4-DB eq	3.07	0.00	0.00	−1.86	−0.22	−0.11	−0.08	0.81
Marine ecotoxicity	kg 1,4-DB eq	6.14	0.00	0.00	−4.55	−0.60	−0.19	−0.04	0.76
Agricultural land occupation	m^2a	683.44	0.00	0.00	−48.99	−4.09	−3.33	−3.19	623.85
Metal depletion	kg Fe eq	4473.95	0.00	0.00	−4289.87	−154.80	−3.88	−1.50	23.91
Fossil depletion	kg oil eq	1740.37	1.46	0.00	−1362.34	−71.83	−142.02	−21.30	144.33

5.1.3. Linear Version

In the linear building, it is considered to be demolished at the end-of-life stage. Thus, in the linear version, Steel, cast iron, aluminium, glass, and gypsum boards are recycled, and plywood is landfilled. In the linear arrangement of the modular building, components cannot be dismantled in a way to be reused. As opposed to the DfD version, most of the joints are welded in the linear version, which barricades the salvageability. Similar to the DfD version, the negative impacts from the disposal are accounted for in the end-of-life cycle stage (C). In contrast, the positive effects of reusing and recycling (D) are discounted from the current product system. Table 7 tabulated the environmental performance of the A1, C and D life cycle stages of the linear version of the modular unit for the 12 midpoint impact categories. The highest percentage saving is shown by the metal depletion, similar to the DfD version, where the total to A1 ratio is approximately 2%. It was followed by particulate matter formation and photochemical oxidant formation, with a total to A1 ratio proportion of 7% and 9%, respectively. As the primary building material of the modular unit, steel contributes the highest to the savings. The lowest benefit is recorded by the agricultural land occupation (a total to A1 ratio of ~96%), similar to the DfD version caused mainly by the landfilling of plywood.

Table 7. Midpoint impact values of the modular unit for the linear version.

Impact Category	Unit	A1	C			D			Total
			Gypsum Board	Glass	Plywood	Steel	Cast Iron	Aluminum	
Global warming potential	kg CO_2 eq	8409.07	4.10	0.23	2.96	−6276.47	−291.93	−562.87	1285.09
Terrestrial acidification	kg SO_2 eq	32.74	0.03	0.00	0.00	−23.43	−1.09	−2.9936	5.27
Freshwater eutrophication	kg P eq	0.30	0.00	0.00	0.00	−0.22	−0.01	−0.02	0.05
Human toxicity	kg 1,4-DB eq	907.54	0.04	0.05	0.02	−450.43	−20.95	−65.67	370.61
Photochemical oxidant formation	kg NMVOC	34.94	0.06	0.00	0.00	−28.97	−1.35	−1.60	3.08
Particulate matter formation	kg PM_{10} eq	30.91	0.12	0.00	0.00	−25.88	−1.20	−1.70	2.25
Terrestrial ecotoxicity	kg 1,4-DB eq	0.75	0.00	0.00	0.00	−0.20	−0.01	−0.01	0.53
Freshwater ecotoxicity	kg 1,4-DB eq	3.07	0.00	0.00	0.00	−1.23	−0.06	−0.11	1.68
Marine ecotoxicity	kg 1,4-DB eq	6.14	0.00	0.00	0.00	−2.89	−0.13	−0.17	2.95
Agricultural land occupation	m^2a	683.44	0.00	0.00	0.00	−22.35	−1.04	−2.83	657.22
Metal depletion	kg Fe eq	4473.95	0.00	0.00	0.00	−4254.64	−135.23	−3.82	80.25
Fossil depletion	kg oil eq	1740.37	1.46	0.08	0.00	−1295.49	−60.26	−112.25	273.93

5.1.4. Comparison of DfD and Linear Version

Tables 6 and 7 highlight that the DfD version of the modular unit performed better regarding all environmental impacts than the linear version. For example, considering the global warming potential (climate change), the overall impact of the DfD version is 472.36 kg CO_2 eq compared to 1285.09 kg CO_2 eq by linear unit. These observations support the designing for disassembly and reuse CE strategy thinking at the design stage of a modular unit. Consequently, the modular building can be designed to salvage the components at the end-of-life phase, creating multiple life cycles of reusing as opposed to the traditional way of recycling. Notably, the DfD version favours significantly in reducing the human toxicity potential compared to the linear version. The overall human toxicity potential of the DfD modular unit is 34.84 kg 1,4-DB-eq versus 370.61 kg 1,4-DB-eq created by the linear version of the same modular unit.

Moreover, in contrast to the second highest favourable environmental impact of the DfD version (Human toxicity), it is particulate matter formation in the linear version. This is caused primarily by recycling cast iron and steel instead of reusing. A reduction in environmental savings from recycling instead of reusing cast iron and steel are approximately 92% and 21%, respectively (see Figure 5). Notably, glass recycling creates overall negative impacts as opposed to glass reusing, where it has positive environmental performance. This factor considerably affects the change in overall savings of the linear version compared to the DfD version, as shown in Figure 5. Thus, this indicates the elevated potential of reuse compared to recycling practices, and it shows the importance of planning for DfD strategies at the design stage of a modular building [9,49].

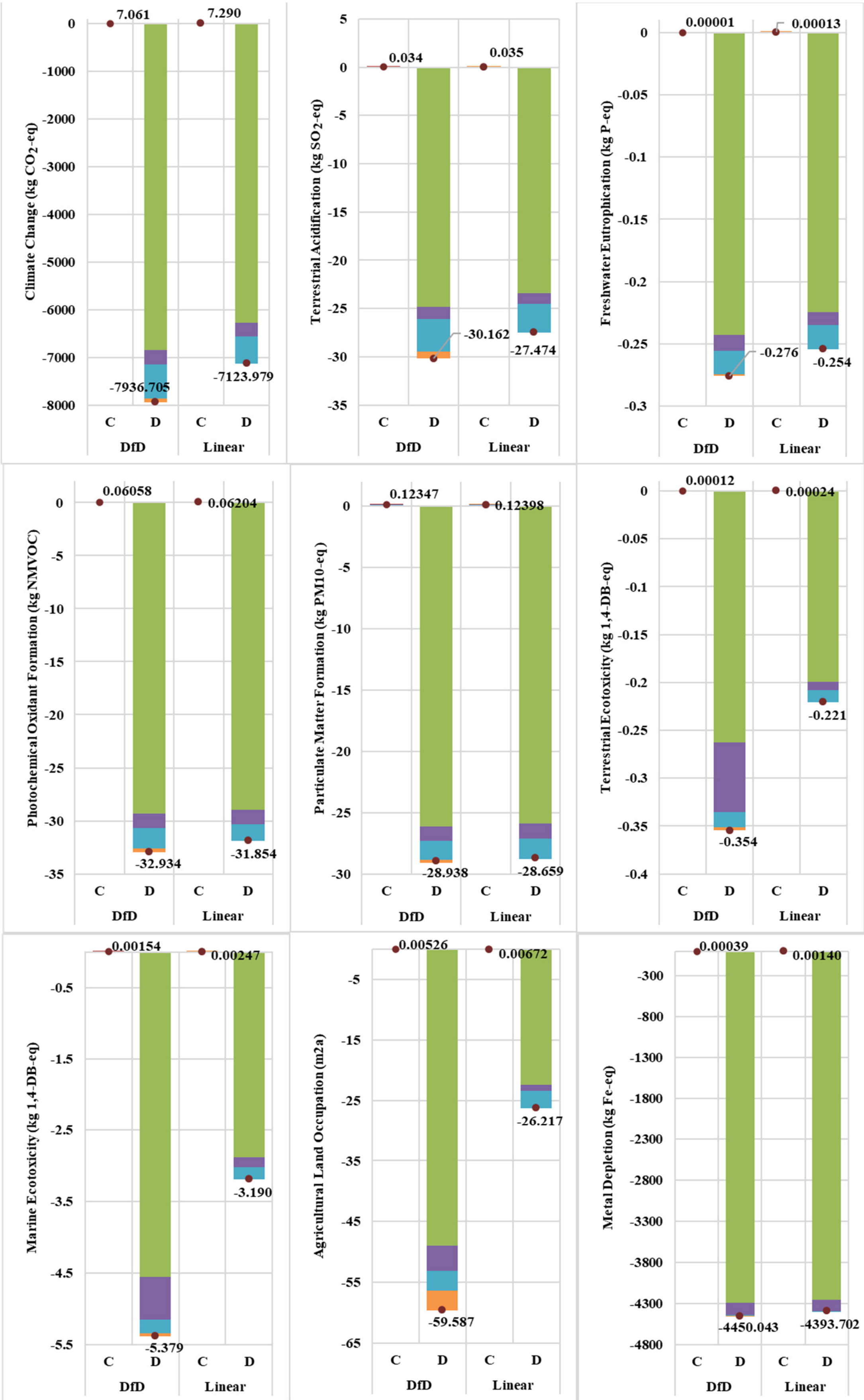


Figure 5. *Cont.*

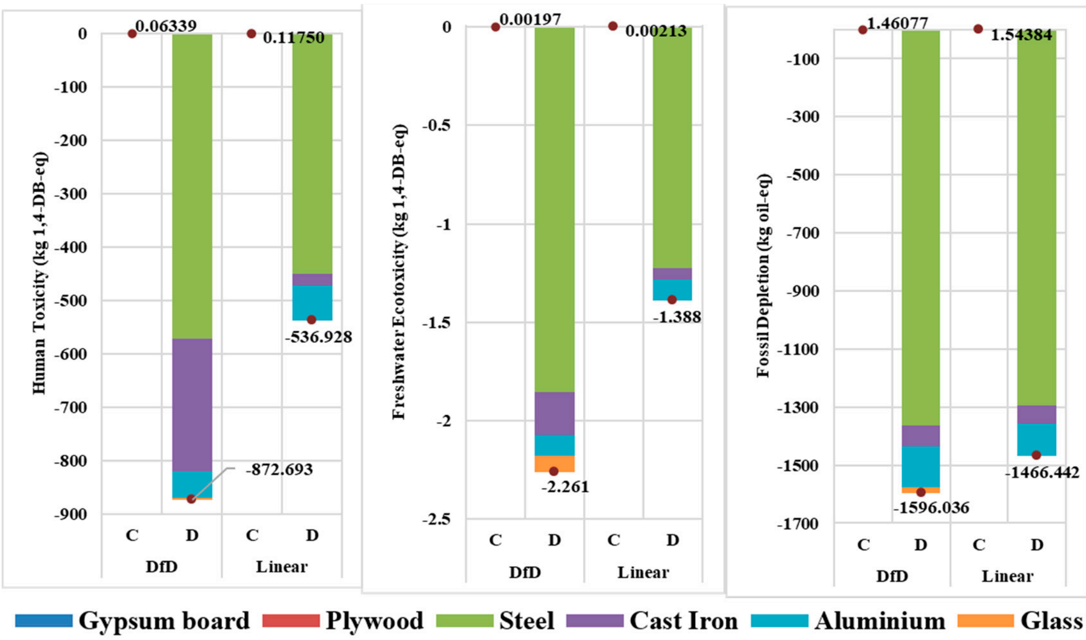


Figure 5. Comparison of end-of-life cycle (C) and benefits beyond the life cycle (D) for DfD and linear modular unit versions.

5.1.5. Midpoint Impacts Normalised Results

The midpoint characterisation values are normalised to have a common unit for inter-comparison of impact categories of DfD and linear versions. Considering the product stage, the most significant environmental impacts are material depletion (10.1), human toxicity (2.8) and marine ecotoxicity (2.5), respectively. Steel is the main contributor due to the majority representation of the building by weight. However, cast iron bears a considerable burden for human toxicity potential apart from steel. Hazardous waste outputs from the steel manufacturing process severely affect the marine ecosystems. Thus, proper discharging of contaminants is crucial in these production outlets. In the DfD modular unit, in considering final cumulative normalised values of the environmental impacts, marine ecotoxicity is the most negative impact category (0.307), as shown in Figure 6. Freshwater ecotoxicity has the second-highest cumulative value with 0.187 points. The least cumulative score is recorded by the photochemical oxidant formation (0.035), followed by the metal depletion (0.054) in the DfD unit. Furthermore, the highest benefit is created by metal depletion, measured by a fall of 10.01 points, which is followed by human toxicity, which is quantified by a drop of 2.67 points. In linear building, similar to the DfD version, marine ecotoxicity shows the highest cumulative value (1.196). However, the second highest is human toxicity, with a score of 1.138. This outcome was significantly resulted by recycling cast iron instead of reusing. Moreover, the greatest saving is recorded by the metal depletion (−9.89) and particular matter formation (−2.04), respectively, as depicted in Figure 7.

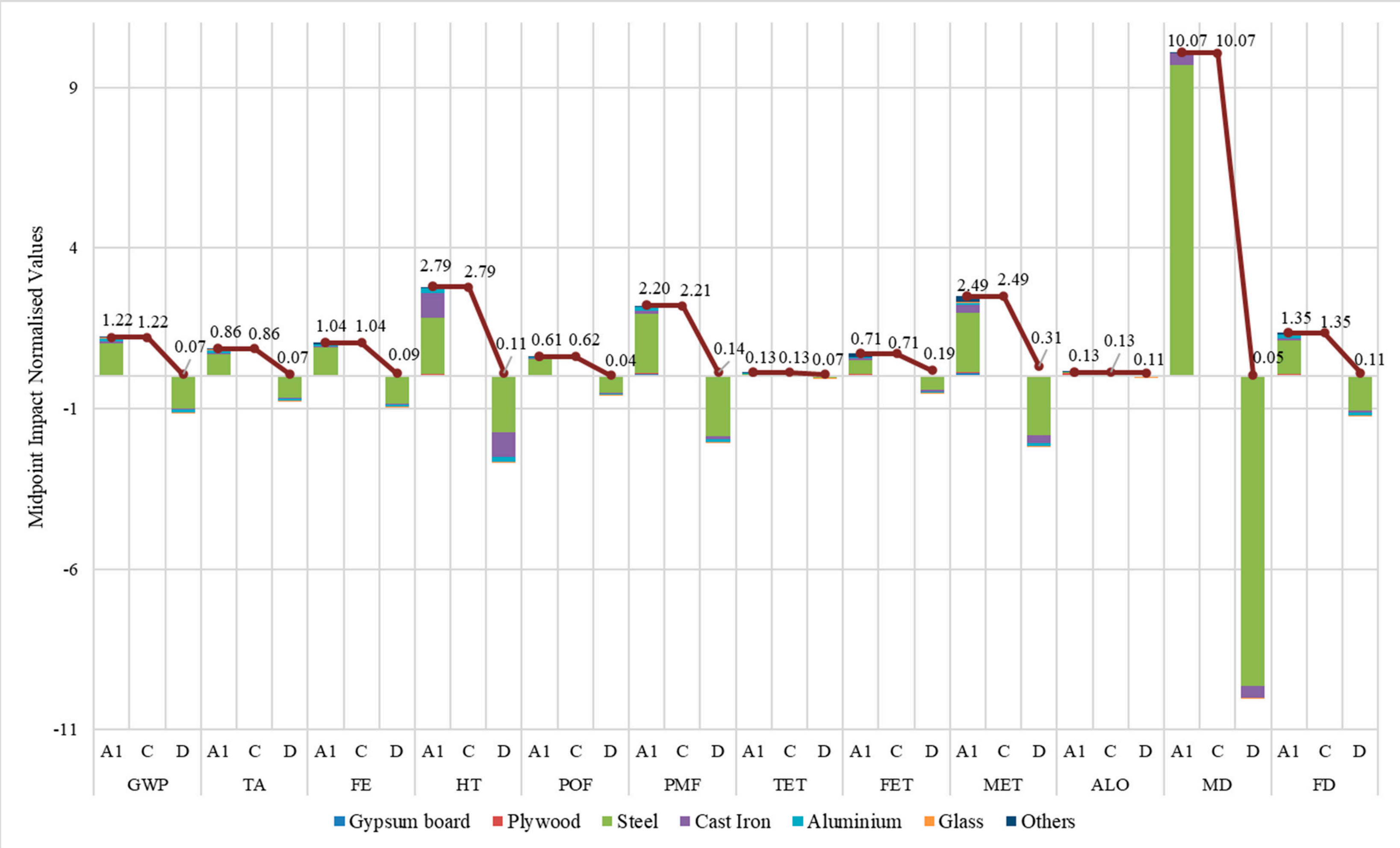


Figure 6. Normalised midpoint impact values of the modular unit for DfD.

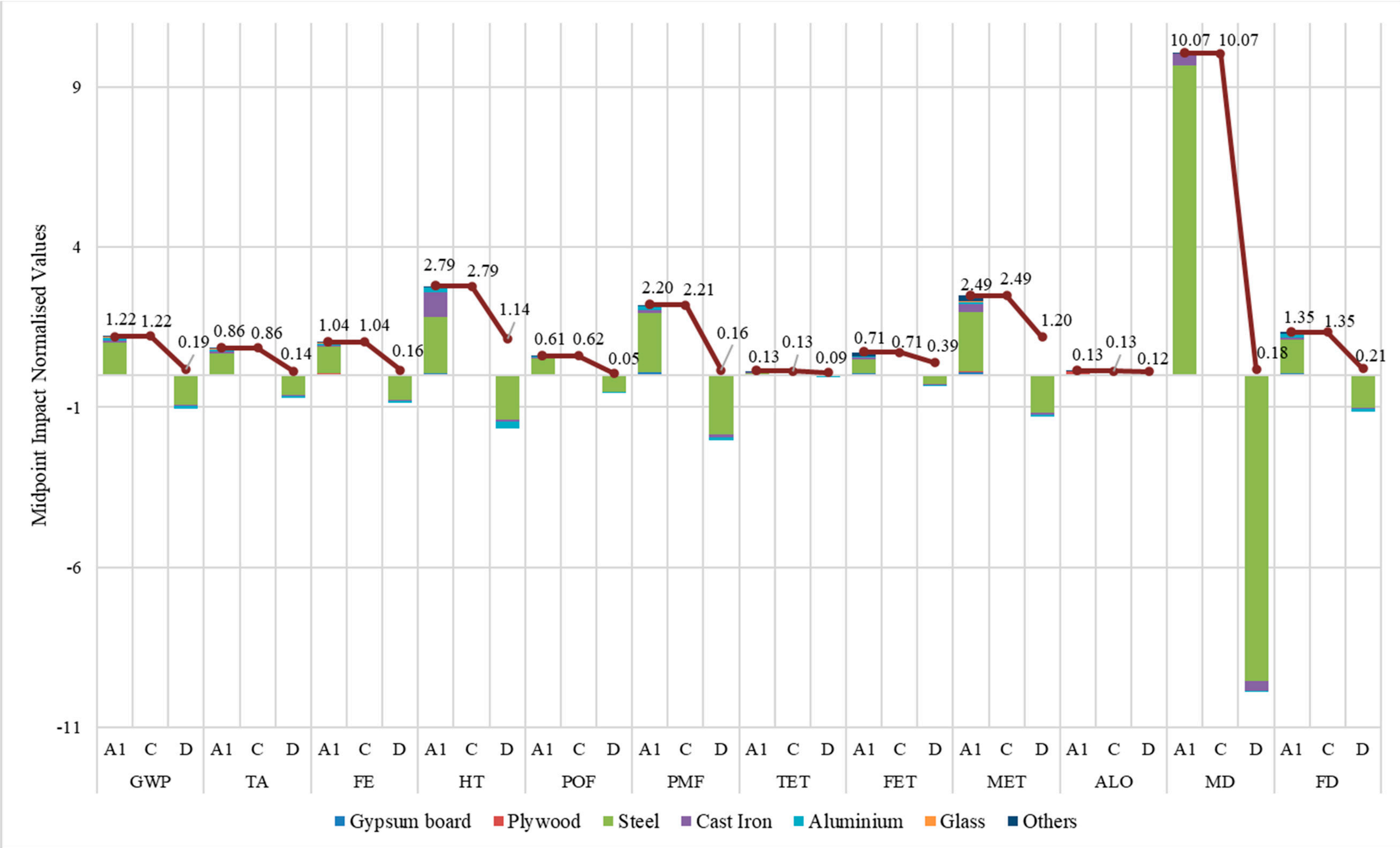


Figure 7. Normalised midpoint impact values of the linear modular unit.

5.2. Sensitivity Analysis

Figure 8 illustrates the GHG emission distribution of the DfD modular version with the change in reuse percentage. First, the reuse percentage was reduced from 100% to 0% for single materials (steel, cast iron, aluminium, and glass). For example, when the steel reuse percentage is changed from 100% to 80%, the reuse percentages of the other three materials are kept at 100% reuse. Similarly, this process is repeated for cast iron, aluminium, and glass. It is assumed that, for example, when 80% of steel is reused, the rest of the 20% is recycled. The former assumption was maintained uniformly for all other materials. Secondly, the cumulative effect of all the four materials is quantified. For example, as shown in Figure 8, at the 80% mark in the light blue colour line, all four materials are reused at 80%. As presented by Melella et al. [50], apart from the recovery potential, factors such as damages that can happen in the disassembly process, handling of elements/materials and subsequent modification activities should be considered to decide the overall reusability. From a recovery potential perspective, adhesive and welded systems have less recovery potentials, 0–20% and 40%, respectively. However, dry systems with clamping and interlocking systems can reach up to 80% and even 100% [44,50]. Thus, these considerations need to be addressed at the design stage to support the end-of-life stage activities.

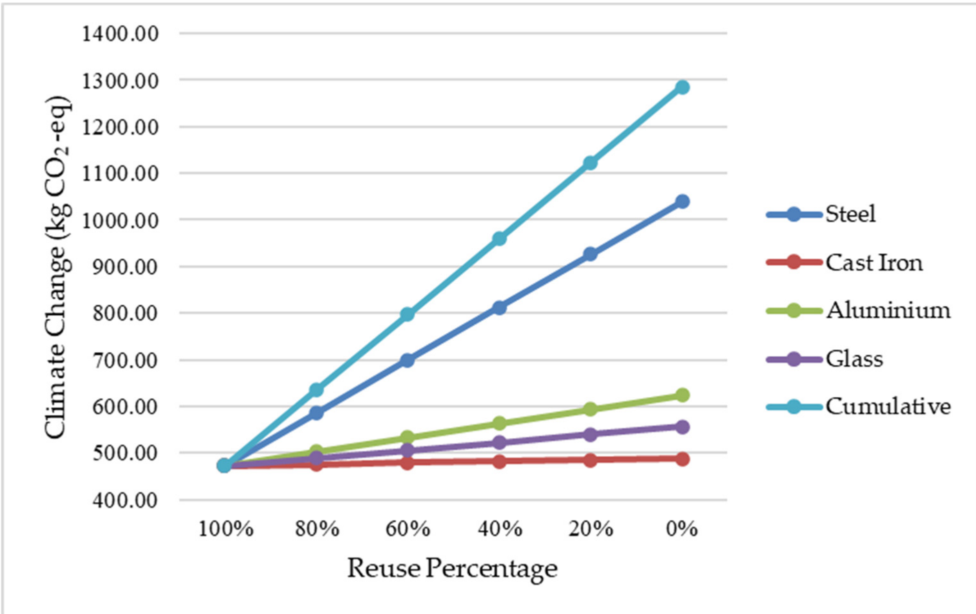


Figure 8. Greenhouse gas emission variation with the change in reuse proportions.

Figure 8 indicates the linear relationship between the GHG emissions and the reuse proportion. As the primary building material, steel is the most sensitive to the change in reuse percentage. This was followed by aluminium, glass and cast iron. GHG emissions rose from 472.36 kg CO_2-eq to 1039.16 kg CO_2-eq when only the steel reuse percentage changed from 100% to 0%. As a percentage, it is an increase of approximately 120%. Thus, as a CE strategy, steel reusing presents significant benefits compared to steel recycling [9]. Table 8 shows the emission variations with the change in reuse scales for the other five impact categories chosen for the sensitivity assessment. Human toxicity is the most affected environmental impact by the shift in reuse percentage. Notably, when cast iron reuse is changed from 100% to 0%, the human toxicity value increased from 649.87%. As found earlier in the discussion, this resulted from cast iron recycling compared to cast iron reusing. One of the key observations is that agricultural land occupation is the least sensitive to the change in reuse percentages. This is because the plywood end-of-life is not changing; it stays as landfilling. Thus, the significant effect of plywood on land occupation is not compensated in any of these strategies. The variation in marine ecotoxicity was also significantly sensitive to reuse percentages of steel and cast iron. When the steel reuse percentage is reduced from 100% to 0%, marine ecotoxicity impact rises by approximately 220%. Similarly, for cast iron, this proportion is approximately 61%. The change in effect of freshwater ecotoxicity is primarily affected by steel reuse and terrestrial ecotoxicity steel and cast iron effect on a similar scale.

Table 8. Environmental impact emission variation with the change in reuse proportions.

Impact Category	% Reuse	Human Toxicity (kg 1,4-DB eq)	Terrestrial Ecotoxicity (kg 1,4-DB eq)	Freshwater Toxicity (kg 1,4-DB eq)	Marine Toxicity (kg 1,4-DB eq)	Agricultural Land Occupation (m^2a)
Steel	100%	34.843	0.398	0.808	0.757	623.850
	80%	59.130	0.411	0.934	1.090	629.177
	60%	83.417	0.424	1.060	1.424	634.505
	40%	107.703	0.436	1.186	1.757	639.832
	20%	131.990	0.449	1.312	2.091	645.160
	0%	156.277	0.462	1.438	2.424	650.487
Cast iron	100%	34.843	0.398	0.808	0.757	623.850
	80%	80.130	0.411	0.840	0.850	624.459
	60%	125.418	0.423	0.871	0.943	625.069
	40%	170.705	0.436	0.903	1.036	625.678
	20%	215.992	0.449	0.935	1.129	626.288
	0%	261.279	0.461	0.967	1.222	626.897
Aluminium	100%	34.843	0.398	0.808	0.757	623.850
	80%	37.816	0.399	0.808	0.760	623.948
	60%	40.788	0.399	0.808	0.763	624.046
	40%	43.760	0.400	0.808	0.765	624.144
	20%	46.732	0.401	0.808	0.768	624.243
	0%	49.704	0.401	0.808	0.771	624.341
Glass	100%	34.843	0.398	0.808	0.757	623.850
	80%	35.395	0.399	0.825	0.765	624.489
	60%	35.946	0.399	0.842	0.773	625.128
	40%	36.497	0.400	0.858	0.782	625.767
	20%	37.049	0.401	0.875	0.790	626.406
	0%	37.600	0.401	0.892	0.798	627.044
Cumulative	100%	34.843	0.398	0.808	0.757	623.850
	80%	107.941	0.425	0.982	1.194	630.524
	60%	181.038	0.452	1.157	1.632	637.198
	40%	254.135	0.478	1.332	2.070	643.872
	20%	327.232	0.505	1.506	2.508	650.546
	0%	400.329	0.532	1.681	2.946	657.220

5.3. Practical Implications to the Sri Lankan Modular Construction Context

Currently, modular construction practicing in the Sri Lankan construction projects are significantly less relative to the conventional methods [3]. More national and local-level manufacturers are required to diffuse modular technologies to the construction market. The current study uses a design-stage modular building unit to showcase the environmental advantages of design for recovering building elements/materials at the disposal stage of the building. The reuse potential of these materials for several product systems possesses environmental savings and the potential for generating cost benefits. The costs covering from an extraction stage to processing and transportation in complex supply chains related to building materials can be reduced by CE approaches such as reduce. Hence, Sri Lankan construction project stakeholders should collaborate to identify and formulate strategies to adopt CE-integrated MC practices in future construction projects. The current post-COVID-19 economic crisis directly affected the Sri Lankan construction industry by spiking material, fuel and logistic costs, causing projects to be at a standstill [39,51]. Hence, long-term philosophies are necessary in the construction sector to overcome these downfalls. Approaches such as modular technologies, DfD and circular economy strategies present significant opportunities to fit it in a long-term solution portfolio. The current research can be referred to as a pilot case to see the positive evidence of these approaches.

Architectural design thinking to elevate material circularity is a crucial aspect that the current study attempted to highlight. Joining systems is imperative to increase the recovery potential of the building components of modular buildings. Thus, employing advanced and appropriate joining technologies is crucial in improving the overall environmental performance of these DfD modular structures. Modular manufacturers and architects in Sri Lanka should work hand in hand with subject area experts, research and development institutions and academia to develop compatible and advanced architectural designs and relevant connection systems. Furthermore, to promote CE principles in construction projects, Sri Lanka needs more industrial and technology developments to support deconstruction, processing, and reverse logistics at the EoL stage. Relevant and adequate machinery and tools should be selected in disassembling activities to increase the proportion of recoveries. Moreover, suitable handling and transporting vehicles are essential to minimise any damages and protect any fragile elements. Although the design-stage predictions show the environmental savings from adopting CE strategies in modular construction, compatible practical setups are in demand to realise the actual potential. Thus, the Sri Lankan construction industry should imminently start working on this long-term philosophy to transform lacklustre construction performances into advanced and efficient states.

5.4. Strategies to Support Circular Economy Approach in Modular Construction

Table 9 presents a set of strategies to aid in the proficient growth of CE-integrated modular construction technologies in construction projects in developing economies. 'Design for disassembly' is one of the significant strategies, if not the most important, for realising CE in MC. DfD was first introduced for buildings in the 1990s, intending to design and construct buildings to salvage durable materials that can be reusable at the demolition stage of the building [49]. The DfD approach aids in keeping durable components/materials in the market chain until their capable service life is delivered [52]. The decisions related to the building's deconstruction destinies, such as the reuse of the entire building, components reuse in other buildings and material reprocessing, play a significant role in DfD. 'Close and early stakeholder collaboration and coordination' is paramount to transforming CE from an impressive theory to real-world construction projects. MC project team, clients, and other practitioners should be aware and informed about the advantages of CE strategies from the project conception. Client involvement in an early planning stage is required to inform and convince the benefits of CE in modular building developments and gain acceptance [35]. Design-stage sustainability assessments, such as the current study, can support as quantified evidence in early decision-making stages. Furthermore, 'digital information platforms such as building information modelling (BIM)' can be employed in MC projects to realise virtual collaboration and coordination of stakeholders [53,54]. Moreover, 'BIM coupled with intelligent technologies such as radio frequency identification (RFID) systems can track building components and materials throughout the building life cycle [26,55]. Thus, this approach can particularly aid in elevating communication and sub-processes in the end-of-life cycle stage.

Table 9. Strategies to promote and implement circular economy-driven modular construction in developing regions.

Strategy Cluster	No	Strategies
Design	S1	Promote and advance design for disassembly (DfD) design approach
	S2	Standardise modular-based DfD designs
	S3	Choice of dry technological systems instead of wet ones to elevate the disassembly potential
	S4	Present multiple design options to attract more clients by demonstrating architectural freedom and creativity
	S5	Design for incorporating alternative sustainable building materials/elements (i.e., local, low-cost, recycled)
	S6	Incorporate the maintainability and durability criteria of the overall modules when developing sustainable alternative designs
Stakeholder collaboration and communication	S7	Close and early stakeholder engagement to understand the importance of CE integration and to formulate corresponding goals and objectives
	S8	Implement digital systems to communicate and collaborate considering the whole project life cycle
Advanced technology integration	S9	Integrating digital information platforms such as BIM
	S10	Integrating with smart technologies such as the internet of things (IoT)
	S11	Employ advanced production technologies such as additive manufacturing and automation
Materials	S12	Timber-based technologies for structural framing, such as CLT and Glulam
	S13	Employ green building material alternatives such as building panels with recycled content
Research and development approaches	S14	Develop mechanisms to incorporate processed construction and demolition waste from conventional construction projects
	S15	Sustainability assessments to evaluate sustainability performance and to identify process and material hotspots
	S16	Comprehensive methodologies to quantify the recovery potentials and reusability indexes at the EoL stage
	S17	Comprehensive assessment methods to quantify regional-base sustainability impacts from EoL deconstruction, transportation, sorting and reprocessing activities
	S18	Build effective and sustainable material passport tools to store and share information in the whole life cycle to benefit EoL and the next product system stages
Whole project life cycle planning	S19	Formulate a disassembly and selective demolition plan to realise the reuse and recycling of building materials and elements at EoL stage
	S20	Comprehensive strategies to support reverse logistics of disassembled or demolished materials to the following processing or product stage
Policy, regulations, codes, and financial support	S21	Government policies and regulations to mandate the use of modular construction and CE approaches
	S22	Develop comprehensive design codes, standards, and technical guidance for synergising MC, DfD and CE methods
	S23	Financial support and investments from government and non-government financial organisations to aid CE diffusion
	S24	Financial incentives from the government to encourage and enable small-scale and local manufacturers to adopt CE-driven MC practices
Improve technical knowledge and general awareness	S25	Industry-level workshops, training, and seminars to enhance the technical skills and knowledge of project teams, labourers and other practitioners
	S26	Awareness programmes on the benefits of CE thinking in MC to key project stakeholders such as manufacturers, builders, and other practitioners
	S27	Promotional and informative programmes (workshops, exhibitions, and online events) to clients and the general public to promote and raise awareness on concepts of MC and CE

From a material perspective, CLT, as an engineered wood material, can provide similar fire and structural protection, decreased environmental burden, and lighter foundation demands compared to other timber, concrete, and steel structures [56–58]. Thus, developing regions should focus more on these technologies to reduce environmental loads from building materials such as steel and concrete. The lack of research and development initiatives related to MC and CE is a significant impeding factor in South Asian economies. More research on digitising material information is crucial in aiding life cycle visibility and CE philosophy. For example, material passport systems combined with BIM provide essential guidelines on handling building materials at the construction phase and ways to benefit at the EoL stage through various recovery opportunities [59]. Moreover, developing regions can learn from policy and regulation implementations related to CE integration in developed countries. Ruocco et al. [44] stated that the Italian CAM for Buildings (Minimum Environmental Criteria) demands that a minimum of 50% by weight of the building components should be reusable and recyclable. On top of that, out of 50%, at least 15% must allocated by non-structural building materials. Governments can support by financing and investing to impose new government buildings such as hospitals and schools to aid economies of scale [53]. An example can be seen in Australia: the Permanent Modular School Buildings Programme (PMSB), by the Victorian School Building Authority (VSBA), has planned to replace the old school buildings with brand new modular classrooms in 100 public schools around Victoria, Australia [60,61]. Thus, in Sri Lanka, these kinds of initiatives are required to promote, motivate, and support manufacturers and builders and to utilise the economies of scale to the full extent of CE-driven MC. Uthpala and Ramachandra [62] found that awareness and public negative perceptions are significantly impeding the promoting and adoption of modern methods of construction, such as MC, in Sri Lanka. Therefore, improving both technical knowledge and general awareness is critical to implementing CE philosophy in the Sri Lankan construction industry.

6. Conclusions and Future Research Directions

The building industry, a primary creator of construction demolition waste, is in an early transition stage from a linear economy to a circular economic model [12]. MC, an evolving construction method, contains some distinctive qualities supporting the circularity of materials and building components. It is vital to DfD of modular buildings to aid the closed-loop material flow and reuse of building elements. Moreover, design-stage sustainability evaluations such as LCA integrated with the CE phenomenon will help critical decision making in the early life cycle phase of modular building projects. Thus, this study conducted a design-stage LCA with CE essence to predict the behaviour of EoL disposal practices. The assessment employs two versions (DfD and linear) of the design-stage case study modular unit to demonstrate the potential environmental benefits of CE strategies.

The results highlighted that the DfD version of the modular unit performed better in terms of all environmental impacts compared to the linear version. Further, it showed the elevated potential of reuse compared to recycling practices, and it indicates the importance of going for DfD-driven CE strategies at the design stage of a modular building. Sensitivity assessment found Steel, as the primary building material, is the most sensitive to the change in reuse percentage. The main limitation of this study is the exclusion of manufacturing, use and downstream transportation and reverse logistics phases. Moreover, some of the process steps at the EoL stage are assumed to be followed by general practices in Sri Lanka.

The current study derives several future research directions that the relevant researchers could pursue. First, this study has focused only on the environmental aspect; future research can focus on conducting cost estimations at the design stage. This estimation should identify the potential savings from using the second string of materials for the following product system. Second, further research could aim to analyse the effect of alternative materials at the EoL stage. This approach could be extended to both environmental and economic dimensions. For example, using timber-based framing instead of steel structures and employing sustainable panel alternatives such as panels with recycled content. Third, comprehensive foresight on logistics aspects at the EoL stage, from deconstruction to the subsequent product system, could be explored. Reverse logistics uncertainties should be understood in the preliminary phases to promote circularity. Finally, future research can broaden the CE phenomenon by incorporating the 9R approach.

Author Contributions: Conceptualization, J.J., A.K.K., M.S., J.A.S.C.J., G.Z. and S.A.U.O.; Methodology, J.J., A.K.K., M.S. and S.A.U.O.; Software, J.J. and S.A.U.O.; Validation, A.K.K., M.S., J.A.S.C.J. and G.Z.; Formal analysis, J.J. and S.A.U.O.; Writing—original draft, J.J.; Writing—review & editing, M.S., A.K.K., J.A.S.C.J., G.Z. and S.A.U.O.; Supervision, M.S., A.K.K., J.A.S.C.J. and G.Z.; Project administration, A.K.K., M.S., J.A.S.C.J. and G.Z.; Funding acquisition, A.K.K., M.S., J.A.S.C.J., G.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data will be made available on request.

Acknowledgments: The authors acknowledge the Journal for providing a free waiver for the publication of this research.

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

References

1. Hu, X.; Chong, H.-Y. Environmental sustainability of off-site manufacturing: A literature review. *Eng. Constr. Archit. Manag.* **2019**, *28*, 332–350. [CrossRef]
2. Yin, X.; Liu, H.; Chen, Y.; Al-Hussein, M. Building information modelling for off-site construction: Review and future directions. *Autom. Constr.* **2019**, *101*, 72–91. [CrossRef]
3. Jayawardana, J.; Kulatunga, A.K.; Sandanayake, M.; Zhang, G.; Jayasinghe, J.A.S.C. Life Cycle Assessment for Modular-Constructed Buildings: A Proposed Methodological Framework. In *Proceedings of the ICSECM 2021, 12th International Conference on Structural Engineering and Construction Management*; Springer Nature: Singapore, 2022; pp. 519–532.
4. Xu, X.; Ding, X.; Wang, Q.; Chen, T.; Deng, R. Comparative Analysis and Empirical Study of Prefabrication Rate Calculation Methods for Prefabricated Buildings in Various Provinces and Cities in China. *Buildings* **2023**, *13*, 2042. [CrossRef]
5. Jayawardana, J.; Jayasinghe, J.A.S.C.; Sandanayake, M.; Kulatunga, A.K.; Zhang, G. Prefabricated Construction in Sri Lanka: A Proposed Adoption Strategy and a Pilot Case Study from Sustainability Perspective. *Engineer* **2023**, *56*, 71–80. [CrossRef]
6. Wong, P.S.; Zwar, C.; Gharaie, E. Examining the drivers and states of organizational change for greater use of prefabrication in construction projects. *J. Constr. Eng. Manag.* **2017**, *143*, 04017020. [CrossRef]
7. Kamali, M.; Hewage, K. Life cycle performance of modular buildings: A critical review. *Renew. Sustain. Energy Rev.* **2016**, *62*, 1171–1183. [CrossRef]
8. Ismail, S.; Hon, C.K.; Crowther, P.; Skitmore, M.; Lamari, F. The drivers and challenges of adopting the Malaysia industrialised building system for sustainable infrastructure development. *Constr. Innov.* 2022, *ahead of print*.
9. Minunno, R.; O'Grady, T.; Morrison, G.M.; Gruner, R.L. Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building. *Resour. Conserv. Recycl.* **2020**, *160*, 104855. [CrossRef]
10. Moraga, G.; Huysveld, S.; Mathieux, F.; Blengini, G.A.; Alaerts, L.; Van Acker, K.; De Meester, S.; Dewulf, J. Circular economy indicators: What do they measure? *Resour. Conserv. Recycl.* **2019**, *146*, 452–461. [CrossRef]
11. Circle Economy and Bain & Company. *A Circular Future for the European Construction Sector: Light Commercial and Residential Buildings*; Circle Economy and Bain & Company: Amsterdam, The Netherlands, 2022.
12. Bertino, G.; Kisser, J.; Zeilinger, J.; Langergraber, G.; Fischer, T.; Österreicher, D. Fundamentals of building deconstruction as a circular economy strategy for the reuse of construction materials. *Appl. Sci.* **2021**, *11*, 939. [CrossRef]
13. Jayawardana, J.; Kulatunga, A.K.; Jayasinghe, J.A.S.C.; Sandanayake, M.; Zhang, G. Environmental Sustainability of Off-Site Construction in Developed and Developing Regions: A Systematic Review. *J. Archit. Eng.* **2023**, *29*, 04023008. [CrossRef]
14. Pons, O.; Wadel, G. Environmental impacts of prefabricated school buildings in Catalonia. *Habitat Int.* **2011**, *35*, 553–563. [CrossRef]
15. Paya-Marin, M.; Lim, J.; Sengupta, B. Life cycle energy analysis of a modular/off-site building school. *Am. J. Civ. Eng. Archit.* **2013**, *1*, 59–63. [CrossRef]
16. Boyd, N.; Khalfan, M.M.; Maqsood, T. Off-site construction of apartment buildings. *J. Archit. Eng.* **2013**, *19*, 51–57. [CrossRef]
17. Smith, R.E. *Prefab Architecture: A Guide to Modular Design and Construction*; John Wiley & Sons: New York, NY, USA, 2010.
18. Lawson, M.; Ogden, R.; Goodier, C. *Design in Modular Construction*; CRC Press: Boca Raton, FL, USA, 2014.
19. Hwang, B.-G.; Shan, M.; Looi, K.-Y. Key constraints and mitigation strategies for prefabricated prefinished volumetric construction. *J. Clean. Prod.* **2018**, *183*, 183–193. [CrossRef]
20. Bello, A.O.; Khan, A.A.; Idris, A.; Awwal, H.M. Barriers to modular construction systems implementation in developing countries' architecture, engineering and construction industry. *Eng. Constr. Archit. Manag.* **2023**. [CrossRef]

21. Wuni, I.Y.; Shen, G.Q. Barriers to the adoption of modular integrated construction: Systematic review and meta-analysis, integrated conceptual framework, and strategies. *J. Clean. Prod.* **2020**, *249*, 119347. [CrossRef]
22. Munmulla, T.; Hidallana-Gamage, H.D.; Navaratnam, S.; Ponnampalam, T.; Zhang, G.; Jayasinghe, T. Suitability of Modular Technology for House Construction in Sri Lanka: A Survey and a Case Study. *Buildings* **2023**, *13*, 2592. [CrossRef]
23. Sarathchandra, A. Completion of Sri Lanka's First Prefabricated Prefinished Volumetric Construction Modular Building. 2022. Available online: https://www.linkedin.com/search/results/content/?fromMember=%5B%22ACoAACOxacYBpH9H6Khnp7xcDqy5TV8rw85QOPI%22%5D&heroEntityKey=urn%3Ali%3Afsd_profile%3AACoAACOxacYBpH9H6Khnp7xcDqy5TV8rw85QOPI&keywords=akila%20sarathchandra&position=0&searchId=54e7a500-7873-43e9-beee-29d468bfa99b&sid=5PE&update=urn%3Ali%3Afs_updateV2%3A(urn%3Ali%3Aactivity%3A6970776559859240961%2CBLENDED_SEARCH_FEED%2CEMPTY%2CDEFAULT%2Cfalse) (accessed on 6 November 2023).
24. O'Grady, T.M.; Brajkovich, N.; Minunno, R.; Chong, H.Y.; Morrison, G.M. Circular Economy and Virtual Reality in Advanced BIM-Based Prefabricated Construction. *Energies* **2021**, *14*, 4065. [CrossRef]
25. Garusinghe, G.D.A.U.; Perera, B.A.K.S.; Weerapperuma, U.S. Integrating Circular Economy Principles in Modular Construction to Enhance Sustainability. *Sustainability* **2023**, *15*, 11730. [CrossRef]
26. Minunno, R.; O'Grady, T.; Morrison, G.M.; Gruner, R.L.; Colling, M. Strategies for applying the circular economy to prefabricated buildings. *Buildings* **2018**, *8*, 125. [CrossRef]
27. Kamali, M.; Hewage, K.; Sadiq, R. Conventional versus modular construction methods: A comparative cradle-to-gate LCA for residential buildings. *Energy Build.* **2019**, *204*, 109479. [CrossRef]
28. Maués, L.M.F.; do Nascimento, B.D.M.O.; Lu, W.; Xue, F. Estimating construction waste generation in residential buildings: A fuzzy set theory approach in the Brazilian Amazon. *J. Clean. Prod.* **2020**, *265*, 121779. [CrossRef]
29. Zairul, M. The recent trends on prefabricated buildings with circular economy (CE) approach. *Clean. Eng. Technol.* **2021**, *4*, 100239. [CrossRef]
30. Charef, R.; Morel, J.-C.; Rakhshan, K. Barriers to implementing the circular economy in the construction industry: A critical review. *Sustainability* **2021**, *13*, 12989. [CrossRef]
31. Khan, A.; Yu, R.; Liu, T.; Guan, H.; Oh, E. Drivers towards adopting modular integrated construction for affordable sustainable housing: A Total Interpretive Structural Modelling (TISM) method. *Buildings* **2022**, *12*, 637. [CrossRef]
32. Wuni, I.Y.; Shen, G.Q. Holistic review and conceptual framework for the drivers of offsite construction: A total interpretive structural modelling approach. *Buildings* **2019**, *9*, 117. [CrossRef]
33. Tsz Wai, C.; Wai Yi, P.; Ibrahim Olanrewaju, O.; Abdelmageed, S.; Hussein, M.; Tariq, S.; Zayed, T. A critical analysis of benefits and challenges of implementing modular integrated construction. *Int. J. Constr. Manag.* **2021**, *23*, 656–668. [CrossRef]
34. Pan, W.; Zhang, Z. Benchmarking the Sustainability of Concrete and Steel Modular Construction for Buildings in Urban Development. *Sustain. Cities Soc.* **2023**, *90*, 104400. [CrossRef]
35. Mackenbach, S.; Zeller, J.; Osebold, R. A roadmap towards circularity-modular construction as a tool for circular economy in the built environment. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2020.
36. Satola, D.; Kristiansen, A.B.; Houlihan-Wiberg, A.; Gustavsen, A.; Ma, T.; Wang, R.Z. Comparative life cycle assessment of various energy efficiency designs of a container-based housing unit in China: A case study. *Build. Environ.* **2020**, *186*, 107358. [CrossRef]
37. Wuni, I.Y.; Shen, G.Q. Developing critical success factors for integrating circular economy into modular construction projects in Hong Kong. *Sustain. Prod. Consum.* **2022**, *29*, 574–587. [CrossRef]
38. ISO. ISO 14040:2006-Environmental Management—Life Cycle Assessment—Principles and Framework. Available online: https://www.iso.org/standard/37456.html (accessed on 8 February 2021).
39. Jayawardana, J.; Sandanayake, M.; Jayasinghe, J.A.S.C.; Kulatunga, A.K.; Zhang, G. A comparative life cycle assessment of prefabricated and traditional construction–A case of a developing country. *J. Build. Eng.* **2023**, *72*, 106550. [CrossRef]
40. Goedkoop, M.; Heijungs, R.; Huijbregts, M.; Schryver, A.D.; Struijs, J.V.Z.R.; Van Zelm, R. ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. *Hague Minist. VROM* **2009**, *1*, 1–126.
41. Huijbregts, M.A.; Steinmann, Z.J.; Elshout, P.M.; Stam, G.; Verones, F.; Vieira, M.; Zijp, M.; Hollander, A.; Van Zelm, R. ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *Int. J. Life Cycle Assess.* **2017**, *22*, 138–147. [CrossRef]
42. Amarasekera, H. Construction Timber in Sri Lanka–Future Trends and Technologies. 2023. Available online: Chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/http://dr.lib.sjp.ac.lk/bitstream/handle/123456789/12565/Current-use-of-construction-timber-and-future-trends-Construction-Indusry-seminar.pdf?sequence=1 (accessed on 6 November 2023).
43. Dailymirror. CLT Houses for Green Lanka. 2018. Available online: https://www.dailymirror.lk/article/CLT-houses-for-green-Lanka-147629.html (accessed on 6 November 2023).
44. Di Ruocco, G.; Melella, R.; Sabatano, L. Timber buildings deconstruction as a design solution toward near zero CO2e emissions. *Buildings* **2023**, *13*, 157. [CrossRef]
45. Ren, L.; Zhou, S.; Peng, T.; Ou, X. A review of CO_2 emissions reduction technologies and low-carbon development in the iron and steel industry focusing on China. *Renew. Sustain. Energy Rev.* **2021**, *143*, 110846. [CrossRef]
46. Kang, Z.; Liao, Q.; Zhang, Z.; Zhang, Y. Carbon neutrality orientates the reform of the steel industry. *Nat. Mater.* **2022**, *21*, 1094–1098. [CrossRef] [PubMed]

47. Seth, R.; Tam, K. Toxic impact assessment of a manufacturing process: Illustrative application to the automotive paint process. *Int. J. Environ. Stud.* **2006**, *63*, 453–462. [CrossRef]
48. Yi, Z.; Yali, X.; Yongsen, L. Economic and Social Impact Assessment of the Alternatives to DDT Usage for Antifouling Paint Production in China. *Chin. J. Popul. Resour. Environ.* **2008**, *6*, 48–55. [CrossRef]
49. Eckelman, M.J.; Brown, C.; Troup, L.N.; Wang, L.; Webster, M.D.; Hajjar, J.F. Life cycle energy and environmental benefits of novel design-for-deconstruction structural systems in steel buildings. *Build. Environ.* **2018**, *143*, 421–430. [CrossRef]
50. Melella, R.; Di Ruocco, G.; Sorvillo, A. Circular construction process: Method for developing a selective, low CO2eq disassembly and demolition plan. *Sustainability* **2021**, *13*, 8815. [CrossRef]
51. Jayawardana, J.; Jayasinghe, J.A.S.C.; Kulatunga, A.K.; Sandanayake, M.; Zhang, G. Prefabricated Construction in Sri Lanka: From a Sustainability Perspective. In *International Conference on Sustainable Built Environment*; Springer Nature: Singapore, 2022; pp. 451–460.
52. Akbarieh, A.; Jayasinghe, L.B.; Waldmann, D.; Teferle, F.N. BIM-based end-of-lifecycle decision making and digital deconstruction: Literature review. *Sustainability* **2020**, *12*, 2670. [CrossRef]
53. Marinelli, M.; Konanahalli, A.; Dwarapudi, R.; Janardhanan, M. Assessment of Barriers and Strategies for the Enhancement of Off-Site Construction in India: An ISM Approach. *Sustainability* **2022**, *14*, 6595. [CrossRef]
54. Mostafa, S.; Kim, K.P.; Tam, V.W.; Rahnamayiezekavat, P. Exploring the status, benefits, barriers and opportunities of using BIM for advancing prefabrication practice. *Int. J. Constr. Manag.* **2020**, *20*, 146–156. [CrossRef]
55. Ahmadian FF, A.; Rashidi, T.H.; Akbarnezhad, A.; Waller, S.T. BIM-enabled sustainability assessment of material supply decisions. *Eng. Constr. Archit. Manag.* **2017**, *24*, 668–695. [CrossRef]
56. Shahnewaz, M.; Tannert, T.; Alam, M.S.; Popovski, M. Experimental and finite element analysis of cross laminated timber (CLT) panels. In Proceedings of the First International Conference on Advances in Civil Infrastructure and Construction Materials, Dhaka, Bangladesh, 14–15 December 2015.
57. Ferdous, W.; Bai, Y.; Ngo, T.D.; Manalo, A.; Mendis, P. New advancements, challenges and opportunities of multi-storey modular buildings–A state-of-the-art review. *Eng. Struct.* **2019**, *183*, 883–893. [CrossRef]
58. Passarelli, R.N. The environmental impact of reused CLT panels: Study of a single-storey commercial building in Japan. In Proceedings of the 2018 World Conf. on Timber Engineering, Seoul, Republic of Korea, 20–23 August 2018.
59. Atta, I.; Bakhoum, E.S.; Marzouk, M.M. Digitizing material passport for sustainable construction projects using BIM. *J. Build. Eng.* **2021**, *43*, 103233. [CrossRef]
60. Gunawardena, T.; Mendis, P.; Ngo, T.; Rismanchi, B.; Aye, L. Effective use of offsite manufacturing for public infrastructure projects in Australia. In *International Conference on Smart Infrastructure and Construction 2019 (ICSIC) Driving Data-Informed Decision-Making*; ICE Publishing: London, UK, 2019.
61. Navaratnam, S.; Ngo, T.; Gunawardena, T.; Henderson, D. Performance review of prefabricated building systems and future research in Australia. *Buildings* **2019**, *9*, 38. [CrossRef]
62. Uthpala, H.; Ramachandra, T. Study on Modern Methods of Constructions Used in Sri Lanka. *Constr. Mater. Syst.* **2015**, 155–162.