buildings

MDPI

Article

Comparison of the Embodied Carbon Emissions and Direct Construction Costs for Modular and Conventional Residential Buildings in South Korea

Hanbyeol Jang [1], Yonghan Ahn [2] and Seungjun Roh [3,*]

[1] Department of Smart City Engineering, Hanyang University, Ansan 15588, Gyeonggi-do, Korea; zmsquf96@hanyang.ac.kr
[2] Department of Architectural Engineering, Hanyang University, Ansan 15588, Gyeonggi-do, Korea; yhahn@hanyang.ac.kr
[3] School of Architecture, Kumoh National Institute of Technology, Gumi 39177, Gyeongsangbuk-do, Korea
* Correspondence: roh@kumoh.ac.kr

Abstract: Modular construction is an innovative new construction method that minimizes waste and improves efficiency within the construction industry. However, practitioners are hampered by the lack of environmental and economic sustainability analysis methods in this area. This study analyzes the embodied carbon emissions and direct construction costs incurred during the production phase of a modular residential building and provides comparison to an equivalent conventional residential building. Major drawings and design details for a modular residential building in South Korea were obtained, and the quantity take-off data for the major construction materials were analyzed for a modular construction method and a conventional construction method using a reinforced concrete structure under the same conditions. Focusing on major construction materials during the production phase, the embodied carbon emissions assessment revealed that adopting a modular construction approach reduced the environmental impact by approximately 36%, as compared to the conventional reinforced concrete method. However, in terms of the direct construction cost, the modular construction was approximately 8% more expensive than the conventional reinforced concrete construction method.

Keywords: modular construction; modular residential building; embodied carbon emission; major construction material; direct construction cost

Citation: Jang, H.; Ahn, Y.; Roh, S. Comparison of the Embodied Carbon Emissions and Direct Construction Costs for Modular and Conventional Residential Buildings in South Korea. *Buildings* **2022**, *12*, 51. https://doi.org/10.3390/buildings12010051

Academic Editor: Da Yan

Received: 22 November 2021
Accepted: 4 January 2022
Published: 6 January 2022

1. Introduction

The construction industry is suffering from falling orders and poor profit margins in recent years and needs to improve its productivity [1,2]. At present, most buildings constructed in South Korea are built using traditional wet construction methods, such as reinforced concrete (RC) construction, even though this can lead to productivity issues due to a shortage of functional engineering capabilities, a lack of skilled workers, and unfavorable weather conditions [3,4]. It is, therefore, not surprising that construction companies are beginning to show considerable interest in modular construction methods, where units are manufactured under controlled conditions in factories and then transported to the site for assembly to create the building [5]. Modular construction is a technology-intensive dry construction method that increases both construction productivity and efficiency [6–8].

Off-site construction, which includes modular construction, is the term used to refer to the pre-fabrication or fabrication of individual units that are assembled on-site to construct the final building [9]. It provides various benefits, including high-quality units that are easy to renovate and maintain, a shorter construction duration, reduced field labor costs, module reuse options, and better environmental characteristics [10–14]. Most research in this area has focused on the benefits of modular construction, such as its integrated design approach, structure, and productivity. However, few studies have performed comprehensive environmental impact assessments or carried out economic evaluations on the modular construction methods, such as those uses for other non-traditional construction methods [15,16]. Recently, the Intergovernmental Panel on Climate Change (IPCC) special report on global warming stated that at least 45% reduction in carbon dioxide emissions is required by 2030. It is suggested that by 2050, carbon neutrality should be achieved with zero global net carbon emissions [17]. The construction industry accounts for more than 30% of global carbon emissions, indicating that a reduction in carbon emissions from the construction industry is inevitable [14,18,19]. To ensure the overall sustainability of modular construction methods, in-depth studies on aspects such as the environmental impact assessments and the economic evaluation of modular construction methods are needed [20–22].

Therefore, this study analyzes the embodied carbon emissions and direct construction cost for the production phase of a modular residential building and compares the results with those of an equivalent, conventional residential building. We focused on the material production phase because, in modular construction methods, this phase has been reported to result in higher embodied carbon emissions than other project stages [23,24].

2. Literature Review

In modular construction, individual modules are manufactured at a factory or another offsite location, transported to the site, and assembled on-site to create the final building [25,26]. This high-efficiency method takes advantage of the benefits of factory manufacturing processes, where the structure, interior, and exterior equipment for each unit are assembled in a controlled environment, by skilled workers under ideal conditions [13,27–30]. The individual modules are then assembled into the final building on-site using one of the modular construction methods shown in Figure 1 [27,31].

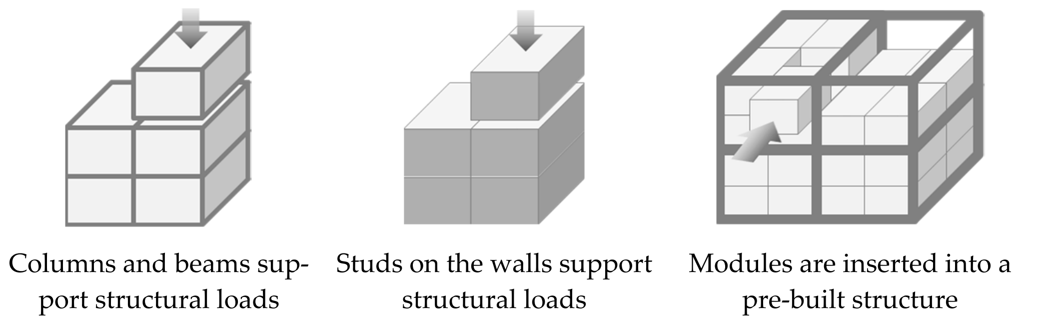

Figure 1. Modular construction methods, adapted from ref. [27].

There are three main benefits of modular construction: (1) higher quality, (2) shorter construction period, and (3) eco-friendly building methods [4,32,33]. A consistently high fabrication quality can be achieved through repeated task performance by skilled factory workers [34]. There are also benefits to be gained from the increases in factory productivity [13]. Additionally, there are time efficiencies, as modules can be manufactured in the factory concurrent to the foundation work carried out at the site, which reduces the overall construction period and hence the costs (refer to Figure 2) [8,25,35]. Finally, modular construction confers environmental advantages because of the minimal use of wet construction methods on the site [8,36]. Most waste results from wet construction methods, such as pouring concrete, which accounts for more than 80% of the total waste [25,37]. Modular construction has been shown to reduce waste by 10–15%, as compared to conventional construction methods [21,38]. Recent research on modular housing has generally focused on analyzing the environmental impact of modular housing methods [19,39], with research on the cost and life cycle assessment (LCA)-based eco-friendly performance of modular construction being conducted in many countries [23,40,41].

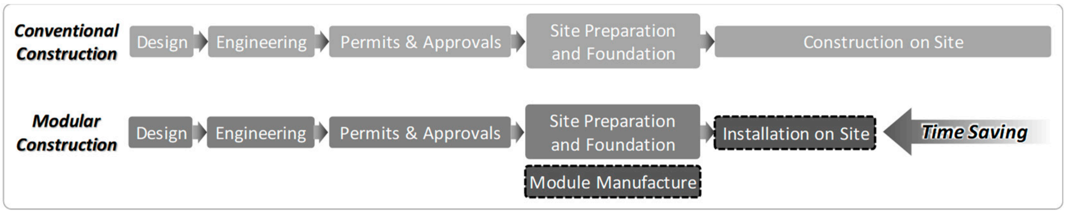

Figure 2. Comparison of modular and conventional RC construction methods, adapted from ref. [11,42].

To reduce problems affecting the construction industry in South Korea, there is increasing support for efforts to supply modular housing. However, few researchers have sought to quantitatively assess the cost and environmental impact of modular residential buildings across the entire building process. With the development of efficient passive element technologies for buildings and the growing public awareness of the need to engage in more eco-friendly building practices, an in-depth analysis of the environmental impact of the carbon emissions associated with the greater use of modular building methods is clearly necessary if we are to be able to judge the validity of supporting the widespread use of modular housing.

Mao et al. [19] compared the environmental effects of semi-prefabrication and RC building techniques using a process-based method. Although each building considered in their study was actually built, the target buildings did not have exactly the same size or shape, so the RC building data had to be modified to match the size of the modular construction building for their analysis. The material production, transportation, construction, and operation stages were analyzed to obtain an environmental impact assessment. Overall, the greenhouse gas emissions of the modular construction building were lower, with 85% of the emissions occurring at the construction material production stage. Aye et al. [32] analyzed the environmental effects of prefabricated modular steel, prefabricated modular timber, and concrete buildings using the input–output analysis method of the embodied energy analysis method. For the target buildings, two types of modular construction were redesigned based on the previously constructed concrete building. Their environmental impact assessment excluded the disposal and recycling stages based on the existing literature, because they add up to less than 1% of the impact across the building's entire life cycle. Their analysis showed that the embodied energy of the prefabricated modular steel building was approximately 1.5 times greater than that of the concrete building, and that of the prefabricated modular timber building was approximately 1.08 times greater. However, because the modular method means that the individual modules can often be reused, their analysis suggested that it should be possible to reduce the embodied energy by approximately 81% when the final stages of the entire life cycle are taken into account, including disposal and reuse. As the amount of embodied energy and environmental impact from the material production stage is relatively high, the assessment of the environmental impact in the material production stage in modular construction is crucial.

Park et al. [43] conducted a comparative analysis of carbon emissions from prefabricated modular and RC buildings by applying an LCA to analyze the material at every stage from production onwards, across the entire life cycle of the building. Carbon emissions were analyzed based on 30 years of use to examine each building's environmental impact during its operational lifetime. The differences were further analyzed by applying a reusable scenario for modular construction. The results of this analysis revealed that carbon emissions during use were the highest, followed by those generated during the production phase. Reuse reduced carbon emissions at the disposal stage. It is important to note that although all the buildings analyzed [43] were actually built, the results of the analysis were limited because of the different locations and sizes of the buildings. Kim [44] conducted an LCA of modular construction using wood and redesigned conceptual buildings based on modular construction drawings, although the LCA phase was limited to the material production stage through to the operation stage. According to this analysis, the entire life cycle energy consumption of the modular construction was approximately 4.6%

lower, and carbon emissions were reduced by approximately 3%. However, this researcher found it difficult to find a conventional building built on a similar scale as the modular construction example, so the utility of the analysis results is limited because average data of the construction industry had to be utilized.

As noted earlier, the difference in the environmental impact emissions during the material production stage is greatest when comparing modular construction to conventional construction methods. Therefore, in this study, we focused on carbon emissions during the material production stage.

In addition, when comparing modular structures with RC structures, the results of the analysis are necessarily limited because of the analysis of two different types of buildings that are not perfectly identical. To address this issue, we conducted an analysis of an actual modular construction project and an RC building redesigned under the same conditions using the original design data. It is also important to bear in mind that compared to many studies designed to assess the environmental impact of modular building approaches, an analysis considering the modular construction cost aspect alone is insufficient. To address the limitations of the studies reported in the existing literature on modular construction methods, we simultaneously conducted an environmental impact assessment and economic evaluation of the material production stage of modular construction. Through this approach, a study was designed and conducted to compensate for the lack of existing research by considering the lack of research on buildings of the same location and scale, economic, and environmental aspects.

3. Materials and Methods

The major drawings and design details of the modular residential building selected for this study were utilized for this analysis. The input quantities of the major construction materials required for the residential building area were calculated, and the embodied carbon emissions for the production phase were assessed based on these construction materials. The results of this analysis were then compared with those for the production phase of the equivalent RC structure planned under the same conditions.

3.1. Materials

The target project was South Korea's second modular residential building, with the aim of improving housing welfare for beginners in society, the elderly, and the weak in housing in October 2019. The project for this analysis was a modular residential building involving two types of modular construction methods. The building analyzed in this study was a modular residential building located in South Korea, consisting of a total of 40 households, with one basement and six above-ground floors. An overview and the front view of the project are presented in Table 1 and Figure 3.

Table 1. Project overview.

Division	Contents	
	B-Wing	**C-Wing**
Project	1st District of Public Housing in Cheonan Dujeong District	
Supply Area	485.80 m^2	653.32 m^2
No. of Households	20 households	20 households
Floors	B1F–6F	
Structure	B1F–1F	RC (A-wing)
	2F–6F	Modular (B-wing, C-wing)

Figure 3. Front view of target building.

This building is divided into three areas, as shown in Figure 4: the common section, designated A-wing, was built using the conventional RC construction method, while the residential sections, consisting of part of the B-wing and the C-wing, with 20 households in each, were built using two different modular construction methods. In this study, only the B-wing, which was built using a column and beam support structure, was selected for analysis and compared to the same residential building.

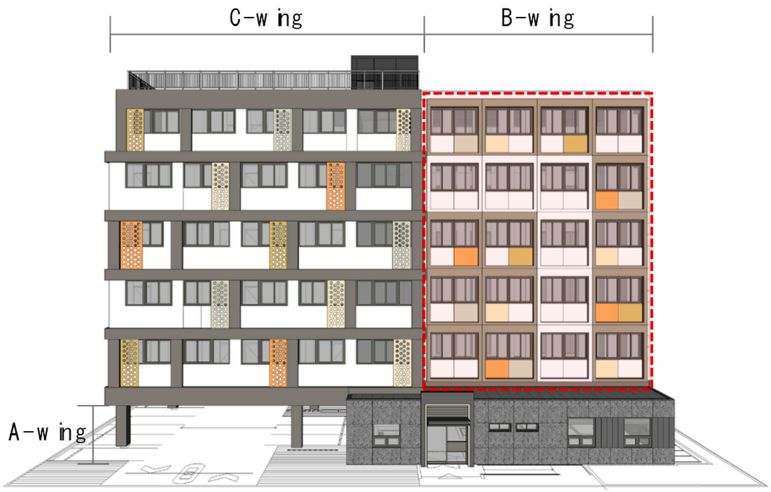

Figure 4. Division of target building.

In modular construction, the material production phase is reported to produce higher carbon emissions than the other phases [19,23,32]. Therefore, we analyzed the embodied carbon emissions created during the material production phase based on the major construction materials. At the time the building was constructed, the major construction materials were limited to ready-mixed concrete (RMC), rebar, steel frame, metal, glass, gypsum board, cement, tiles, blocks, sand, and stone materials, with a cumulative total of 95% or more of the embodied carbon emissions of the input materials. Table 2 compares the embodied carbon emissions typically produced by construction materials commonly used for residential buildings as a result of modular and RC construction methods.

Table 2. Quantity of major construction material using the two building systems.

Materials	Unit	Modular	Reinforced Concrete
RMC	ton	210.96	814.20
Steel	ton	53.65	-
Gypsum Board	ton	42.38	2.25
Metal	ton	22.90	11.41
Sand	ton	13.01	46.40
Rebar	ton	7.28	24.56

3.2. Methods

3.2.1. Embodied Carbon Emissions Assessment

LCA methodologies are considered the most versatile technique for assessing the environmental impact of different materials [45,46]. Although a number of different analytical methods have been used to define the components and characteristics of the LCA program, most were originally designed for refrigerators, microwave ovens, general consumer goods, or other raw materials and resources [47–49]. LCA in a building can be evaluated by applying international LCA guidelines, such as ISO 14040 [50], to assess the environmental impact across the entire process, which is assessed separately by goal and scope definition, list analysis, and impact assessment [51–55].

The life cycle of a building can be divided into three main stages: production, construction, and use and demolition [56–59]. The scope of the LCA's evaluation is, therefore, divided into "Cradle to Gate", "Cradle to Gate with Option", and "Cradle to Grave" [60–62]. "Cradle to Gate" assesses only the material production stage, and "Cradle to Grave" covers the entire life cycle of a building from the material production stage to the dismantling and disposal stage [63–65].

Embodied carbon emissions are associated with material production, construction, transportation, and demolition stages [66]. In this study, the analysis focused on embodied carbon emissions during the material production stage of the building. Embodied carbon emissions can be evaluated by multiplying the input quantities of the major construction materials and applying the embodied carbon emissions factor for each.

Embodied carbon emissions = quantities $\times$ embodied carbon emission factor.

The embodied carbon emission factors published by the Korea Environmental Industry and Technology Institute (KEITI) were applied to assess embodied carbon emissions in the production stages of modular and RC residential buildings [67]. Table 3 lists the embodied carbon emission factors in the production phase for several major construction materials.

Table 3. Embodied carbon emission factors in the production phase for major construction materials.

Material	Material Characteristics	Units	Embodied Carbon Emission Factor
RMC	24 MPa	$kg\text{-}CO_2/m^3$	414
	18 MPa	$kg\text{-}CO_2/m^3$	409
Steel	Channel	$kg\text{-}CO_2/kg$	0.404
Glass	Double Glazing	$kg\text{-}CO_2/m^2$	22.4
Gypsum Board	-	$kg\text{-}CO_2/kg$	0.138
Rebar	-	$kg\text{-}CO_2/kg$	0.438
Block	-	$kg\text{-}CO_2/kg$	0.123
Tile		$kg\text{-}CO_2/kg$	0.353
Cement	-	$kg\text{-}CO_2/kg$	1.060
Sand	-	$kg\text{-}CO_2/m^3$	3.870

3.2.2. Cost Analysis

In the construction sector, the life cycle cost (LCC) is a method used to analyze the overall cost of a construction project [68–70]. The costs of design, construction, maintenance, and disposal are all considered in this calculation [71–73], which is used by project stakeholders to assess the economic feasibility of construction projects and select the optimal alternatives. For example, a project's high initial construction cost might be justified by the subsequent lower maintenance costs of the building based on a customized cost list for the project developed during the life cycle cost analysis [2,72]. Given that the current study focused on the embodied carbon emissions produced during the material production stage of the building process, the direct construction costs including the material costs, labor costs, and expenses and material transport were included in the economic analysis [74]. Direct construction costs can be evaluated by multiplying the input quantities of the major construction materials and applying the unit material costs, labor costs, and expenses for each. Table 4 shows the unit costs of major construction materials.

Table 4. Unit material cost of major construction materials.

Material		Unit	Material Cost *
RMC	24 MPa	USD/m^3	50.9
	18 MPa	USD/m^3	45.3
Steel	Hot Rolled Steel	USD/ton	645.2
	Channel	USD/ton	661.3
Glass	Double Glazing, 16 mm	USD/m^2	18.2
	Double Glazing, 22 mm	USD/m^2	22.8
Gypsum Board	Fireproof Board	USD/m^2	6.0
Rebar	SD400, HD10	USD/ton	542.9
	SD400, HD13	USD/ton	535.2
Block	190 mm × 57 mm × 90 mm	USD/each	0.04
Tile	Porcelain Tile	USD/m^2	6.9
	Porcellaneous Tile	USD/m^2	7.3
Cement	Ordinary Portland Cement	USD/pack (40 kg)	2.8
Sand	-	USD/m^3	23.4

* 1 United States Dollar (USD) = 1240 Korea Won (KRW).

Direct construction costs = quantities × (material costs + labor costs + expenses).

This section showed the case and methods to be dealt with in this study. In order to compare and analyze the environmental and economic aspects of public housing with the modular construction method and the existing construction method, Cheonan Dujeong Public Housing, an example of obtaining data that can be analyzed, was selected as the target case. In addition, for quantitative analysis, carbon emission factors and cost standards available in Korea are presented along with the equation. In the next chapter, the results of analyzing the environmental and economic aspects, respectively, by applying the methodology introduced above to the case are presented.

4. Results

4.1. Embodied Carbon Emissions

Table 5 shows the results of the assessment of the embodied carbon emissions of the main construction materials used in this study. As the data presented in the table show, the total embodied carbon emissions value of the construction materials for the modular construction method was calculated to be 135,787 kg-CO_2 (279.51 kg-CO_2/m^2), and the total embodied carbon emissions value for the RC method was assessed at 212,559 kg-CO_2 (437.54 kg-CO_2/m^2).

Table 5. Results of the assessment of the embodied carbon emissions.

Materials	Modular (B-Wing)		Reinforced Concrete	
	Embodied Carbon Emissions (kg-CO_2)	Proportion (%)	Embodied Carbon Emissions (kg-CO_2)	Proportion (%)
Metal	47,961	35.32	24,793	11.66
RMC	37,967	27.96	146,506	68.92
Steel	29,719	21.89	-	-
Glass	6238	4.59	8047	3.79
Gypsum Board	5849	4.31	310	0.15
Cement	4236	3.12	19,886	9.36
Rebar	3191	2.35	10,757	5.06
Tile	474	0.35	1669	0.79
Block	121	0.09	408	0.19
Sand	31	0.02	112	0.05
Stone	-	-	71	0.03
Total	135,787	100	212,559	100
Per m^2	279.51	-	437.54	-

The major contributions of embodied carbon emissions to the RC construction material came from the RMC, metal, and cement, which accounted for 68.92%, 11.66%, and 9.36%, respectively, of the total embodied carbon emissions. For the modular methods, the metals, RMC, and steel frames were the major contributors, accounting for 35%, 27%, and 21%, respectively.

Although the metal, steel, and gypsum boards were responsible for higher embodied carbon emissions in the modular construction design than in the RC construction design, the embodied carbon emissions of the RMC were almost four times higher in the RC construction than in the modular construction, and were largely responsible for the overall embodied carbon emissions of the RC methods being approximately 1.6 times higher than those of the modular construction methods. Figure 5 presents a comparison of the embodied carbon emissions for the modular and RC construction methods.

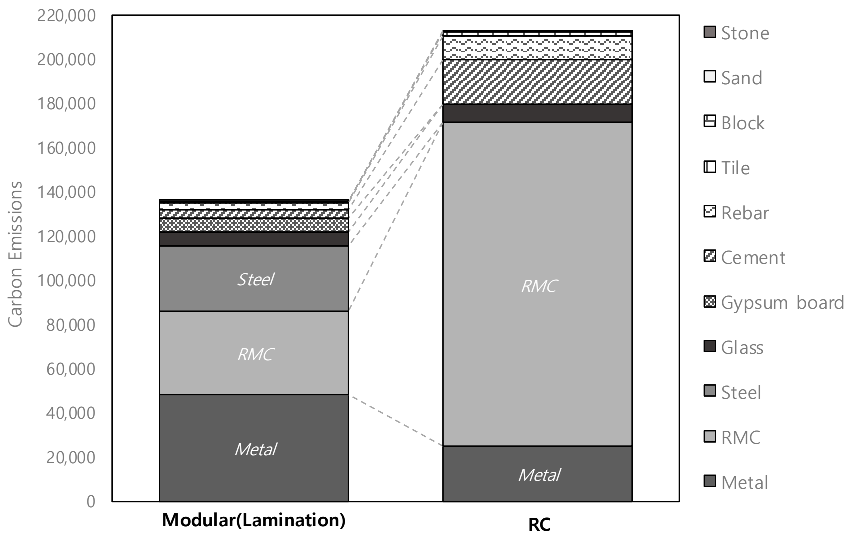

Figure 5. Comparison of the modular and RC building embodied carbon emissions.

4.2. Direct Construction Cost

The direct construction costs of the modular construction method and the RC construction method were analyzed based on a detailed statement of the national modular public housing demonstration complex project [68]. Given that the embodied carbon emissions analysis in the current study covered only the material production stage, the scope of the cost analysis was limited to the direct construction costs, including the material and labor costs, and expenses.

Table 6 and Figure 6 show the results of the direct construction costs of the modular and RC construction methods. The direct construction cost analysis for the RC construction revealed that the highest costs were for reinforced concrete and metal work, accounting for 29.43% and 19.93%, respectively, of the total direct construction costs for the RC method. The total direct construction cost was 441,580 USD (908.97 USD/m^2) at a current exchange rate of 1 USD = 1240 KRW.

Table 6. Direct construction costs for the modular and RC construction methods.

Activities	Modular (B-Wing)		Reinforced Concrete	
	Cost (USD) *	Proportion (%)	Cost (USD) *	Proportion (%)
Metal work	186,202	39.01	88,020	19.93
Reinforced concrete work	-	-	129,968	29.43
Carpentry work	92,976	19.48	-	-
Miscellaneous	70,145	14.70	35,484	8.04
Windows	37,123	7.78	41,083	9.30
Interior finishing work	29,875	6.26	40,366	9.14
Temporary work	-	-	28,764	6.51
Roofing and gutter work	20,668	4.33	4700	1.06
Tile work	5750	1.20	19,398	4.39
Painting work	18,005	3.77	3124	0.71
Waterproof work	704	0.15	17,793	4.03
Glass	7487	1.57	16,831	3.81
Plastering	3124	0.65	6908	1.56
Stone work	5118	1.07	5969	1.35
Masonry work	155	0.03	546	0.12
Aggregate and Transportation	-	-	2626	0.59
Total	477,332	100	441,580	100
Per m^2	982.57	-	908.97	-

* 1 USD = 1240 KRW.

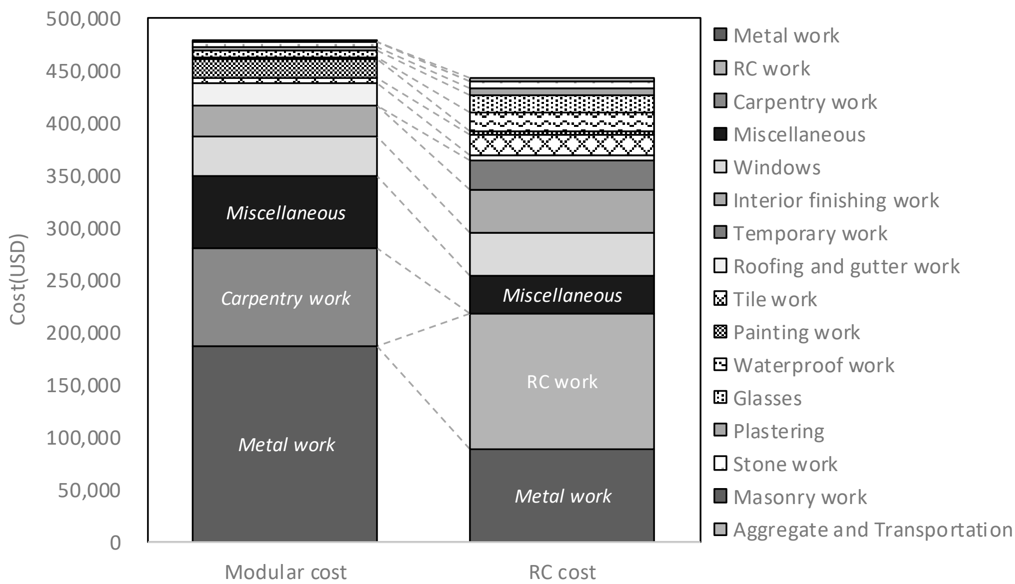

Figure 6. Comparison of modular construction and RC construction costs.

The total direct construction cost for the modular construction method was assessed at 477,332 USD (982.57 USD/m^2). The analysis of the direct construction costs for the modular construction method showed that the construction cost of the metal work was significantly higher than that of the RC method, closely followed by the carpentry work. The cost of the metal work was relatively high because the metal work items included the construction of the metal support structure. In modular construction, a steel frame is commonly utilized for each module to facilitate transport and construction. The next largest portion of modular construction costs was carpentry work, because most of the walls in the module are constructed using lightweight, fireproof plaster walls. The cost of installing these walls accounted for approximately 83.4% of the cost of carpentry work. Although the cost of metalwork and woodwork accounts for a large portion of the cost of modular construction, there is no need for reinforced concrete, which is an expensive part of RC construction, so it is possible to cut costs in this aspects.

Comparing the overall direct construction cost of modular and RC construction methods, the construction costs for modular construction were approximately 8.1% higher. However, considering the potential for reusing the individual modules, the reduction in the material cost made possible by the mass production of modules, and improved work productivity due to learning effects, this premium is partially offset by the considerable economies that can be achieved, thus lowering the unit cost of production over the module's entire life cycle.

This section presented, in detail, the analysis results of environmental and economic aspects that occur in the material production stage when the local carbon emission unit and unit price were applied to the Cheonan Dujeong public housing case. Considering only the material production stage, it was concluded that the modular method was advantageous from an environmental point of view compared to the existing method, but relatively disadvantageous from an economic point of view. In the next section, the contents of this study are comprehensively summarized, and limitations and future research directions are presented together.

5. Discussion

The construction industry is increasingly utilizing the latest modular construction methods to improve productivity. If this progress is to continue, it is necessary to demonstrate the superior sustainability characteristics of modular construction by analyzing the efficiencies that can be achieved, in terms of both its environmental and economic feasibility.

In this study, the embodied carbon emissions and direct construction costs of the modular and RC methods were analyzed and compared. This evaluation considered both environmental and economic aspects, thus validating the effectiveness and value for money of the modular method. As interest in sustainable construction methods continues to grow, it will inevitably highlight the need to introduce a comprehensive evaluation method for sustainability in the construction industry.

The findings of this study confirmed that modular construction can reduce embodied carbon emissions during the material production phase, as compared to the equivalent RC structure, even though the direct construction cost was slightly higher. As in the results of similar previous studies, this finding is considered in the same context as the result that the environmental impact of RC structures is greater when comparing the environmental impact of RC structures and modular (steel) structures. (refer to Table 7) [75]. Based on the conclusions of this study, it is expected that the application of modular construction will yield environmental benefits in addition to the previously identified advantages of modular construction.

Table 7. Characteristics summary table of RC method and modular method.

Classification	Previous Studies		This Study
	Reinforced Concrete (RC)	**Modular**	**Modular**
Environment	By using concrete, which is a carbon-intensive material, as the main material, a lot of environmental impact occurs.	By minimizing the use of ready-mixed concrete and using materials with a high reuse rate, it is possible to reduce carbon emissions by up to 88% [58].	The modular construction method reduced embodied carbon emissions in the material production stage by approximately 36%.
Cost	In general, the initial cost is less compared to the modular method.	By mass production and using regular factory workers, it is possible to reduce the cost of materials by about 10% [2,68].	The modular construction method was approximately 8.1% higher than the reinforced concrete construction method.
Time	It is highly influenced by external factors such as weather, so the possibility of air delay is high.	By simultaneously manufacturing factories and on-site work, it is possible to shorten the construction period by 50% compared to the existing method [76].	-
Quality	Influence by external factors is high, and quality problems occur frequently.	Manufactured by standardized working methods in the factory to ensure quality.	-
Safety	The on-site work period is long and the safety accident rate is high due to the heavy equipment.	It is possible to reduce the occurrence of safety accidents by minimizing field work.	-

However, this study evaluated only the material production stage and did not perform a comprehensive comparison between the modular method and the traditional RC method. In particular, favorable aspects, such as ease of recycling and reduction of waste, were not considered in the evaluation of modular construction [77]. More meaningful research results will be obtained if economic efficiency and environmental assessment are reevaluated through a full life cycle cost analysis that considers embodied carbon emissions.

6. Conclusions

This study compared and analyzed the embodied carbon emissions produced and direct construction costs incurred during the material production phase of a residential building and compared the outcomes of the modular and RC construction methods. This process enabled us to calculate the embodied carbon emissions and direct construction costs of these two methods and identify their characteristics through an analysis of their environmental performance and cost. This study produced the following findings:

1. The total embodied carbon emissions value of the construction materials for the modular construction method was assessed at 135,787 kg-CO_2 (279.51 kg-CO_2/m^2). The modular construction method reduced embodied carbon emissions in the material production stage by approximately 36%, as compared to the conventional RC method. This result was significantly affected by the large input of ready-mix concrete, with its high embodied carbon emissions, utilized in RC construction and not modular construction.
2. When comparing the direct construction costs for the modular and RC construction methods, the modular method was more expensive. This is because the metal work component of the modular construction method involves the construction of a metal structure that lightens the weight of the module and, thus, facilitates both its transportation to the site and its construction. However, because the advantages of the modular construction method, which include ease of repair and high recycling rates, were not considered in this study, a further cost review will be needed to obtain a full life cycle perspective.

3. According to an analysis of the direct construction costs for the two methods, the direct construction cost of the modular construction method was 477,332 USD (982.57 USD/m^2), which was approximately 8.1% higher than that of the RC construction method. However, as this study only dealt with the initial stage of material production and excluded the possibility of reuse, which is one of the core tenets of modular construction, these results only show part of the story.

Author Contributions: Conceptualization, H.J.; methodology, H.J. and S.R.; analysis, H.J., Y.A. and S.R.; visualization, S.R.; writing—original draft, data curation, H.J.; writing—reviewing and editing, Y.A. and S.R. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2019R1F1A1063046).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the co-author. The data are not publicly available due to the data security maintenance.

Acknowledgments: This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2019R1F1A1063046).

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

References

1. Tam, V.W.; Fung, I.W.; Sing, M.C.; Ogunlana, S.O. Best practice of prefabrication implementation in the Hong Kong public and private sectors. *J. Clean. Prod.* **2015**, *109*, 216–231. [CrossRef]
2. Kim, K.-T.; Lee, Y.-H. Economic Feasibility Study on the Unit Modular Fabrication Method According to the Life Cycle Costing Methodology. *Struc. Cons.* **2011**, *27*, 207–214.
3. Jaillon, L.C.; Poon, C.S. The evolution of prefabricated residential building systems in Hong Kong: A review of the public and the private sector. *Autom. Constr.* **2009**, *18*, 239–248. [CrossRef]
4. Xu, X.; Zhao, Y. *Some Economic Facts of the Prefabricated Housing*; Industry Report; Rutgers Business School: Newark, NJ, USA, 2010.
5. Mao, C.; Xie, F.; Hou, L.; Wu, P.; Wang, J.; Wang, X. Cost analysis for sustainable off-site construction based on a multiple-case study in China. *Habitat Int.* **2016**, *57*, 215–222. [CrossRef]
6. Kamali, M.; Hewage, K.; Milani, A.S. Life cycle sustainability performance assessment framework for residential modular buildings: Aggregated sustainability indices. *Build. Environ.* **2018**, *138*, 21–41. [CrossRef]
7. Li, Z.; Shen, Q.; Alshawi, M. Measuring the impact of prefabrication on construction waste reduction: An empirical study in China. *Resour. Conserv. Recycl.* **2014**, *91*, 27–39. [CrossRef]
8. Baldwin, A.; Poon, C.S.; Shen, L.-Y.; Austin, S.; Wong, I. Designing out waste in high-rise residential buildings: Analysis of precasting methods and traditional construction. *Renew. Energy* **2009**, *34*, 2067–2073. [CrossRef]
9. Li, Z.; Shen, Q.; Xue, X. Critical review of the research on the management of prefabricated construction. *Habitat Int.* **2014**, *43*, 240–249. [CrossRef]
10. Nahmens, I.; Ikuma, L.H. Effects of Lean Construction on Sustainability of Modular Homebuilding. *J. Arch. Eng.* **2012**, *18*, 155–163. [CrossRef]
11. Kamali, M.; Hewage, K. Life cycle performance of modular buildings: A critical review. *Renew. Sustain. Energy Rev.* **2016**, *62*, 1171–1183. [CrossRef]
12. Ahn, Y.H.; Kim, K.-T. Sustainability in modular design and construction: A case study of 'The Stack'. *Int. J. Sustain. Build. Tech. Urban Develop.* **2014**, *5*, 250–259. [CrossRef]
13. Ganiron, T.U.; Almarwae, M. Prefabricated Technology in a Modular House. *Int. J. Adv. Sci. Technol.* **2014**, *73*, 51–74. [CrossRef]
14. Pervez, H.; Ali, Y.; Petrillo, A. A quantitative assessment of greenhouse gas (GHG) emissions from conventional and modular construction: A case of developing country. *J. Clean. Prod.* **2021**, *294*, 126210. [CrossRef]
15. Atmaca, N. Life-cycle assessment of post-disaster temporary housing. *Build. Res. Inf.* **2016**, *45*, 524–538. [CrossRef]
16. Giriunas, K.; Sezen, H.; Dupaix, R.B. Evaluation, modeling, and analysis of shipping container building structures. *Eng. Struct.* **2012**, *43*, 48–57. [CrossRef]
17. Masson-Delmotte, V.; Zhai, P.; Pörtner, H.-O.; Roberts, D.; Skea, J.; Shukla, P.R.; Pirani, A.; Moufouma-Okia, W.; Péan, C.; Pidcock, R. Global warming of 1.5 C. An IPCC Special Report on the Impacts of Global Warming of 2018, 1. Available online: https://www.ipcc.ch/sr15/ (accessed on 20 November 2021).
18. Han, Y.; Skibniewski, M.J.; Wang, L. A Market Equilibrium Supply Chain Model for Supporting Self-Manufacturing or Outsourcing Decisions in Prefabricated Construction. *Sustainability* **2017**, *9*, 2069. [CrossRef]

19. Mao, C.; Shen, Q.; Shen, L.; Tang, L. Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: Two case studies of residential projects. *Energy Build.* **2013**, *66*, 165–176. [CrossRef]
20. Cao, X.; Li, X.; Zhu, Y.; Zhang, Z. A comparative study of environmental performance between prefabricated and traditional residential buildings in China. *J. Clean. Prod.* **2015**, *109*, 131–143. [CrossRef]
21. Thormark, C. Including recycling potential in energy use into the life-cycle of buildings. *Build. Res. Inf.* **2000**, *28*, 176–183. [CrossRef]
22. Kamali, M.; Hewage, K. Development of performance criteria for sustainability evaluation of modular versus conventional construction methods. *J. Clean. Prod.* **2017**, *142*, 3592–3606. [CrossRef]
23. Tumminia, G.; Guarino, F.; Longo, S.; Ferraro, M.; Cellura, M.; Antonucci, V. Life cycle energy performances and environmental impacts of a prefabricated building module. *Renew. Sustain. Energy Rev.* **2018**, *92*, 272–283. [CrossRef]
24. Wang, S.; Sinha, R. Life Cycle Assessment of Different Prefabricated Rates for Building Construction. *Build.* **2021**, *11*, 552. [CrossRef]
25. Velamati, S. Feasibility, Benefits and Challenges of Modular Construction in High Rise Development in the United States: A Developer's Perspective. Master's Thesis, Massachusetts Institute of Technology, Cambridge, MA, USA, 2012.
26. Generalova, E.; Generalov, V.; Kuznetsova, A.A. Modular Buildings in Modern Construction. *Procedia Eng.* **2016**, *153*, 167–172. [CrossRef]
27. Lim, S.-H. A Current State of Apartment Construction Technology Development with the Application of Modular Technology. *Rev. Archit. Build. Sci.* **2016**, *60*, 16–21.
28. Schoenborn, J.M. A Case Study Approach to Identifying the Constraints and Barriers to Design Innovation for Modular Construction. Master's Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA, 27 April 2012.
29. Lacey, A.; Chen, W.; Hao, H.; Bi, K. Review of bolted inter-module connections in modular steel buildings. *J. Build. Eng.* **2019**, *23*, 207–219. [CrossRef]
30. Lacey, A.W.; Chen, W.; Hao, H.; Bi, K. Structural response of modular buildings–an overview. *J. Build. Eng.* **2018**, *16*, 45–56. [CrossRef]
31. Srisangeerthanan, S.; Hashemi, M.J.; Rajeev, P.; Gad, E.; Fernando, S. Review of performance requirements for inter-module connections in multi-story modular buildings. *J. Build. Eng.* **2020**, *28*, 101087. [CrossRef]
32. Aye, L.; Ngo, T.; Crawford, R.H.; Gammampila, R.; Mendis, P. Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules. *Energy Build.* **2012**, *47*, 159–168. [CrossRef]
33. Thirunavukkarasu, K.; Kanthasamy, E.; Gatheeshgar, P.; Poologanathan, K.; Rajanayagam, H.; Suntharalingam, T.; Dissanayake, M. Sustainable Performance of a Modular Building System Made of Built-Up Cold-Formed Steel Beams. *Buildings* **2021**, *11*, 460. [CrossRef]
34. Chiang, Y.H.; Chan, E.H.W.; Lok, L.K.-L. Prefabrication and barriers to entry—A case study of public housing and institutional buildings in Hong Kong. *Habitat Int.* **2006**, *30*, 482–499. [CrossRef]
35. Xu, Z.; Zayed, T.; Niu, Y. Comparative analysis of modular construction practices in mainland China, Hong Kong and Singapore. *J. Clean. Prod.* **2020**, *245*, 118861. [CrossRef]
36. Faludi, J.; Lepech, M.D.; Loisos, G. Using life cycle assessment methods to guide architectural decision-making for sustainable prefabricated modular buildings. *J. Green Build.* **2012**, *7*, 151–170. [CrossRef]
37. Lawson, R.; Ogden, R. Sustainability and process benefits of modular construction. In Proceedings of the TG57-Special Track 18th CIB World Building Congress, Salford, UK, 10–13 May 2010; p. 38.
38. Hartley, A.; Blagden, A. *Current Practices and Future Potential in Modern Methods of Construction*; Full Final Report WAS003-001; Waste & Resources Action Programme, AMA Research LtD.: London, UK, 2007.
39. Dong, Y.H.; Jaillon, L.; Chu, P.; Poon, C. Comparing carbon emissions of precast and cast-in-situ construction methods–A case study of high-rise private building. *Constr. Build. Mater.* **2015**, *99*, 39–53. [CrossRef]
40. 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]
41. Hong, J.; Shen, G.Q.; Mao, C.; Li, Z.; Li, K. Life-cycle energy analysis of prefabricated building components: An input–output-based hybrid model. *J. Clean. Prod.* **2016**, *112*, 2198–2207. [CrossRef]
42. Blanquet du Chayla, C.; Blanchet, P.; Lehoux, N. A Method to Qualify the Impacts of Certifications for Prefabricated Constructions. *Buildings* **2021**, *11*, 331. [CrossRef]
43. Park, J.-Y.; Kim, S.-H.; Chae, C.-U. A Comparative Analysis on Life Cycle CO Emission between a Modular Housing and a R.C. Apartment Housing. *Plan. Des.* **2014**, *30*, 35–43.
44. Kim, D. *Preliminary Life Cycle Analysis of Modular and Conventional Housing in Benton Harbor*; University of Michigan: Ann Arbor, MI, USA, 2008.
45. Balasbaneh, A.T.; Bin Marsono, A.K.; Gohari, A. Sustainable materials selection based on flood damage assessment for a building using LCA and LCC. *J. Clean. Prod.* **2019**, *222*, 844–855. [CrossRef]
46. Bovea, M.; Vidal, R. Increasing product value by integrating environmental impact, costs and customer valuation. *Resour. Conserv. Recycl.* **2004**, *41*, 133–145. [CrossRef]
47. Xie, H.-B.; Wu, W.-J.; Wang, Y.-F. Life-time reliability based optimization of bridge maintenance strategy considering LCA and LCC. *J. Clean. Prod.* **2018**, *176*, 36–45. [CrossRef]

48. Shi, J.; Wang, Y.; Fan, S.; Ma, Q.; Jin, H. An integrated environment and cost assessment method based on LCA and LCC for mechanical product manufacturing. *Int. J. Life Cycle Assess.* **2019**, *24*, 64–77. [CrossRef]
49. Pons, O.; Wadel, G. Environmental impacts of prefabricated school buildings in Catalonia. *Habitat Int.* **2011**, *35*, 553–563. [CrossRef]
50. *ISO, I. ISO-14040*; Environmental Management–Life Cycle Assessment–Principles and Framework. International Organization for Standardization: Geneva, Switzerland, 2006.
51. Lee, J.-M.; Jang, O.-Y.; Kim, J.-S. Study on Recognition and Satisfaction of Modular Housing through the Post Occupancy Evaluation. *J. Korean Hous. Assoc.* **2014**, *25*, 63–71. [CrossRef]
52. Soust-Verdaguer, B.; Llatas, C.; García-Martínez, A. Simplification in life cycle assessment of single-family houses: A review of recent developments. *Build. Environ.* **2016**, *103*, 215–227. [CrossRef]
53. Ben-Alon, L.; Loftness, V.; Harries, K.; Hameen, E.C. Life cycle assessment (LCA) of natural vs conventional building assemblies. *Renew. Sustain. Energy Rev.* **2021**, *144*, 110951. [CrossRef]
54. Li, D.; Cui, P.; Lu, Y. Development of an automated estimator of life-cycle carbon emissions for residential buildings: A case study in Nanjing, China. *Habitat Int.* **2016**, *57*, 154–163. [CrossRef]
55. Ahmed, I.M.; Tsavdaridis, K.D. Life cycle assessment (LCA) and cost (LCC) studies of lightweight composite flooring systems. *J. Build. Eng.* **2018**, *20*, 624–633. [CrossRef]
56. Bribian, I.Z.; Usón, A.A.; Scarpellini, S. Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. *Build. Environ.* **2009**, *44*, 2510–2520. [CrossRef]
57. Pan, W.; Li, K.; Teng, Y. Rethinking system boundaries of the life cycle carbon emissions of buildings. *Renew. Sustain. Energy Rev.* **2018**, *90*, 379–390. [CrossRef]
58. Minunno, R.; O'Grady, T.; Morrison, G.M.; Gruner, R.L. Investigating the embodied energy and carbon of buildings: A systematic literature review and meta-analysis of life cycle assessments. *Renew. Sustain. Energy Rev.* **2021**, *143*, 110935. [CrossRef]
59. Asdrubali, F.; Venanzi, D.; Evangelisti, L.; Guattari, C.; Grazieschi, G.; Matteucci, P.; Roncone, M. An Evaluation of the Environmental Payback Times and Economic Convenience in an Energy Requalification of a School. *Buildings* **2020**, *11*, 12. [CrossRef]
60. Chau, C.-K.; Leung, T.; Ng, W. A review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings. *Appl. Energy* **2015**, *143*, 395–413. [CrossRef]
61. Islam, H.; Jollands, M.; Setunge, S. Life cycle assessment and life cycle cost implication of residential buildings—A review. *Renew. Sustain. Energy Rev.* **2015**, *42*, 129–140. [CrossRef]
62. Salehian, S.; Ismail, M.A.; Ariffin, A.R.M. Assessment on Embodied Energy of Non-Load Bearing Walls for Office Buildings. *Buildings* **2020**, *10*, 79. [CrossRef]
63. Tae, S.; Shin, S.; Woo, J.; Roh, S. The development of apartment house life cycle CO2 simple assessment system using standard apartment houses of South Korea. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1454–1467. [CrossRef]
64. Venkatraj, V.; Dixit, M. Life cycle embodied energy analysis of higher education buildings: A comparison between different LCI methodologies. *Renew. Sustain. Energy Rev.* **2021**, *144*, 110957. [CrossRef]
65. Mohammad, M.; Masad, E.; Al-Ghamdi, S.G. 3D Concrete Printing Sustainability: A Comparative Life Cycle Assessment of Four Construction Method Scenarios. *Buildings* **2020**, *10*, 245. [CrossRef]
66. Satola, D.; Röck, M.; Houlihan-Wiberg, A.; Gustavsen, A. Life Cycle GHG Emissions of Residential Buildings in Humid Subtropical and Tropical Climates: Systematic Review and Analysis. *Buildings* **2020**, *11*, 6. [CrossRef]
67. *Korea Life Cycle Inventory Database*; Korea Environmental Industry and Technology Institute (KEITI): Seoul, Korea, 2004.
68. Shin, H.K.; Ham, H.R.; Jang, H.J.; Ahn, Y.h. Economic Feasibility Study on the Modular Apartment Housing According to the Life Cycle Costing Methodology: A Case Study on the Modular Apartment Housing in Cheonan. *Korea Facil. Manag. Assoc.* **2019**, *14*, 15–24.
69. Ristimäki, M.; Säynäjoki, A.; Heinonen, J.; Junnila, S. Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design. *Energy* **2013**, *63*, 168–179. [CrossRef]
70. Dhaif, M.; Stephan, A. A Life Cycle Cost Analysis of Structural Insulated Panels for Residential Buildings in a Hot and Arid Climate. *Buildings* **2021**, *11*, 255. [CrossRef]
71. D'Incognito, M.; Costantino, N.; Migliaccio, G. Actors and barriers to the adoption of LCC and LCA techniques in the built environment. *Built Environ. Proj. Asset Manag.* **2015**, *5*, 202–216. [CrossRef]
72. Guoguo, L. *Integration of LCA and LCC for Decision Making in Sustainable Building Industry*; Chalmers University of Technology: Gothenburg, Sweden, 2009.
73. Hromada, E.; Vitasek, S.; Holcman, J.; Heralova, R.S.; Krulicky, T. Residential Construction with a Focus on Evaluation of the Life Cycle of Buildings. *Buildings* **2021**, *11*, 524. [CrossRef]
74. Petrović, B.; Zhang, X.; Eriksson, O.; Wallhagen, M. Life Cycle Cost Analysis of a Single-Family House in Sweden. *Buildings* **2021**, *11*, 215. [CrossRef]
75. Oladazimi, A.; Mansour, S.; Hosseinijou, S.A. Comparative Life Cycle Assessment of Steel and Concrete Construction Frames: A Case Study of Two Residential Buildings in Iran. *Buildings* **2020**, *10*, 54. [CrossRef]
76. Quale, J.; Eckelman, M.J.; Williams, K.W.; Sloditskie, G.; Zimmerman, J.B. Construction Matters: Comparing Environmental Impacts of Building Modular and Conventional Homes in the United States. *J. Ind. Ecol.* **2012**, *16*, 243–253. [CrossRef]

77. Loizou, L.; Barati, K.; Shen, X.; Li, B. Quantifying Advantages of Modular Construction: Waste Generation. *Buildings* **2021**, *11*, 622. [CrossRef]