energies

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Environmental Impact of Demolishing a Steel Structure Design for Disassembly

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Abstract: The encouraging Design for Disassembly appears in the literature more and more often. Such a design appears to offer clear environmental advantages. However, there are still not enough research results to support the existence of these benefits. The authors using the Life Cycle Assessment method, which assesses the energy consumption and greenhouse gas emissions during the demolition and operation of steel structure. Steel is completely recyclable and, in terms of tonnage, is the most recycled material worldwide. We assessed three scenarios: (1) complete re-remelting (recycling) of the structure; (2) partial reuse of construction elements + remelting (recovery + recycling); and (3) complete reuse of the structure (recovery). GaBi software was used for the analysis. It was found that the environmental impact varied significantly among the examined scenarios. The first scenario poses the greatest environmental burden. However, compared to Scenario no. 1, Scenario 3's environmental impact is more than 70% lower.

Keywords: DfD; life cycle assessment; energy savings; global warming potential

Citation: Broniewicz, E.; Dec, K. Environmental Impact of Demolishing a Steel Structure Design for Disassembly. *Energies* **2022**, *15*, 7358. https://doi.org/10.3390/en15197358

Academic Editor: Przemysław Brzyski

Received: 31 August 2022
Accepted: 29 September 2022
Published: 7 October 2022

1. Introduction

The construction industry is responsible for a significant proportion of anthropogenic environmental impacts. In 2015, it accounted for 38% of global energy-related carbon dioxide (CO_2) emissions, which, as a result of the COVID-19 pandemic, decreased to 37% in 2020 [1]. Although the recovery rate of construction and demolition waste in the European Union countries reaches almost 90%, this rate includes waste that is prepared for reuse, recycled or materially recovered, and waste that is used to fill excavations [2]. These unfavorable statistics have prompted interest in research to investigate the construction industry's environmental impact on various aspects (materials, processes). The most comprehensive study at the current knowledge stage analyzes the energy consumption and emissions of buildings over their lifetime, i.e., using Life Cycle Analysis (LCA).

This paper aims to investigate the differences in environmental load in terms of Global Warming Potential (GWP) and primary energy consumption in the processes of demolition and reuse of a steel structure. Three scenarios were assessed: (1) recycling of the whole structure; (2) reuse of parts of the structural elements and recycling of the remaining steel scrap; and (3) reuse of the whole structure (designed for reuse). An LCA method was applied using GaBi software. This study is based on typical construction and demolition practices and steel waste management.

1.1. Design for Disassembly

The idea of Design for Disassembly (DfD) is relatively new and emerged in the 1990s [3], mainly to be able to recover the materials and components used in construction. At the same time, such a design ensures a reduction in the amount of waste to be managed after the decommissioning process. This strategy is based on the fact that most building structures have a limited useful life, and each structure is a depository of natural resources.

Several years earlier, the concept of cleaner production had emerged, aiming to reduce the environmental negative impact. A strong emphasis was placed here on the design process, in which the following areas can be identified [4]:

- designing for reduced consumption and environmental impact of raw materials, components and energy;
- designing for the use of cleaner production techniques and technologies;
- designing for reduction in quantity and harmfulness of post-production waste;
- design for recovery and use of post-consumer waste.

Design for Disassembly is another area where the design focus is on facilitating future disassembly and reusing the same components in another location or project. DfD should be distinguished from recycling, which focuses on reusing reclaimed materials. In traditional building design, designers focus mainly on technological and economic aspects. Therefore, recycling of building materials involves a load on the environment: materials have to be collected, sorted, transported, cleaned, pre-processed and then remanufactured. In many cases, building materials are recycled into products of lesser value, for example, concrete, which is used as road foundation material. In the case of metals, such as structural steel, remanufacturing requires an energy-intensive remelting process [5,6]. In the Design for Disassembly concept, materials, components and structural systems are chosen so they can be reused without having to be processed. What may be required, however, is refurbishment, such as cleaning, repainting, etc.

The DfD concept is not very popular in the literature. Authors who have dealt with DfD have highlighted several benefits associated with reusing structural components or materials [5]. Rios et al. [7] divided them into environmental, social, economic and other. The most significant environmental benefit they identified is 'close the loop', which allows: (1) the extension of the life of raw material mines; (2) lowering of the cost of materials (if the supply chain is mature); and (3) reduction in the embodied energy and carbon emissions of the construction industry. The DfD is ideally in line with the Circular Economy (CE) concept, starting at the beginning of a product's life. Both the design phase and production processes impact sourcing, resource use and waste generation throughout a product's life [8].

In 2020, a standard for voluntary use appeared (ISO 20887:2020): Sustainability in buildings and civil engineering works—Design for disassembly and adaptability—Principles, requirements and guidance [9]. It can help meet the requirements of EU regulation 2020/852 of 18 June 2020 on establishing a framework to facilitate sustainable investment. One of the activities to help the transition to a circular economy is 'design for longevity, repurposing, disassembly' (Art. 13, 1e) [10]. Currently, European Commission is working on the proposal for a new directive on corporate sustainability reporting (CSRD) [11]. ESG (Environmental Social and Governance) reporting, from 2024 onwards, is to cover all large companies and listed SME companies [12]. The circular economy is an issue related to the natural environment. One of the assessment criteria in this field will be the design and construction of buildings to ensure a high degree of removability and adaptability [13].

1.2. Circular Economy in Steel Constructions

Circular Economy (CE) is an approach to an industrial economy that promotes resource conservation to reduce waste and environmental burdens. This strategy can be successfully applied to steel construction buildings. The demolition of buildings consists of two phases: planning and a controlled demolition process that results in steel components suitable for further use. This use can take place in several ways—as remanufacture, recycle and reuse [14]. Even more, resources can be conserved by designing steel products for reuse or remanufacturing. Reuse is advantageous as little or no energy is required for reprocessing. Steel's durability ensures that many products can be partially or fully reused at the end of their life. This can extend the life cycle of the steel product significantly. However, initial design based on life cycle thinking is critical if reuse is to succeed [14].

1.3. Life Cycle Assessment of Buildings

Life Cycle Assessment (LCA) has been used for a long time to assess the environmental impact of processes, services and products in all types of industries. As LCA implies a comprehensive approach to evaluating environmental impacts throughout the life cycle, it is increasingly applied to construction decision-making. In 2011, the European standard EN 15978:2011 was published: Sustainability of construction works—Assessment of environmental performance of buildings—Calculation method [15]. It defines the calculation method to assess the environmental performance of a building and gives the means for the reporting and communication of the outcome of the assessment. The standard applies to new and existing buildings and refurbishment projects. It divides the life cycle of a building into stages, according to Figure 1.

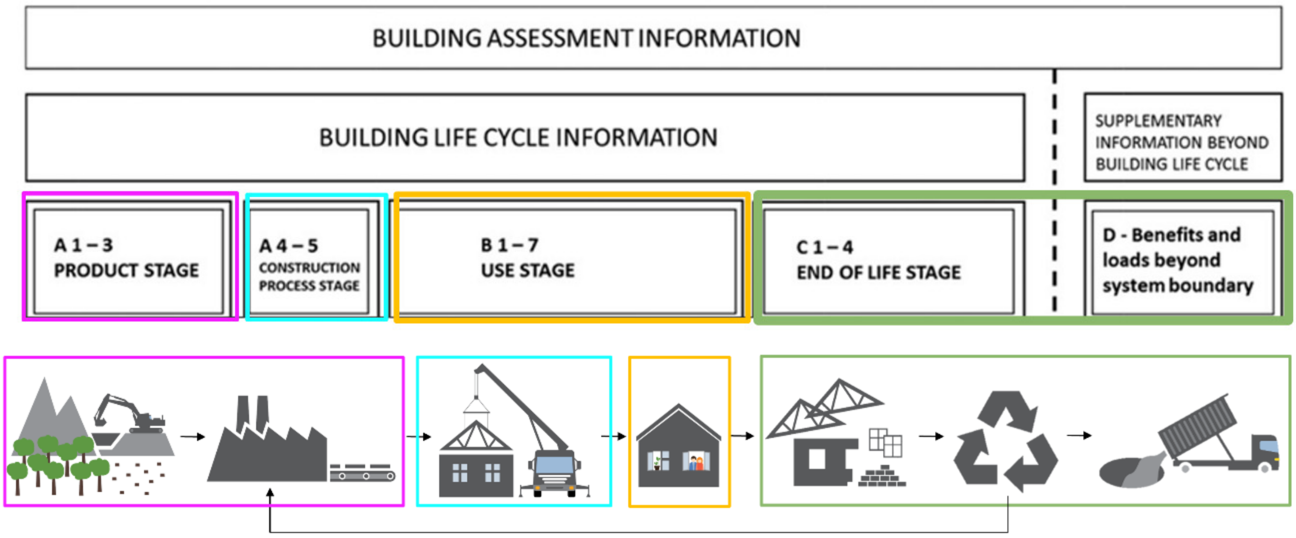

Figure 1. Life cycle stages of a building [15,16].

An analysis of the literature on LCA for construction shows that researchers adopt the subject of the study and the boundaries system differently. Most of the structures analyzed are timber structures, and few studies have examined steel structures. The literature review carried out by Martínez et al. (2016) [17] shows that in more than half of the LCA studies of retrofitted buildings analyzed, the transport and construction modules (including A5—construction installation and C1—demolition) were excluded from the analysis. This was the predicted low environmental impact relative to the rest of the life cycle phases. Based on research carried out by Hong et al. [18], the authors of the publication suggest that research into the importance of transport and construction processes in LCA should not be neglected due to their significant environmental impacts. The research review also found significant differences in the approach to the End of Life (EoL) stage of building structures itself.

2. Materials and Methods

2.1. Goal and Scope, System Boundaries, Scenario Assumptions

The goal of the analysis is to investigate the differences in Global Warming Potential (GWP) and primary energy use in the process of demolishing and reusing a steel structure for three assumed scenarios. The environmental Life Cycle Assessment (LCA) method was used to analyze the 'end of life' phase of the dismantled steel structure. The analysis assumes the reuse of steel in line with a circular economy strategy. Using the diagram in Figure 1, the following phases were assessed: A3—A5 product and construction process stage (A3—manufacturing, A4—transport of construction, A5—construction installation), C1—C3 end of life stage (C1—demolition, C2—transport, C3—waste processing). The C4—disposal stage is not included. Available studies on the End of Life stage have often omitted the demolition stage (C1) [19,20]. However, the course of this stage significantly affects the possibility of reusing or recycling used materials [21]. Analysis of the process of demolition and reuse of structural elements can also help develop design principles for new buildings according to DfD aspects [21].

The authors assumed three possible scenarios: the most unfavorable scenario (Scenario 1), in which the entire structure is melted down; the most advantageous scenario possible to achieve with the current state of technology (Scenario 3), ensuring the use of 90% of the structure; and the intermediate scenario (Scenario 2), in which 50% of the structure is recovered.

In Scenario no. 1, elements from the structure's demolition are treated as steel scrap, remelted at a steelworks 200 km away into steel billets, from which new sections are manufactured. The sections will be used for the construction of the new steel hall. The assumed total transport distance is 500 km.

Scenario no. 2 assumes that 50% of the structural elements can be recovered and reused. Refurbishment is one of the ways to extend the durability of the structure [22]. The remainder will be melted down in electric furnaces, and new sections will be manufactured from it.

In Scenario no. 3, the authors assumed that the entire structure could be reused, except 10% of the sections, which would be unusable due to damage during the disassembly of the structure. In total, 90% of steel recycling is possible, as indicated by Lyu et al. [23] in the case of steel, with demountable modular objects designed for reuse. This is also pointed out by Broniewicz and Broniewicz in the article on the LCA analysis of steel office buildings [24], who analysed the major environmental impacts of a steel structure of a six-storey office building located in Krakow, Poland in the entire life cycle.

At the end of the facility's life, the recovered elements will be transported to another location and used in the same or modified structure. The assumed transport distance is 100 km. An illustration of the scenarios is shown in Figure 2.

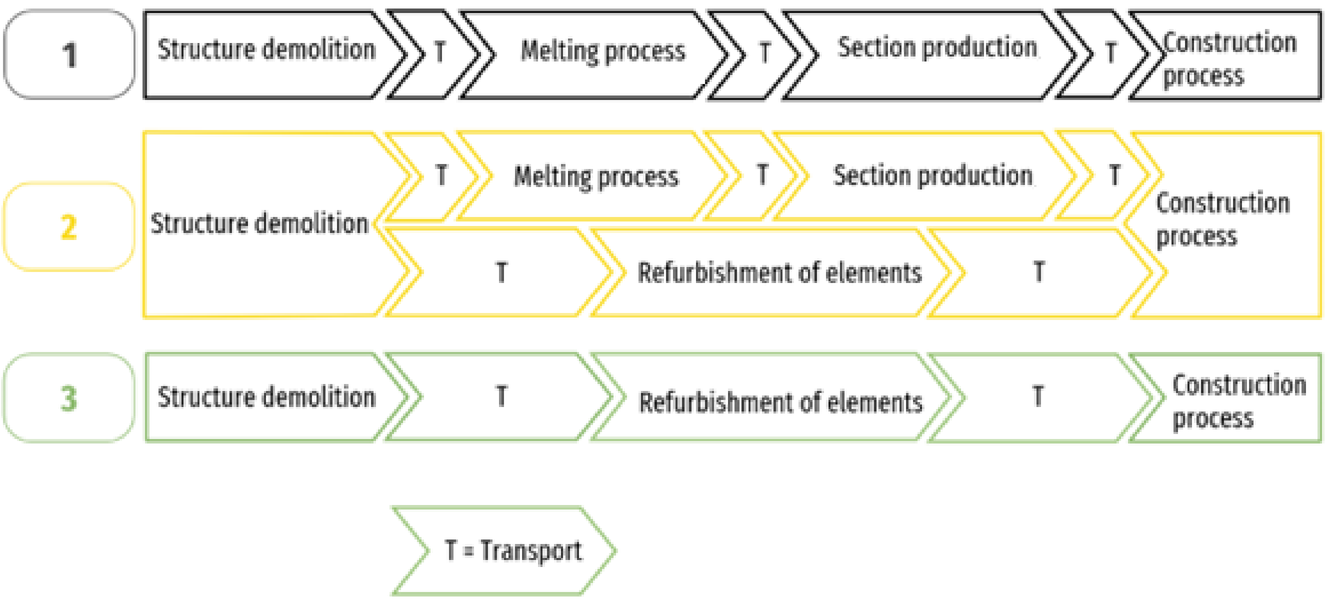

Figure 2. Diagrams of the analyzed scenarios.

Each of the three scenarios considered begins with the demolition of the structure. Under Scenario no. 1, demolition is followed by remelting of scrap steel, fabrication of sections and assembly of the new structure. Scenario no. 3 involves refurbishing the recovered steel elements and assembling a new structure using them. Scenario no. 2 is a combination of the previous two, assuming that only half of the sections will be reusable.

The parameters that may influence the environmental impact assessment of the process adopted in each scenario are presented in Table 1.

Table 1. Parameters adopted for analysis and the impact of their change on the results.

Parameter	The Scenario	Assumed Value	What It Affects	Other Possibilities	The Expected Degree to Which Volatility Affects the Result of the Analysis
Distance from the steelworks	1, 2	road transport 500 km	fuel consumption	e.g., road tr. 700 km; rail tr. 1000 km	low
Distance from the place of reuse	2, 3	road transport 100 km	fuel consumption	e.g., road tr. 200 km, rail tr. 300 km	low
Connections of steel elements	1,2,3	screw	maximum % recovered items possible	rivets welded	very large
Method of manufacturing sections	1,2	hot rolled	energy consumption	cold-formed welded (plated)	large
Method of cleaning the elements	2,3	sandblasting	energy and fuel consumption	manual cleaning	medium

In addition to the parameters used for analysis, Table 1 presents other possible solutions for changing the kind or value. Depending on the change in the value of the parameters, the results of the analysis may vary. The authors determined the expected impact on the obtained results for individual parameters. It should be noted that in the case of structures built for demolition, other types of connections than screws should not be considered.

The impact of changing parameters is not the subject of this article and will be analysed in the future.

2.2. Subject of the Study and Functional Unit

The subject of the study was a hollow section steel hall with a design that allows it to be disassembled and reused (DfD). The structure has a post-and-beam system, is based on a 32 m × 90 m rectangular plan, and is bolted together to allow it to be disassembled later. It consists of six steel girders, 12 columns and roof purlins with a total weight of 135 t. The total area of the sections is approximately 2000 m^2. The structural arrangement ensures ease of assembly and disassembly, as well as ease of adaptation in the case of a change in the purpose of the building. The spacing of the steel frames is 18 m. The functional unit of LCA analysis was defined as one 135 t steel structure. A spatial view of the structure is shown in Figure 3. A scheme of one of the frames is shown in Figure 4.

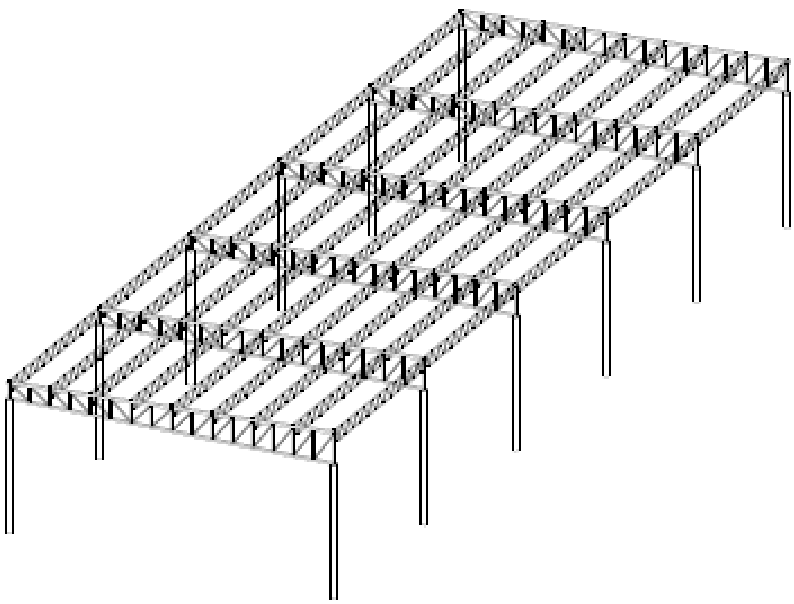

Figure 3. Spatial view of the analyzed structure [25].

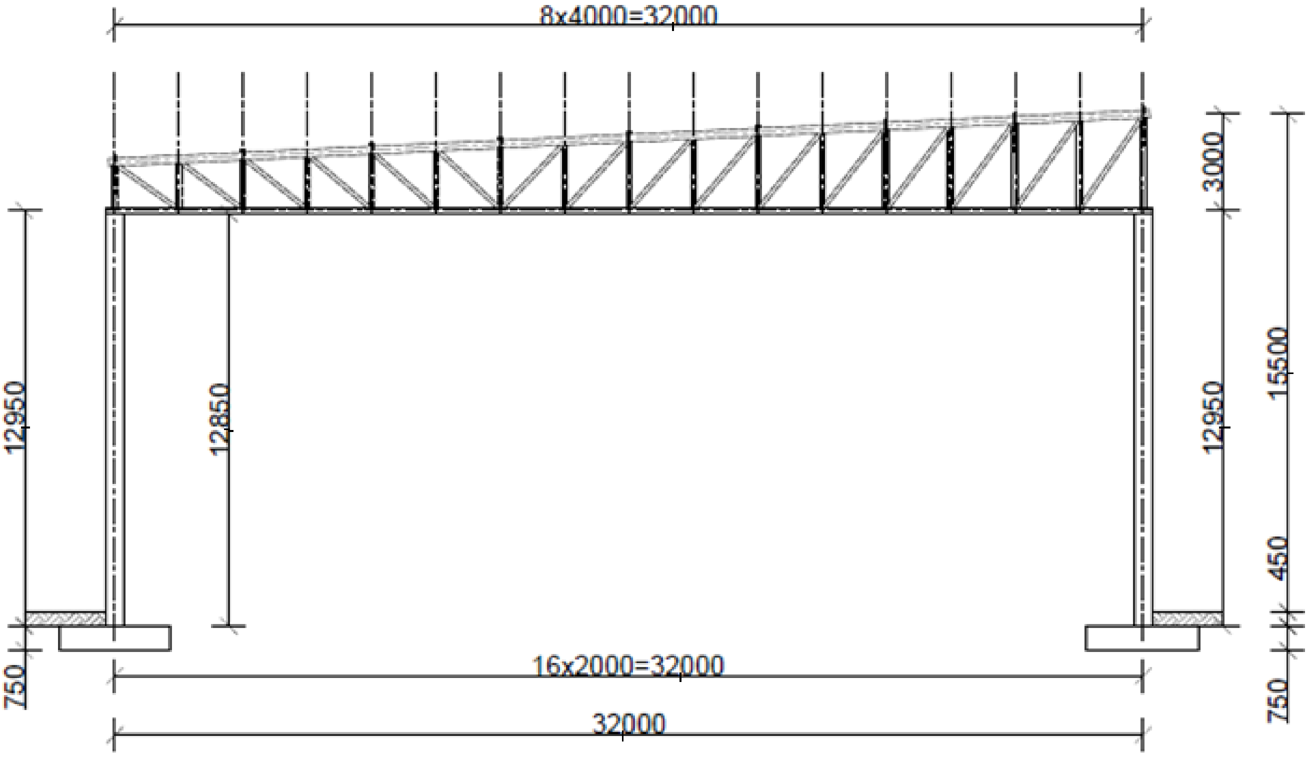

Figure 4. Frame scheme of the structure under consideration [25].

Table 2 summarizes the steel structure data relevant to the analysis.

Table 2. Data of the steel hall under analysis.

Overall dimensions of the hall	32 m × 16 m × 90 m
Weight of the elements	135 t
Area of steel sections	2 007 m^2
Joints	bolted
Hall area	2 880 m^2

2.3. LCIA (Life Cycle Inventory Analysis) Methodology

The analysis was carried out using the environmental life cycle assessment software GaBi v. 10.6.0.110 (Sphera Solutions GmbH, Leinfelden-Echterdingen, Germany) using databases provided by the software developer. GaBi is one of the most widely used LCA tools worldwide. It is a program based on full LCA support, which means that the software both provides data and helps in the implementation of LCA [26]. The program is the tool for carrying out environmental life cycle assessment of products and processes. It allows you to track material and energy flows and emissions to the environment. Thanks to its modular and parameterized architecture, it enables modelling of complex processes and various production variants [27]. The program's databases are generated by ISO 14044, ISO 14064 and ISO 14025 based on work with companies, associations and public authorities. This includes nearly 17,000 datasets from agriculture, construction, chemicals and materials, education, electronics, energy, food and many others. With new products, processes and production methods constantly emerging, these data are updated annually, providing a reliable source of information on life cycle inventories and environmental impact indicators. An overview of the data sources adopted for the analysis is presented in Table 3.

Table 3. Data sources for LCA.

Process		Flow	Data Source
Construction [a]/Demolition [a]		Electricity consumption	Professional screwdriver, straight, high-speed FW-5SXD-7 ATMO (1.1 kW; 85 mth [b c]) [28]
		Fuel consumption	Tower crane LIEBHERR 125K (7 L/h; 240 mth [b]) [29] Wheeled tractor John Deere 6215R (30 L/h; 62 mth [b]) [30] Mobile rough terrain crane REX 25t (16 L/h; 37 mth [b]) [31] Crawler crane 140t—P&H 5150-R (35 L/h; 70 mth [b]) [32]
Transport		Fuel consumption	GaBi: Truck, Euro 6, 26—28t—Sphera
Melting of steel scrap in an electric furnace			GaBi: EAF Steel billet—Sphera
Manufacture of semi-finished products for section production			GaBi: BF Steel billet—Sphera
Manufacturing of sections on a rolling line			GaBi: Steel sections—AISI
Refurbishment of elements [a]	Washing of elements with pressurized water	Water use	GaBi: Process water from surface water—Sphera
		Wastewater	GaBi: Municipal wastewater—Sphera
		Electricity consumption	Pressure washer 20 MPa Karcher HDS 13/20 4SX (10 L/h; 32 mth [b]) [33]
		Fuel consumption	Cargo Delivery Van Peugeot Boxer Furgon PRO L4H2 435 (15 L/h; 2 mth [b]) [34]
	Sand drying	Electricity consumption	Free-fall concrete mixer 250 dm^3 BWE-250k. Altrad Spomasz (1.5 kW; 106 mth [b]) [35] Agregat grzewczy elektryczny TEH 300 TROTEC (70 kW; 106 mth [b]) [36]
	Cleaning of elements to grade Sa 2 1/2	Fuel consumption	Diesel air compressor ATMOS PDP 35 Perkins 5.0 m^3 (6 L/h; 520 mth [b]) [37] Wheeled tractor John Deere 6215R (30 L/h; 42 mth[b]) [30]
	Spray painting of elements with two-component anticorrosion paint	Anticorrosion paint use	GaBi: Emulsion paint—Sphera
		Electricity consumption	Air compressor 20 m^3/min, high-pressure, XATS 377 CD Atlas Copco 186 kW (186 kW, 70 mth [b]) [38]
		Fuel consumption	Cargo Delivery Van Peugeot Boxer Furgon PRO L4H2 435 (15 L/h; 2 mth [b]) [34]

[a] process inventory made in NORMA PRO EDU software, [b] operating hours of the machine in mth., [c] estimated by authors.

Data on specialized processes during the demolition and refurbishment of steel sections were not available in the GaBi program database. The authors carried out an inventory of these processes using the NORMA PRO EDU program. This program is a specialized civil engineering tool, one of the functions of which is the calculation of equipment and material efforts. After providing the measurement value in the appropriate unit for the process, the program calculates them. For most processes, the unit of measurement was the structure's weight, specifically roof trusses with a weight of 50 t, columns with a weight of 50 t and roof purlins with a weight of 35 t. The total weight of the structure was 135 t. The unit of measurement for processes such as cleaning and spray painting the surfaces of the sections was m^2 of surface area. The total surface area of the structural elements was 2007 m^2.

2.4. Implementation of LCA

Three scenarios were modelled in the GaBi program (Figures 5–7), whose processes followed the assumptions in the diagrams in Figure 1.

The authors developed specialized processes such as the steel section refurbishment process. This process consists of washing the grid elements with pressurized water, sandblasting (cleaning the grid elements to grade Sa2½), and spray painting the grid elements with a two-component anticorrosion paint. A schematic diagram of this process, entered in the GaBi program, is shown in Figure 8. The material balance for each scenario is shown in Table 4.

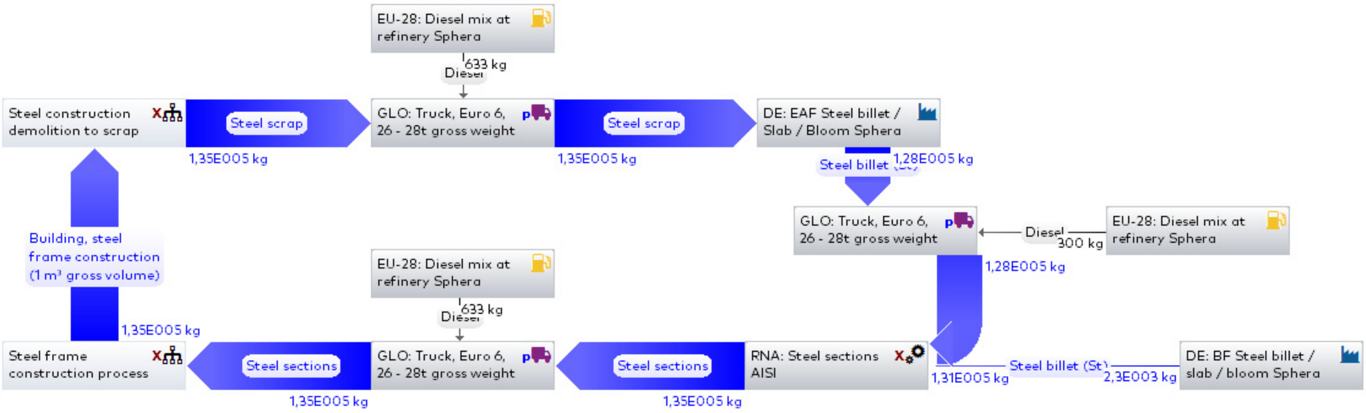

Figure 5. Scenario no. 1: Remelting the entire structure.

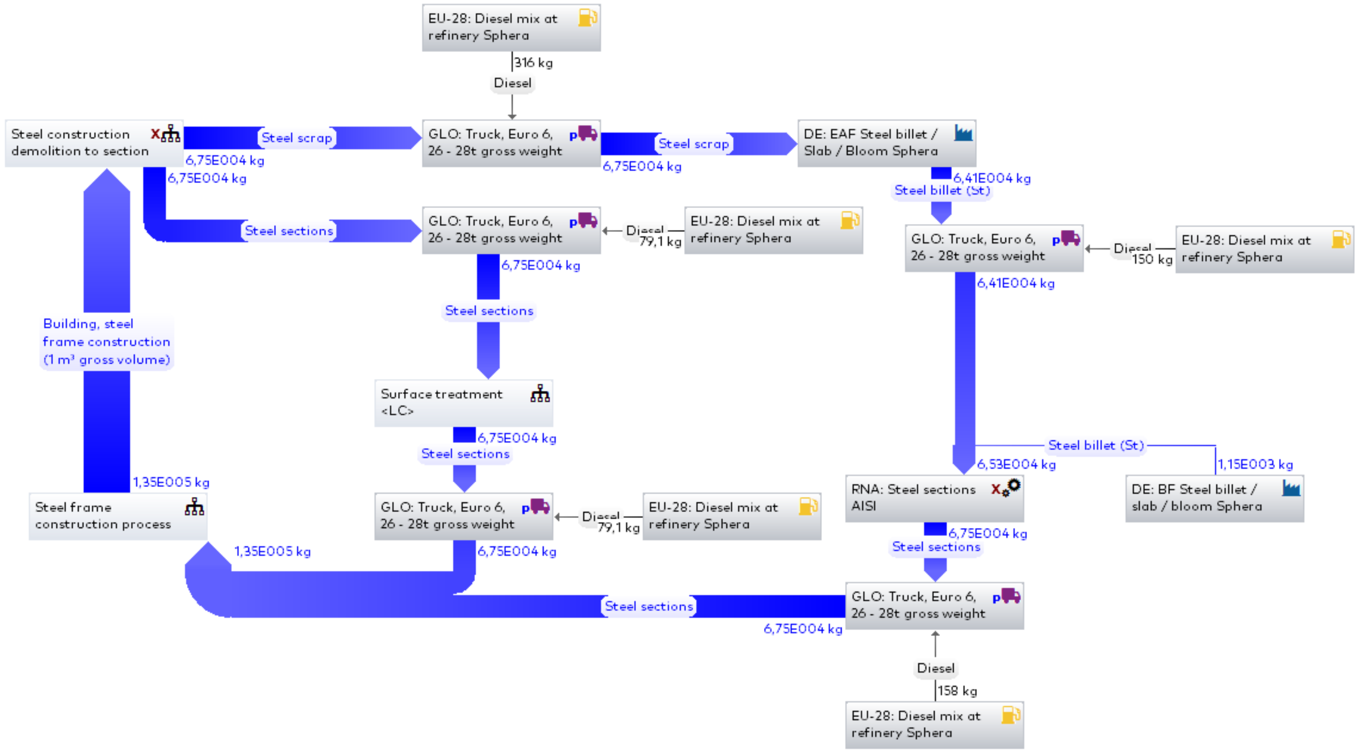

Figure 6. Scenario no. 2: Partial reuse of steel structure components and remelting the rest.

Table 4. Material balance by scenarios.

Scenario No.	Demolition Material Mass	Weight of Recovered Elements	Mass of Steel for Remelting	Mass of Steel Obtained from Remelting	Additional Material for Manufacturing the Missing Elements
1	135 t	-	135 t	128 t	7 t
2	135 t	67.5 t	67.5 t	64.1	3.4 t
3	135 t	122 t	-		13 t

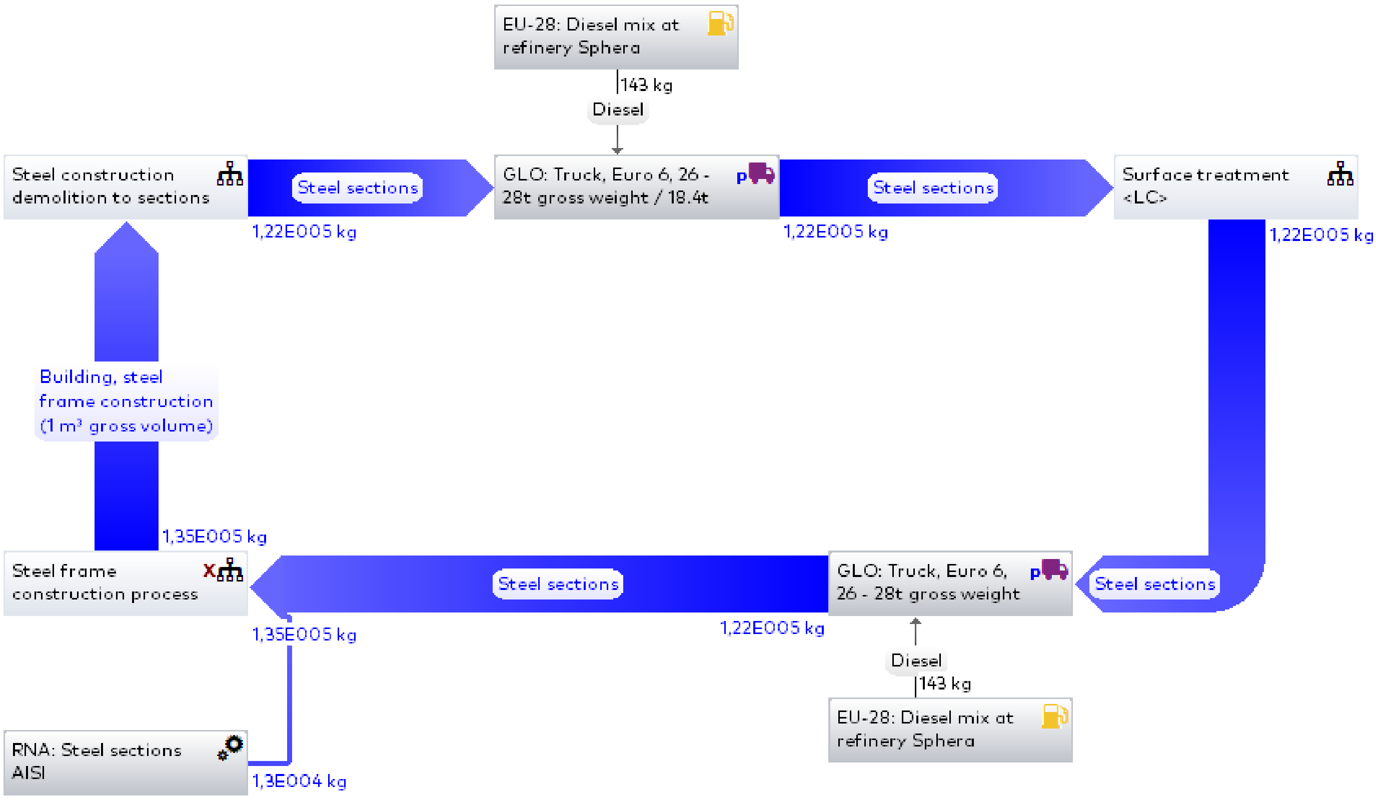

Figure 7. Scenario no. 3: Total reuse of the steel structure.

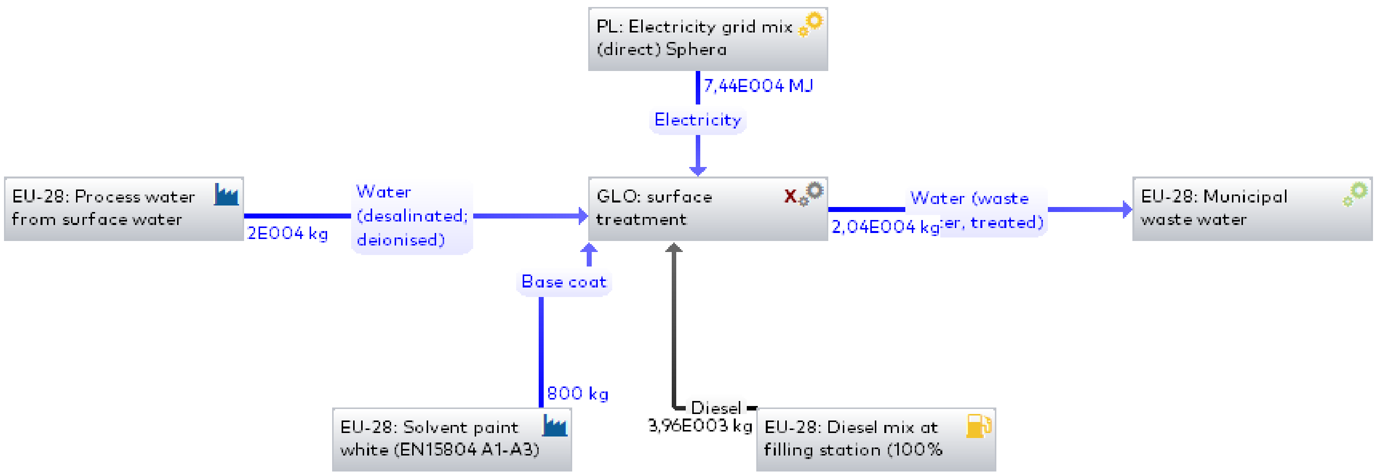

Figure 8. Refurbishment process of steel sections.

3. Results

3.1. Global Warming Potential

The global warming potential, an indicator to quantify the impact on the greenhouse effect, is shown in Figure 9 for the three scenarios considered.

In terms of GWP, the smallest environmental impact is generated by reusing the entire structure and is more than five times smaller than the impact caused by remelting the demolished structure. On the other hand, recovering half of the components used and reusing them reduces the GWP by 84 t CO_2 eq., which is 43% of the impact of remelting the entire structure.

The section manufacturing process is a key factor influencing the GWP potential for the scenarios (Figure 9). This is due to the high energy intensity of the process. The additional processes in Scenario no. 3 (total reuse of the structure) compared to Scenario no.

1 (remelting of the whole structure) resulting from the need to refurbish the components before reuse (refurbishing of steel components, supply of new components if damaged) only represent 18% of the value of the impacts associated with the production of sections from remelted steel scrap. The differences in GWP values for the demolition process are due to the NORMA PRO EDU program's inclusion of a factor for the demolition effort. This coefficient's value determines the machines' effort under different demolition conditions (normal conditions, scrap disassembly). The analysis indicates a marginal impact of transport on GWP. In brackets in Figure 10, the LCA modules of the buildings according to the standard EN 15978:2011 are specified.

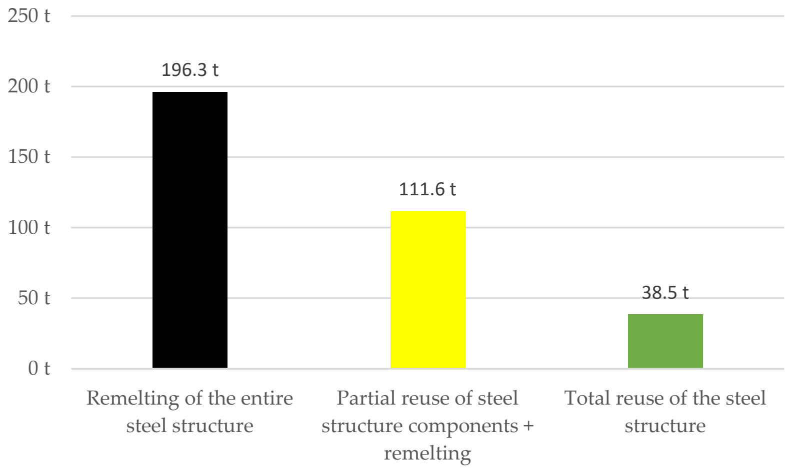

Figure 9. GWP 100 years values in three scenarios [t CO_2 eq.].

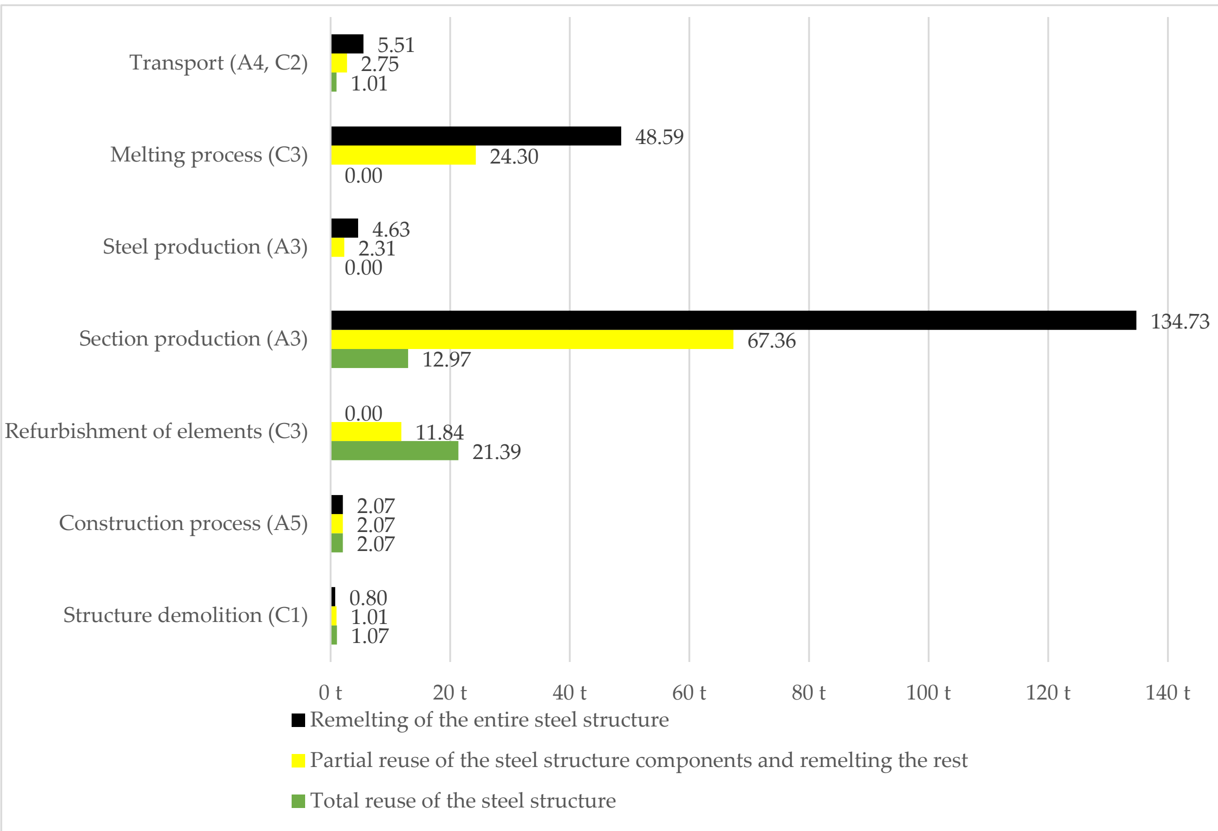

Figure 10. Global Warming Potential in processes (GWP 100 years) [t CO_2 eq.].

3.2. Primary Energy Use

The primary energy use values for the three scenarios considered are shown in Figure 10. Regarding PEU, the lowest energy use occurs when the entire structure is reused and is 3.6 times lower than the energy used in Scenario no. 1, which assumes the melting of the demolished structure. On the other hand, recovering half of the used components and reusing them reduces PEU by more than 1300 GJ (Figure 11).

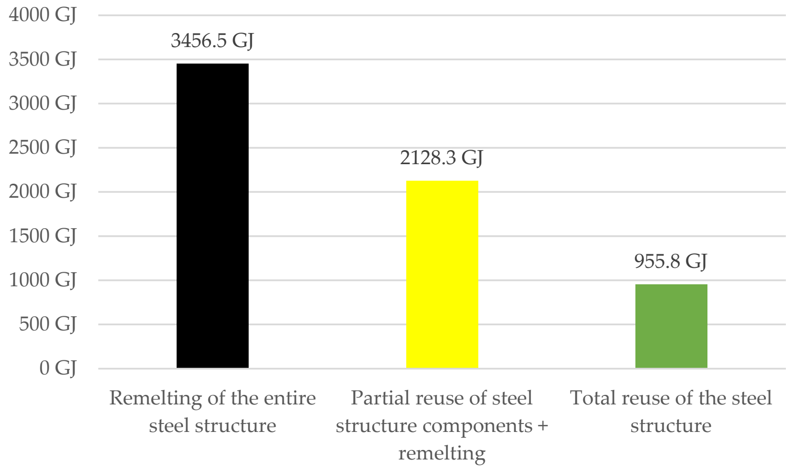

Figure 11. Primary Energy Use in three scenarios [GJ].

In Scenario no. 3, the least environmentally damaging scenario, the main processes causing primary energy use are the assembly of the structure and the refurbishment of steel elements. Meanwhile, in Scenario no. 1, the most energy-consuming process is the manufacturing of sections (Figure 12). The share of individual processes in the total environmental impact in the PEU category is analogous to the GWP. In brackets in Figure 11, the LCA modules of the buildings according to the standard EN 15978:2011 are specified.

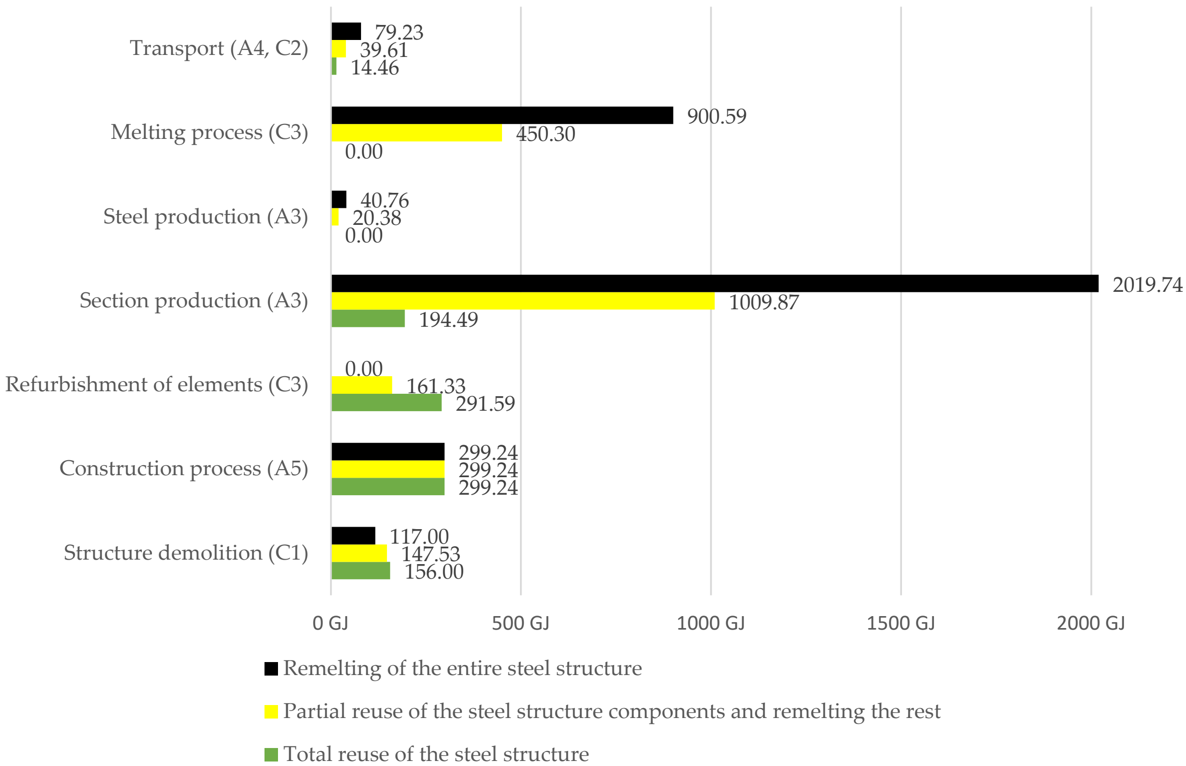

Figure 12. Primary Energy Use in processes [GJ].

4. Discussion

4.1. Comparison with Other Studies

Comparing the results obtained with those of previous studies is challenging due to differences in the scope, boundaries and size of the systems and their applications [39,40]. The studies analyzed were divided into studies showing the impacts of the individual processes of the EoL phase and studies on steel structures.

4.1.1. Studies in Which the Individual Processes of the EoL Phase Are considered

Among the studies dealing with the End of Life phase of building structures, there are few studies on steel structures. In most of the studies, the authors present the results in total for the entire EoL phase without distinguishing between modules C1-C4 or individual processes. Studies by Petrović et al. (2019) [41] and Takano et al. (2015) [42] concern timber structures, the demolition and reuse of which, as well as the treatment of demolition waste, are processes that are not comparable to those of steel structures; both in terms of energy consumption and emissions. However, Petrović et al. (2019) [41] also dealt with environmental impact assessment in terms of carbon footprint and primary energy use. The results obtained for the timber structure analyzed a GWP of 1.69 t CO_2 eq. and primary energy consumption of 8.36 GJ for the entire EoL phase, and included demolition, transport, waste treatment and associated emissions. The authors assessed the impact of the EoL phase as marginal for the whole of the life cycle of the timber structure, estimating its value at 2% of the total GWP impact category. The values obtained related to a unit of building area of 9.4 kg CO_2 eq./m^2 and 46.4 MJ/m^2, respectively, which is lower than that obtained in Scenario no. 3 of this study, which was 13.4 kg CO_2 eq./m^2 and 331.9 MJ/m^2. In the survey by Takano et al. (2015) [42], which was also related to timber structures, all EoL processes were included: deconstruction work; transport for sorting or disposal; waste sorting and processing; and waste disposal (incineration or landfill). The EoL results were added and accounted for 30% of the total GWP, amounting to 455 kg CO_2 eq./m^2. The total primary energy consumption for the EoL phase was estimated in the study to be a maximum of 357 MJ/m^2.

A study by Kakkos et al. (2019) [43] was related to a special UMAR ('Urban Mining and Recycling') building, all the components of which are by design fully reusable, recyclable or compostable and therefore compatible with the circular economy. Compared to a hypothetical building of the same size and standard, constructed with typical materials such as concrete, the UMAR building's design allows for a GWP reduction of 39%. The authors analyzed the entire life cycle of the building, including the EoL, split into C1 and C2-C4 modules. However, the results were only given as a percentage of each impact category's total, making it impossible to compare with the results obtained. No quantitative value of impacts is given. In the study by Dodoo and Gustavsson (2013) [44], which compared the effect of a conventional and passive building with a timber frame as its load-bearing structure, it was determined that the demolition of the building emits 2 kg CO_2 eq./m^2 and consumes 6 kWh/m^2, which is equivalent to 21.6 MJ/m^2. The end-of-life balance was calculated by taking into account the energy used to demolish the building and to recover and transport the concrete, timber and steel used to construct the building. The values of the other processes in the EoL phase given by the authors are negative and determine the benefits of recycling the recovered building materials. In the study by Gustavsson et al. (2010) [45] the impacts from the demolition process were assigned only to fuel consumption (a total of 16 kWh/m^2, which equates to 57.6 MJ/m^2 and 6 kg CO_2/m^2). The value of the calculated benefits of using recovered demolition wood to be burned for energy recovery was given as a further element of the EoL phase analysis. The authors mention the DfD as a future scenario, in which it is possible to reuse wood products (such as lumber, chipboard, and pulp) before burning them to recover energy from the raw material.

A study by the Royal Institution of Chartered Surveyors RICS (2017) [46] gives the average emission factors for the individual modules of the EoL phase of buildings derived from monitored case studies of building demolition in central London. For module C1, i.e., the demolition process, 3.4 kg CO_2/m^2 is given, almost ten times the value obtained in this study (0.37 kg CO_2/m^2). However, the study does not apply to industrial steel structures. The need to calculate the impacts of the C3 module according to individually assumed EoL scenarios was also highlighted.

4.1.2. Research on LCA of Steel

The Australian Steel Institute specified in its publication [47] that the total life cycle emissions of structural steel are 2.35 t CO_2 eq. per ton of product. The authors of this study assessed the impact of the construction phase (A3–A5) and the EoL phase (C1–C3), obtaining a result of 1.45 t CO_2 eq./t. Comparing these studies, it can be concluded that construction and transport processes, as well as waste treatment, account for most of the life-cycle impact of steel structures.

The study by Oladazimi et al. [48] highlights the fact that the EoL phase is usually neglected in building life cycle analyses. The results were obtained using GaBi software. The total emissions in the EoL phase of a steel frame were determined to be 5640 t CO_2 eq. With a structure mass of 756 t, this impact can be represented as 7.46 t CO_2 eq./t, which when compared to this study is five times higher, yet this impact was still almost 30% lower than the impact of the concrete-framed building compared in the study with 7750 t CO_2 eq. However, the results of that study are difficult to compare with those obtained by the authors, as the steel frame was assessed together with 2543 m^3 of concrete (it is not indicated for what purpose it was used). In the study by Kim et al. [49] the total environmental impact of a steel-framed multi-storey building has been assessed. Results for individual life cycle phases were not provided. The energy consumption for processes related to the processing of structural steel was estimated at a total of 1267 TOE, which equates to 53 TJ over the life cycle, which can be calculated at 42.3 GJ/t per unit mass of steel used. The authors of this publication obtained a value of 7.98 GJ/t for the least energy-intensive of Scenario no. 3 and 25.61 GJ/t for the most energy-intensive Scenario no. 1, considering only the construction phase (A3–A5) and the EoL of the structure (C1–C3). The CO_2 value for steel was 5102 t CO_2 or approximately 4.1 t CO_2/t of steel over the life cycle. This study obtained a minimum of 0.29 t CO_2 eq./t and a maximum of 1.45 t CO_2 eq./t. It should be noted that the steel section processes were assessed to be the most energy-intensive and the most emission-intensive, the same as in this study.

4.2. Limitations and Future Work

Comparison with previous work has shown that the results can differ to a huge extent. The present work provides detailed original inventory data from the process of demolition and reuse of steel structural elements. However, some limitations must be considered when interpreting the results and comparing them with other studies, for example, differences in the processes that were taken into account when performing the analysis or the lack of inclusion of the concrete foundations of the hall in the study.

In the next study, the authors want to focus on a sensitivity analysis of the results obtained to analyze the influence of critical parameters identified in Table 1. Parameters such as the way the sections are manufactured and the distance of the dismantled structure from the steel remelting and steel refurbishment sites can be mentioned here. Those parameters that significantly impact the results and are associated with significant uncertainty will be modified to assess the extent to which they affect the overall outcome of the study.

5. Conclusions

Despite some simplifications associated with the analysis used, including the distance of steel transport and the adoption of EU-averaged processes, the results obtained illustrate the scale of the differences between the scenarios. It is possible to save about 70% of primary energy and avoid about 80% CO_2 eq. emissions compared to the most unfavorable scenario, Scenario no. 1, which involves remelting the entire structure. Incorporating the DfD strategy into the architectural process would reduce energy and carbon emissions in the construction sector. However, the DfD process is not without its challenges. The lack of regulation of recycled materials and uncertainty about the quality and quantity of materials used continue to discourage the use of the DfD method. Another major challenge, for now, is the cost and speed of the process, as demolishing a structure is considered cheaper and faster than taking the structure apart piece by piece. However, studies by the EPA have shown that deconstruction can be cost-competitive for demolition if sufficient materials are recovered at a reasonable market value [3].

Global research indicates that technical competence is insufficient to succeed in a DfD strategy. Factors such as stringent legislation, policy and design process are also crucial in designing buildings suitable for demolition [50]. European Union legislation is slowly moving in this direction, for example, through the planned extension of Corporate Sustainability Reporting (CRS).

Author Contributions: Conceptualization, E.B. and K.D.; methodology, E.B. and K.D.; software, K.D.; validation, E.B. and K.D.; formal analysis, E.B. and K.D.; resources, K.D.; data curation, K.D.; writing, E.B. and K.D.; visualization, E.B. and K.D. 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.

Acknowledgments: The research was carried out as part of research work no. WZ/WB-IIL/4/2022 and WI/WB-IIŚ/6/2020 at the Bialystok University of Technology and financed by a subsidy provided by the Ministry of Education and Science.

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

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