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Carbon Dioxide Emissions from Various Structural Frame Materials of Single-Family Houses in Nordic Countries

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Abstract

Since the choice of material for the construction of single-family houses has a major impact on the buildings' total carbon dioxide emissions, this study examines the carbon dioxide emissions from various structural frame (frame) materials used for single-family houses in the Nordic countries. The analysed frame materials are wood, concrete, and steel as they are the most frequently chosen for single-family houses in these countries. To map the carbon dioxide emissions from the frame materials, a literature review of existing life cycle analyses of the materials is conducted. To present the results, a typical wall is employed for each material; the width and height of the walls are 1 m, while the depth varies for the different materials. The walls are designed to illustrate the results, which are reported in kg CO_2/m^3. Moreover, the study includes interviews with housing manufacturers to get the building industry's views on the choice of frame material with regard to carbon dioxide emissions. The results show that there are major differences in the carbon dioxide emissions from the three frame materials. The wooden, steel, and concrete frames emit 96 kg CO_2/m^3, 209 kg CO_2/m^3, and 602 kg CO_2/m^3, respectively. The results confirm that the wooden frame has the lowest carbon dioxide emissions, which makes it the most environmentally friendly frame in the Nordic countries when compared with the steel and concrete frames.

Keywords: Carbon dioxide emissions, Structural frame, Material, Wood, Concrete, Steel, Single-family house.

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1. Introduction

Carbon dioxide emissions are the factor with the largest influence on the greenhouse effect, so today's society strives to reduce greenhouse gas emissions. Currently, the building sector accounts for a large part of Sweden's greenhouse gas emissions [1] and aims to reduce emissions to achieve a greener future, as outlined in Sweden's part of the EU climate goals. The structural frame (frame) plays a very important structural role in a single-family house and comprises a large

part of the house; the choice of frame material, therefore, contributes significantly to the building's carbon dioxide emissions during its working life.

Sweden has a long history of using wood as a building material, thanks to the forest-rich nature of the Nordic region. Wood is used as a raw material in creating building materials, for example for frames. The forests also bind the carbon dioxide in the air, after which it is stored in wood until it is decommissioned. Additionally, wood is a renewable resource, and the carbon dioxide emitted by a decommissioned tree can thus be absorbed by a new one. Studies have shown that wooden frames emit less greenhouse gases than concrete and steel frames. The carbon dioxide emitted from wood can be reduced by recycling the material efficiently. Moreover, the fact that wood is a natural raw material means that less energy is required for it to be used as a frame material than concrete or steel.

Concrete, one of the more commonly used building materials, involves high carbon dioxide emissions; the majority of these emissions are due to the production of cement [1-3]. The reason for the large environmental impact of cement production is the high heat required to get the limestone to the right temperature. The extensive processing of concrete during its production requires concrete to be recycled after its use, mainly to mitigate damage to the environment and reduce greenhouse gas emissions, particularly carbon dioxide. Further, the cement clinker utilised in heating during the production of cement is expected to be replaced by another binder, such as slag or fly ash [4]. This solution is expected to reduce the total greenhouse gas emissions from the production of concrete for house frames. The positives of concrete include its long working life [5] and the fact that it requires little maintenance during the use stage. In addition, concrete becomes carbonated during its working life; this means that concrete absorbs carbon dioxide from the air and stores it within the material until it decomposes.

Presently, Swedish steel production makes use of coal. During production, carbon dioxide is formed when coal is burned and binds together with oxygen, which leads to unwanted carbon dioxide emissions. To reduce the emissions, companies such as LKAB, Vattenfall, and SSAB have come up with a solution to use hydrogen in the production of steel instead of coal. When hydrogen is bound together with oxygen, water is formed instead of carbon dioxide. This would decrease the carbon dioxide emissions involved in the production of steel material for frames. To mitigate the environmental impact of steel production, it is also important to recycle the used frame material.

Some previous studies have been performed on the carbon dioxide emissions from building materials, including wood, concrete, and steel, in some of the Nordic countries [6-13]. These studies are discussed in Section 3 of this article. Moreover, Jyosyula, et al. [14] evaluated the impact of lightweight construction materials on the carbon dioxide emissions from a reinforced concrete building. The emissions benefits of engineered wood products in a low-carbon future were reported by Winchester and Reilly [15]. Zhang, et al. [16] reviewed low carbon emissions projects in the world's steel industry. The carbon dioxide emissions from recycled and natural aggregate concrete were assessed by Sabău, et al. [17]. Theoretical carbon dioxide emissions from cement production were analysed by Nie, et al. [18]. Zhang, et al. [19] proposed a carbon flow tracing and carbon accounting method to explore the carbon dioxide emissions from the iron and steel industries.

However, limited information has been published until now on the comparative carbon dioxide emissions from the various frame materials (wood, concrete, and steel) used to construct single-family houses in the Nordic countries, which is the focus of the current article. To investigate these carbon dioxide emissions, previously conducted life cycle analyses (LCAs) of the frame materials are taken into consideration. An LCA involves the entire building's life cycle and includes all aspects of the building's working life in the form of influencing factors. An example of such an aspect is the location of the building, which affects the transport required and the availability of locally produced materials. Depending on the building's location, there are therefore different levels of carbon dioxide emissions. Consequently, to achieve the goal of this study, existing LCAs of the materials in the literature [6-13] are reviewed. A typical wall is designed to demonstrate the results for each material. In addition, interviews are done with housing manufacturers to obtain the building industry's perspective on the choice of frame material with respect to carbon dioxide emissions.

2. Materials and Methods

This research was carried out using a literature review and interviews. The literature review was performed with the aim of analysing the carbon dioxide emissions from various frame materials (wood, concrete, and steel) as measured through LCAs. The collected data were then compiled to allow conclusions to be drawn.

An LCA depends on the aspect of environmental impact one chooses to study. The analysis is always based on a product or service. The product in the analysis should be clearly defined to allow values to be assigned to its environmental impacts. Depending on which aspect is considered, it results in different types of environmental impacts. One aspect could be the carbon dioxide emissions that contribute to the greenhouse effect. The LCA takes into account the total life cycle of the product, which includes four main stages: production, construction, use, and end-of-life.

Figure 1 illustrates typical walls with an area of 1 m^2. The thickness of the walls differs due to the load-bearing properties of the different materials. Further details of these typical walls are displayed in Figure 2. As the figure shows, the wooden wall consists of two wooden studs and a wooden sill with dimensions of 45 mm × 220 mm. The concrete wall is a block of pure concrete with dimensions of 1000 mm × 150 mm. The steel wall includes two steel studs and a steel sill with dimensions of 4 mm × 195 mm.

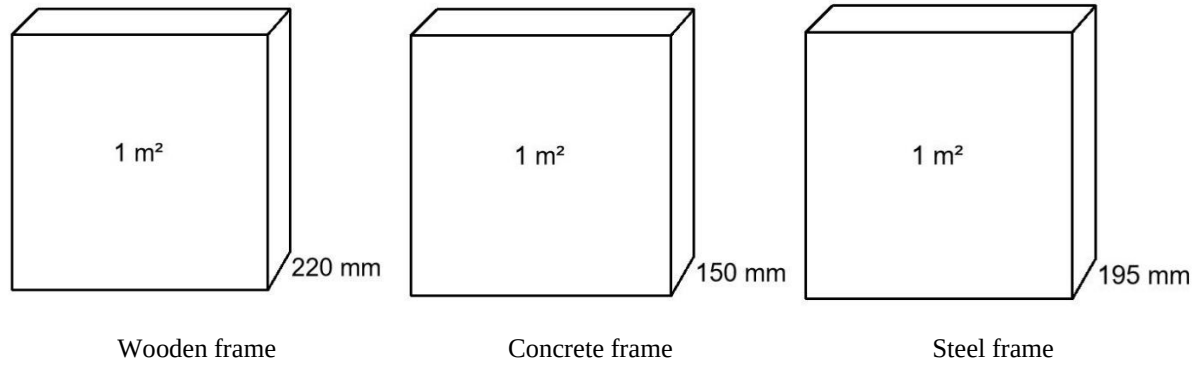

Figure 1.
Typical walls.

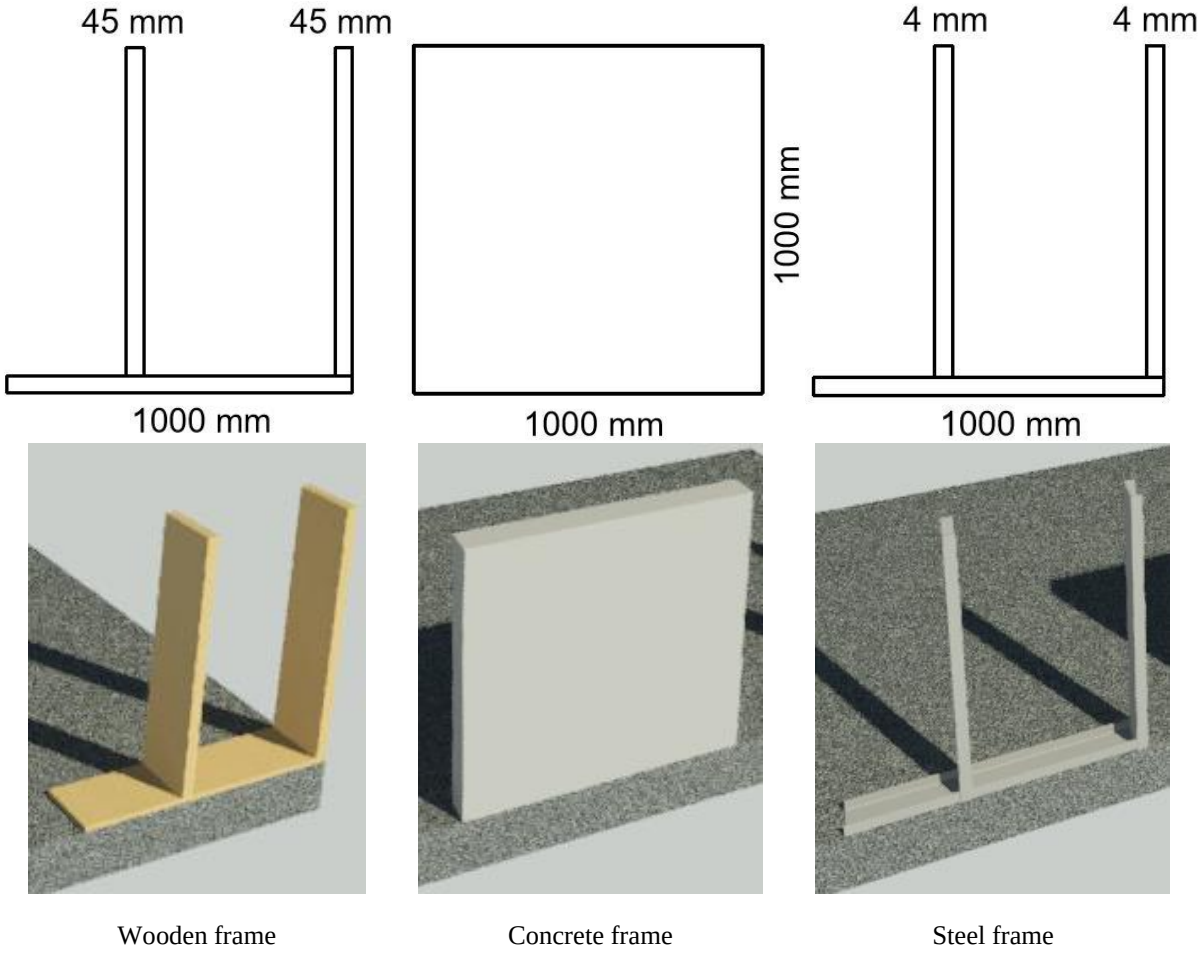

Figure 2.
Details of different typical walls.

2.1. Selected Literature

The selected literature [6-13] for this study presents data on the carbon dioxide emissions from the frame materials in different units, therefore, their data were converted to a common unit, kg CO_2/m^3, to be able to compare the carbon dioxide emissions from the typical walls.

To achieve the results from the frame materials in the desired unit, kg CO_2/m^3, the data of the selected articles had to be converted to kg CO_2/m^2, and the approach differed according to how the carbon dioxide emissions were reported in each article. In some cases, the carbon dioxide emissions were already given in kg CO_2/m^2, which facilitated the approach. When the studies' data were converted to kg CO_2/m^2, it was divided by the thickness of the typical wall so that the results could be compared and presented in the current research. In cases where it was not possible to calculate the articles' carbon dioxide emissions from the frame materials in kg CO_2/m^2, the ratio between the volume of the typical wall and the volume of the building frame in the article was considered in the calculations, so that the final results could be obtained in the unit kg CO_2/m^3.

Furthermore, an average value for the carbon dioxide emissions was calculated for each typical wall. In this way, it became possible to present diagrams of the carbon dioxide emissions from the typical walls and their average values in order to compare and discuss them.

2.1.1. Wooden Frame

The production stage (A1-A3) is the sub-process in an LCA during which most carbon dioxide is emitted. During the production of wood, an average of 0.0863 kg CO_2/kg is emitted in Sweden [20], while it is -1.7 kg CO_2/kg in Norway [21] and 0.068 kg CO_2/kg in Finland [22], as can be seen in Table 1.

Table 1.
Carbon dioxide emissions during the production stage (A1-A3) for a wooden frame.

Country	Carbon dioxide emission (kg CO_2/kg)
Sweden	0.0863
Norway	-1.7
Finland	0.068

2.1.2. Concrete Frame

The production of concrete emits an average of 0.1221 kg CO_2/kg in Sweden [20] and 0.099 kg CO_2/kg in Finland [22]. Table 2 lists these carbon dioxide emissions.

Table 2.
Carbon dioxide emissions during the production stage (A1-A3) for a concrete frame.

Country	Carbon dioxide emission (kg CO_2/kg)
Sweden	0.1221
Finland	0.099

2.1.3. Steel Frame

Steel production emits 3.0125 kg CO_2/kg in Sweden [20], while Finland thanks to its more environmentally friendly production emits 2.3 kg CO_2/kg [22]. These values are illustrated in Table 3.

Table 3.
Carbon dioxide emissions during the production stage (A1-A3) for a steel frame.

Country	Carbon dioxide emission (kg CO_2/kg)
Sweden	3.0125
Finland	2.3

2.2. Interviews

The study also included interviews with certain companies. These companies are experienced manufacturers of single-family houses, which means that they are knowledgeable in this area. By getting different companies' views on the choice of frame material with regard to carbon dioxide emissions, we could strengthen the validity and reliability of the research from the practical and theoretical perspectives as well. These interviews served to confirm the data collected from the literature review. The interviews were done with the Swedish companies Österling Bygg, Obos (Smålandsvillan and Myresjöhus), Hudikhus, Fiskarhedenvillan, and Eksjöhus. These companies, as experienced single-family house manufacturers, are well acquainted with the various frame materials that we have chosen to analyse because these materials are the typical frame alternatives for the construction of single-family houses in Sweden and the rest of the Nordic region. Since the manufacturers of single-family houses do not deal with the production stage (A1-A3) in an LCA, the interview questions were based on their expected knowledge of the other stages of the LCA. At the time of the interviews, it was important to document the answers to be able to compile the collected data at a later stage. Documentation took place by recording the conversations, subject to the participants' consent. If a participant did not consent to have the interview recorded, carefully written notes were used in place of the recording.

3. Results and Discussion

The obtained results are presented in the categories of wooden, concrete, and steel frames, and are discussed below.

3.1. Wooden Frame

Fufa, et al. [12] reported the carbon dioxide emissions from four different wooden structures in Sweden, Norway, Germany, and France. However, the current study focused only on the Nordic countries. The carbon dioxide emissions from the walls in Sweden and Norway were 25 kg CO_2/m^2 and 20 kg CO_2/m^2, respectively. The carbon dioxide emissions from a building in Helsinki, Finland, were studied by Takano, et al. [10]. The carbon dioxide emissions from the walls of this building were 20 kg CO_2/m^2. Emami, et al. [13] also conducted a study on the carbon dioxide emissions from a building in Finland. The carbon dioxide emissions were based on two different LCA databases, SimaPro and GaBi. Thus, the frame's carbon dioxide emissions were calculated separately for SimaPro and GaBi.

Consequently, the total carbon dioxide emissions from the wooden frames in Norway and Sweden in the study carried out by Fufa, et al. [12] were achieved as 50 kg CO_2/m^3 and 68 kg CO_2/m^3, respectively. Meanwhile, the total carbon dioxide emissions from the wooden frames in the research done by Takano, et al. [10] and Emami, et al. [13] were obtained as 69 kg CO_2/m^3 and 196 kg CO_2/m^3, respectively. These results are demonstrated in Figure 3. The wooden frames in Finland had the highest average carbon dioxide emissions (Figure 4). This can be due to many factors, one of which is the carbon dioxide emission during the production stage. Finland had higher carbon dioxide emissions during the production stage than Norway, though they were lower than Sweden, as indicated in Table 1. The carbon dioxide emissions during the production stage are not the only factor contributing to the total carbon dioxide emissions from these countries; other factors that contribute to this issue include the transport distance to the building site, the amount of material used for the building, how the building's wooden frame is constructed, how the building is maintained during the use stage, and how the material is decommissioned.

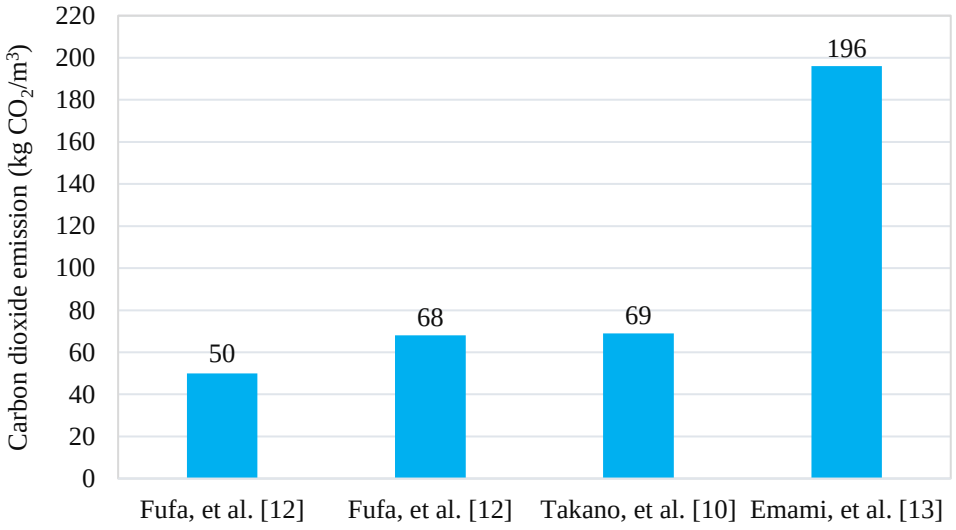

Figure 3.
Carbon dioxide emissions from wooden frames.

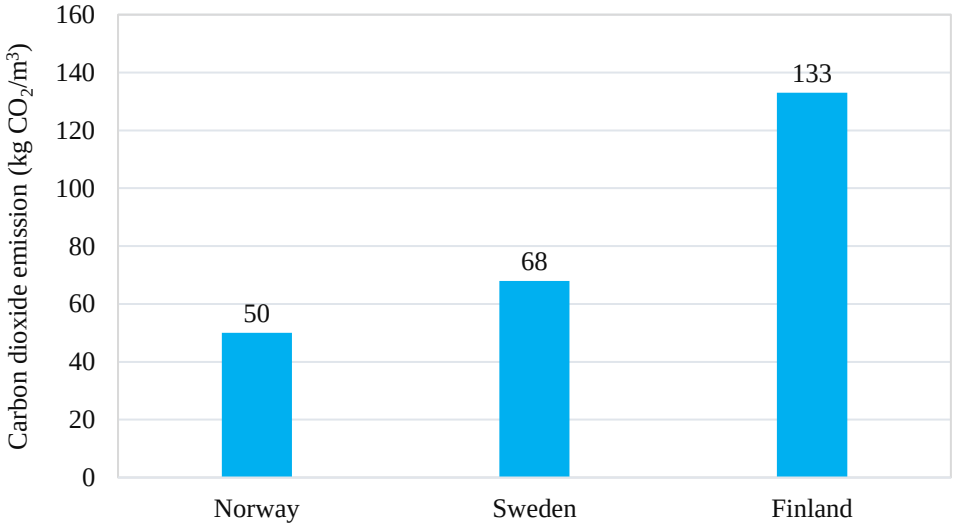

Figure 4.
Average carbon dioxide emissions from wooden frames in Norway, Sweden, and Finland.

3.2. Concrete Frame

Sinha, et al. [11] studied the carbon dioxide emissions from a concrete building in Stockholm, Sweden. The carbon dioxide emissions were based on three different LCA databases: SimaPro, GaBi, and ELP. The carbon dioxide emissions from the building's concrete differed and were stated in the unit kg CO_2/kg. Also, the carbon dioxide emissions from three different buildings were investigated by Junnila [7]. The most suitable of these three buildings, case B, was selected for this research. The frame accounted for 3% of the building's total carbon dioxide emissions, where the total carbon dioxide emissions were 3100 kg CO_2/m^2. As a result, the concrete frame of the building emitted a total of 93 kg CO_2/m^2 in Finland. Takano, et al. [10] analysed the carbon dioxide emissions from a concrete frame in Finland. They recorded the carbon dioxide emissions of 74 kg CO_2/m^2 for the concrete frame. Another study on the carbon dioxide emissions from a concrete building in Finland was conducted by Emami, et al. [13]. The proportions of concrete in the building for SimaPro and GaBi were 43% and 33%, respectively.

The total carbon dioxide emissions from the concrete frames considered in this research were obtained and are compared in Figure 5. The higher average carbon dioxide emissions from the concrete frame in Sweden than from those in Finland can be observed in Figure 6. The lower average carbon dioxide emissions in Finland can be attributed to lower carbon dioxide emissions during the production stage, which can be seen in Table 2. Other factors that can affect the carbon dioxide emissions from these frames have been discussed in Section 3.1.

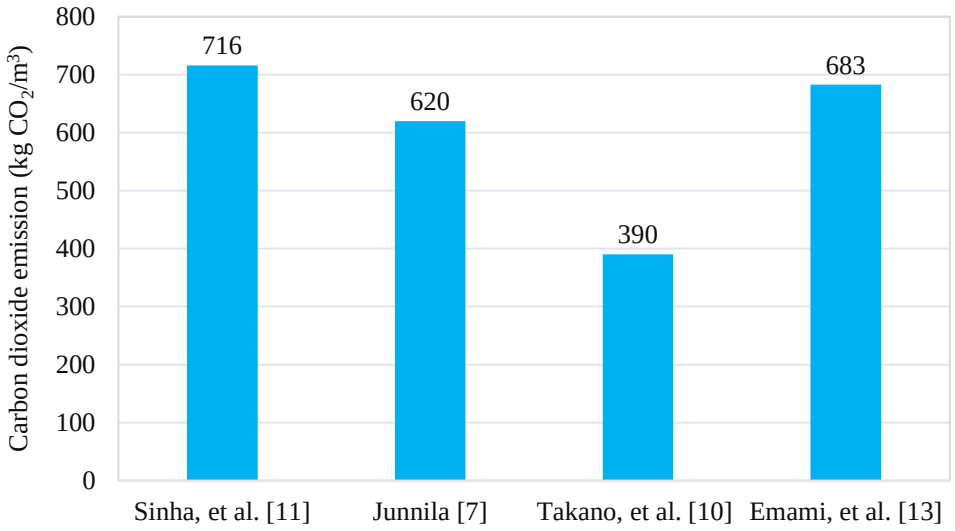

Figure 5.
Carbon dioxide emissions from concrete frames.

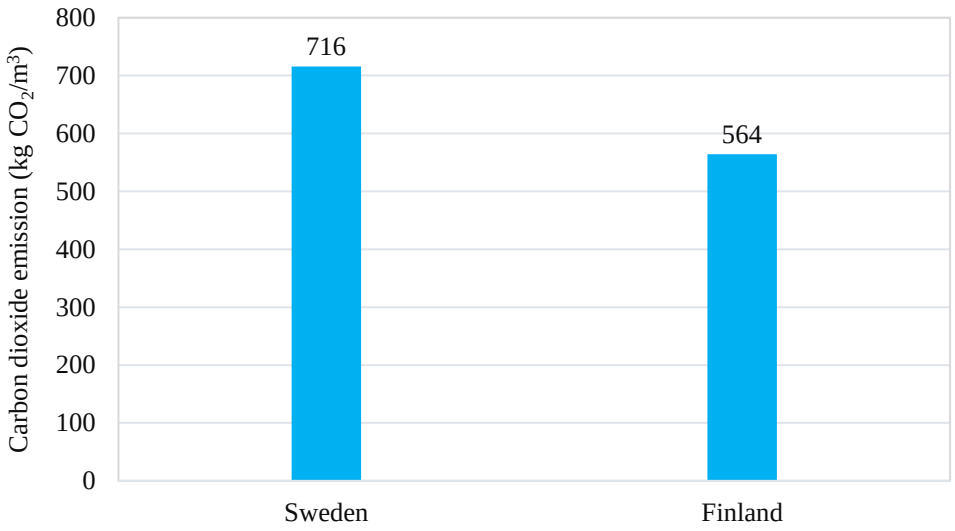

Figure 6.
Average carbon dioxide emissions from concrete frames in Sweden and Finland.

3.3. Steel Frame

Rossi, et al. [8] carried out LCAs of residential buildings in three different European locations, including Luleå in Sweden. LCAs of seven frames of different materials in Sweden were conducted by Jönsson, et al. [6]. Of these seven different frames, the steel frame was selected as the most suitable for the current study. Takano, et al. [10] studied the influence of the selected building materials on the environmental parameters of buildings in Finland, from which a steel frame was chosen for this part of the current research. Moreover, an LCA of a single-family house with a steel frame in Kiruna, Sweden, was performed by Coelho, et al. [9].

The carbon dioxide emissions from the steel frames in the above-mentioned studies, i.e., Rossi, et al. [8]; Jönsson, et al. [6]; Takano, et al. [10], and Coelho, et al. [9], were calculated as 251 kg CO_2/m^3, 410 kg CO_2/m^3, 105 kg CO_2/m^3, and 69 kg CO_2/m^3, respectively. These values are displayed in Figure 7. Figure 8 demonstrates that the steel frames in Sweden had higher average carbon dioxide emissions than those in Finland. The higher average carbon dioxide emissions in Sweden can be explained by higher carbon dioxide emissions during the production stage, as listed in Table 3. Other factors influenced the carbon dioxide emissions from the frames; these have been discussed in Section 3.1.

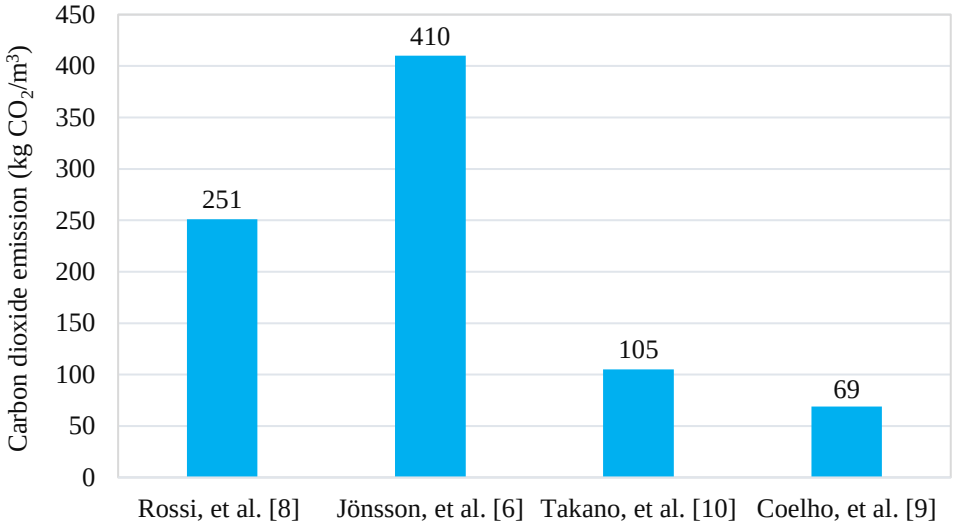

Figure 7.
Carbon dioxide emissions from steel frames.

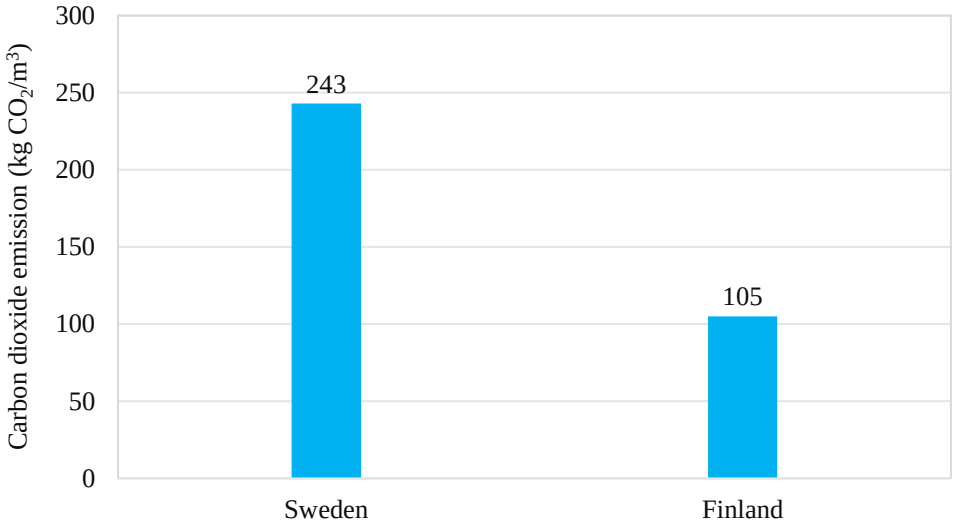

Figure 8.
Average carbon dioxide emissions from steel frames in Sweden and Finland.

3.4. Comparison of Carbon Dioxide Emissions from Wooden, Concrete, and Steel Frames

The carbon dioxide emissions from each type of frame are compared in Table 4. According to the table, the wooden frame accounted for the lowest carbon dioxide emissions, with 96 kg CO_2/m^3. The steel frame was the second-highest carbon dioxide emitter (209 kg CO_2/m^3), and the concrete frame had the highest carbon dioxide emissions, with 602 kg CO_2/m^3. As a consequence, the wooden, steel, and concrete frames accounted for 11%, 23%, and 66% of the emitted carbon dioxide, respectively. Therefore, the wooden frame has been demonstrated to be the most environmentally friendly frame in terms of its carbon dioxide emissions.

Table 4.
Carbon dioxide emissions from frames of different materials.

Type of frame	Average carbon dioxide emission (kg CO_2/m^3)	Average carbon dioxide emission (%)
Wooden frame	96	11
Concrete frame	602	66
Steel frame	209	23

3.5. Summary of Interview Results

The results of the interviews with the companies are summarised in this section. It should be noted that the respondent from Obos was also the respondent from Myresjöhus and Smålandsvillan, as they are subsidiaries of Obos. Österling Bygg focuses on truck transport. The respondent from Österling Bygg stated that they extremely rarely take the carbon dioxide emissions from the frames into account in turnkey contracts and never in construction contracts. They mostly build with wooden frames and base their choice on the fact that wood is the best, easiest, and most cost-effective material for their projects.

Given the volume of elements that Obos manufactures in Vrigstad (Smålandsvillan), only one truck trip is required to deliver the elements of an entire villa to a site. In Myresjö, plan elements are manufactured to enable the transport of as many components as possible to the building site. They believe that a wooden frame has the lowest carbon dioxide impact during the production stage. According to them, the residual material is used effectively when the elements required for the building are manufactured in their factories, as the residual material can be reused for subsequent frame elements instead of becoming construction waste at the building site. The respondents from Obos, which has been manufacturing single-family houses with wooden frames since 1927, said that the tradition of constructing with wood has become an active choice today based on its many advantages, including the carbon dioxide impact of the frame material throughout its life.

Hudikhus also transports frame materials by truck. The respondent from Hudikhus believed that the difference in carbon dioxide emissions during construction is marginal and the big difference is probably in the production of the frame material. The company has been manufacturing wooden houses for 60 years and uses only wooden frames. When asked whether they base their choice of frame material on its carbon dioxide emissions, the respondent answered that while people did not think much about climate change in Hudikhus's early history, they see a bright future for wood as a frame material in light of the climate challenges facing the world. When asked whether the company takes the carbon dioxide impact of the frame material into consideration during decommissioning, they answered that since they do not choose a frame material from different alternatives, the question is not relevant to them.

The respondent from Fiskarhedenvillan stated that they work intensively with LCA calculations and take the environmental impact into account when deciding on materials and methods. Fiskarhedenvillan also sets itself the goal of always implementing environmentally based improvements to the house models they offer. Their transport of the frame materials usually takes place by truck, except when it concerns a single building on an island or similar. When the respondent was asked which frame material he thinks emits the lowest levels of carbon dioxide during construction, he answered wood because 95% of their houses are made of wood and they do not have much experience building in other ways; however, lightweight concrete or stone is also used in some of their houses. The choice to focus on wooden frames is based on tradition and their experience with the material, although it has now been demonstrated through calculations and evaluations that it is the material with the lowest carbon dioxide emissions. In addition, the respondent pointed out that they always try to ensure the materials' proper sustainability. One of the environmentally based improvements that Fiskarhedenvillan is working on is the accurate decommissioning of the buildings' materials. They noted that they think it should be easy to replace materials and sort and recycle them, so they avoid gluing together and attaching different materials in a way that makes them difficult to sort and/or reuse.

Eksjöhus usually uses trucks with trailers to transport frame materials to building sites. The respondent from Eksjöhus, like the other small house manufacturers, believed that wood is the frame material that emits the lowest amount of carbon dioxide during construction. The frame material that they mostly build with is wood, but the respondent mentioned that this is not based on its carbon dioxide emissions. Finally, the respondent stated that they do not consciously consider decommissioning of the frame material; on the other hand, they are aware that wood is resource-efficient to decommission.

This summary of the interviews has confirmed that wood is the most common frame material for single-family houses in Sweden.

4. Conclusion

Carbon dioxide emissions from various frame materials (wood, concrete, and steel) used in the construction of single-family houses in the Nordic countries were evaluated in this study. Some of the existing LCAs in the literature were reviewed and investigated. A typical wall was considered for each material to represent the results. The literature review showed that the best choice of frame material with regard to carbon dioxide emissions is wood, based on the fact that wood is a natural raw material that needs little processing to serve as a frame material, and it has the further helpful property of binding the carbon dioxide in the air. Steel proved to be the second-best frame material, while concrete was the worst. The wooden, steel, and concrete frames were responsible for 11%, 23%, and 66% of the emitted carbon dioxide, respectively. Furthermore, interviews were carried out with housing manufacturers to gain the building industry's perspective on the choice of frame material with respect to its carbon dioxide emissions. The interviews indicated that the wooden frame was the most common type for single-family houses in Sweden. Obos, Fiskarhedenvillan, Eksjöhus, and Hudikhus have a long tradition of constructing single-family houses with wooden frames. They had positive opinions of the carbon dioxide emissions from wooden frames and believed that wood has a bright future as a frame material. Our study supported their continued choice of wood for frames because wood has by far the lowest carbon dioxide emissions compared with steel and concrete. However, not all the interviewed manufacturers based their choice of frame material on its carbon dioxide emissions. For example, the respondent from Österling Bygg stated that their choice of frame material was based on what was the best, easiest, and most cost-effective material for their projects, which is why they have chosen to use wood. At present, the wooden frame, as the lowest carbon dioxide emitter, is used by all the interviewed single-family house manufacturers, which is positive from a sustainability point of view, as the building sector accounts for a large proportion of carbon dioxide emissions and thus needs to reduce them for a greener future to be achieved.

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