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A Comparative Analysis of the Environmental Impacts of Wood–Aluminum Window Production in Two Life Cycle Assessment Software

Michal Sečkár [1,*], Marián Schwarz [1], Adam Pochyba [1] and András Polgár [2]

[1] Department of Environmental Engineering, Faculty of Ecology and Environmental Sciences, Technical University in Zvolen, T. G. Masaryka 24, 960 01 Zvolen, Slovakia

[2] Institute of Environmental Protection and Nature Conservation, Faculty of Forestry, University of Sopron, Bajcsy-Zsilinszky u. 4, 9400 Sopron, Hungary

* Correspondence: xseckarm@is.tuzvo.sk

Abstract: In the construction sector, there is a shift towards environmentally conscious practices that prioritize the minimization of environmental burdens. In this study, we dealt with a cradle-to-gate life cycle assessment (LCA) of a wood–aluminum window in two software tools. SimaPro (PRé Sustainability) and Sphera LCA for Experts (formerly known as GaBi) were selected. The results from both software tools were compared to assess the output uniformity of the two selected tools. The results indicate the similarities and differences in the software tools. The most similar results were achieved for impact categories Photochemical Ozone Formation (1.1% difference), Human Toxicity, cancer (total) (3.6% difference), Climate Change (3.7% difference) and for Resource Use, fossils (4.5% difference), respectively. On the other hand, the results were most different in the impact categories Ozone Depletion (84.7% difference), Resource Use, minerals and metals (75% difference), Ecotoxicity, freshwater—inorganics (35.6%) and Ecotoxicity, freshwater (total) (31.2%), respectively. The differences in the LCA results between SimaPro and GaBi were analyzed in-depth and were mainly attributable to using different databases in the transportation process and due to different system boundaries in some processes, with the Ecoinvent data containing significantly more background processes and inconsistencies in the implemented characterization factors.

Keywords: life cycle assessment; window; SimaPro; GaBi; software tools; environmental impacts

Citation: Sečkár, M.; Schwarz, M.; Pochyba, A.; Polgár, A. A Comparative Analysis of the Environmental Impacts of Wood–Aluminum Window Production in Two Life Cycle Assessment Software. *Sustainability* **2024**, *16*, 9581. https://doi.org/10.3390/su16219581

Academic Editor: Antonio Caggiano

Received: 24 September 2024
Revised: 30 October 2024
Accepted: 31 October 2024
Published: 4 November 2024

1. Introduction

Life cycle assessment (LCA) is a method in which a product (mostly a physical object) or service is evaluated from the initial extraction of raw materials, through production and use to the end of its life cycle. LCA analysis can identify hotspots between life cycle phases or processes in a system. Depending on the chosen method, LCA focuses not only on global warming impacts, but also on various other environmental impacts [1]. The construction industry is undergoing a significant shift towards sustainable practices, with an increasing emphasis on minimizing environmental impacts. On a global scale, the construction sector consumes up to 60% of raw materials, which underlines its significant impact on the depletion of natural resources. This heavy reliance on raw materials in the construction industry highlights the urgent need for sustainable practices in the industry and encourages efforts to improve material efficiency, reduce waste and explore renewable alternatives. Addressing these challenges is critical to reducing the industry's environmental footprint and aligning with global sustainability goals [2–4]. Reducing environmental impacts is essential in the pursuit of sustainable construction [5]. Interestingly, consumers may approach sustainability as a deciding factor between options rather than as an initial priority. Consumers are also generally open to choosing more sustainable options, but feel that limited information holds them back [6]. While LCA is well documented, with established and available methodologies, there are still significant challenges to its adoption in construction projects that shape the focus of future research [7]. However, the field of LCA for building materials, including wood–aluminum windows, is growing as sustainability becomes a primary concern in architecture and construction. Researchers focus on the environmental impacts of hybrid materials and the intersection between energy performance, resource consumption and end-of-life disposal. The types and properties of windows significantly affect the environmental and cost-effectiveness of buildings [8]. Windows made from recyclable materials, especially aluminum, support the circular economy, as recycled aluminum can significantly reduce the environmental impact when it is recycled into new products [9]. The combination of wood and aluminum offers a frame design that combines the low environmental impact of wood with the durability of aluminum, making it relatively low-maintenance. This combination also promises long life and strong environmental properties, even in mild to harsh climates. Moreover, wood provides excellent thermal insulation and aesthetic value [10,11]. From an LCA perspective, wood is a renewable resource that absorbs carbon during its growth, making it more sustainable compared to other materials such as pure aluminum or PVC. This focus is based on a common recognition of the impact of buildings on the environment during their life cycle, from material extraction and construction to operation and eventual demolition. LCA can help identify the environmental benefits of using recycled materials or incorporating energy-efficient technologies. Furthermore, by quantifying environmental impacts, LCA facilitates comparisons between different design options and construction methods. This approach allows architects, engineers and developers to optimize building designs for a minimal environmental footprint. Two software tools, SimaPro (PRé Sustainability) and Sphera LCA for Experts (here referred to as GaBi), were selected for comparison. SimaPro and GaBi are the two leading software tools that are used worldwide. These two software tools contain all the essentials that LCA software should include (user interface, databases, an impact assessment database with methodologies, calculator that combines numbers from the databases in accordance with the modeling of the product system in the user interface) [12]. The choice to compare these two software platforms is driven by their differing methodologies, databases and modeling capabilities, which can lead to variations in results. The distinctions of this study from previous research are the assessment of the wood–aluminum window system in two different software tools and the subsequent in-depth comparison of the differences in the results.

The goal of this study was to assess the environmental footprint of wood–aluminum window during the pre-use phase. In addition, this study compared the consistency of the results between two LCA software tools, SimaPro and GaBi. The main contributions of this study are an evaluation of the environmental impact of the life cycle of a wood–aluminum window in two software tools, a comparison of their results and an analysis of the reasons why the results differ.

2. Materials and Methods

In this study, we follow the four-phase framework in international LCA standards ISO 14040 and ISO 14044 [13,14], which includes goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA) and life cycle interpretation.

2.1. Goal and Scope Definition

Goal of the study was to quantify the environmental impacts of wood–aluminum window in the pre-use phase and to test the output uniformity of the two LCA software tools (SimaPro and GaBi). These software tools were chosen because SimaPro and GaBi are widely recognized as the best and most reliable software tools for conducting life cycle analyses [15]. Wood-aluminum window is produced in Slovakia. The functional unit consists of a 1 m^2 window on the 1 piece of reference window. A reference or otherwise standard window is a window made by the manufacturer, for which the LCIA results are then converted to 1 m^2. This functional unit is the standard unit used in most LCA studies of windows. A cradle-to-gate LCA was performed, where gate means a manufactured window ready for use. The process starts with production of scantlings. Then, the scantlings are processed (planing, grinding, machining and drilling); the surface treatment is applied (preservative and paint production included); the glazing is installed together with the gaskets and finally the hardware, gaskets; and aluminum structure is installed on the outside of the window (production of glazing, hardware, extruded aluminum and gaskets included). System boundaries are shown in Figure 1. The following relevant impact categories of The Environmental Footprint 3.1 (adapted) V1.00/EF 3.1 normalization and weighting set midpoint method were studied (units in brackets): Acidification (mol H^+ eq), Climate Change (kg CO_2 eq), Ecotoxicity, freshwater (CTUe—comparative toxic units, ecotoxicity), Ecotoxicity, freshwater—inorganics (CTUe), Ecotoxicity, freshwater—organics CTUe), Particulate Matter (disease inc.), Eutrophication, marine (kg N eq), Eutrophication, freshwater (kg P eq), Eutrophication, terrestrial (mol N eq), Human Toxicity, cancer (CTUh—comparative toxic units, human toxicity), Human Toxicity, cancer—inorganics (CTUh), Human Toxicity, cancer—organics (CTUh), Human Toxicity, non-cancer (CTUh), Human Toxicity, non-cancer—inorganics (CTUh), Human Toxicity, non-cancer—organics (CTUh), Ionizing Radiation (kBq U-235 eq), Land Use (Pt—soil quality index), Ozone Depletion (kg CFC11 eq), Photochemical Ozone Formation (kg NMVOC eq—Non Methane Volatile Organic Compounds), Resource Use, fossils (MJ), Resource Use, minerals and metals (kg Sb eq), Water Use (m^3 depriv.).

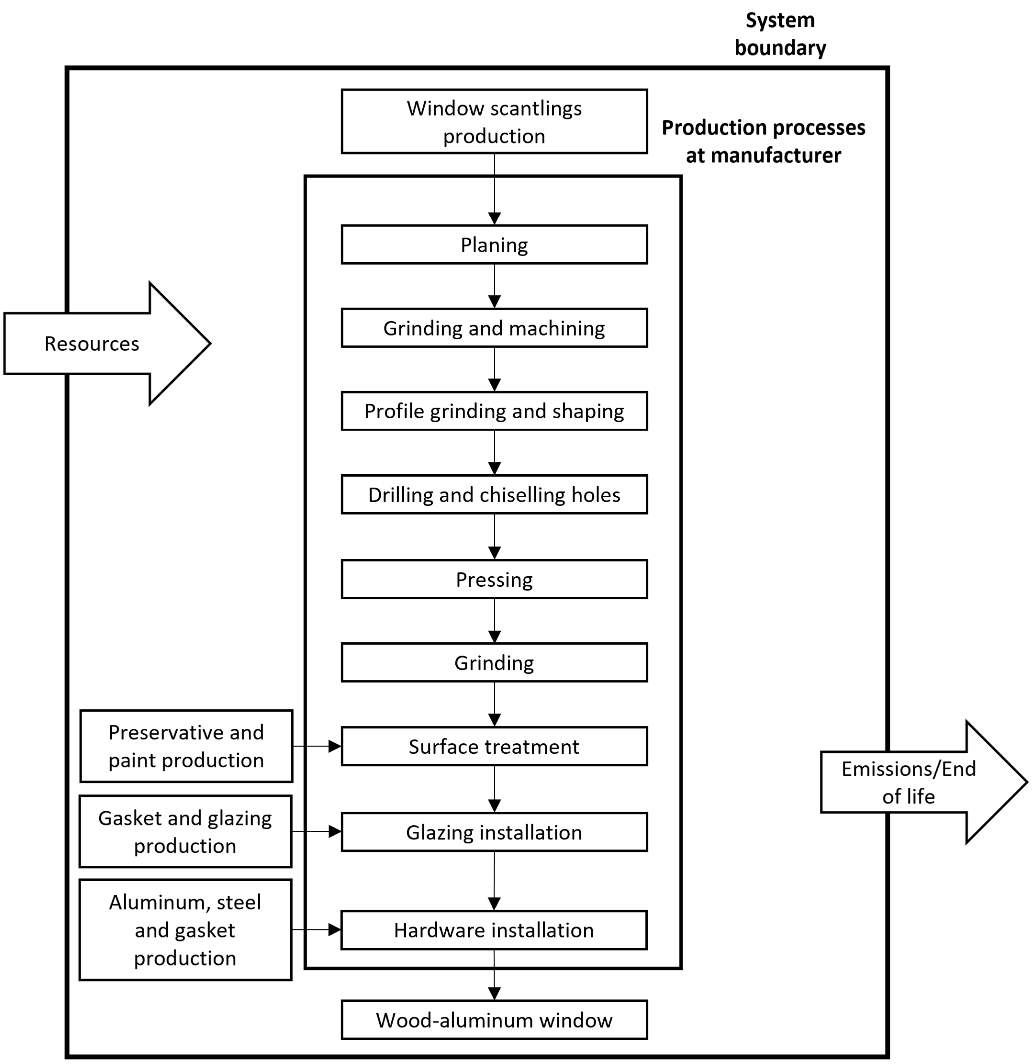

Figure 1. System boundary of wood–aluminum window production.

2.2. Life Cycle Inventory

The LCI analysis for each phase of the studied life cycle stages requires data from different sources. For production and extraction of raw materials, as secondary data sources published data and data from databases were used. For window production, secondary production processes are specific and require primary data collection. Data from the manufacturer of wood–aluminum windows in Slovakia, from the Ecoinvent database and the GaBi database (only in the case of transport in GaBi), were used. The reference window has an area of 1.8204 m^2. Figure 2 shows the view from inside the building through the window. The opening part of the window has a width of 1100 mm and a height of 1350 mm. The frame has an outer circumference of 5420 mm and an inner circumference of 5160 mm.

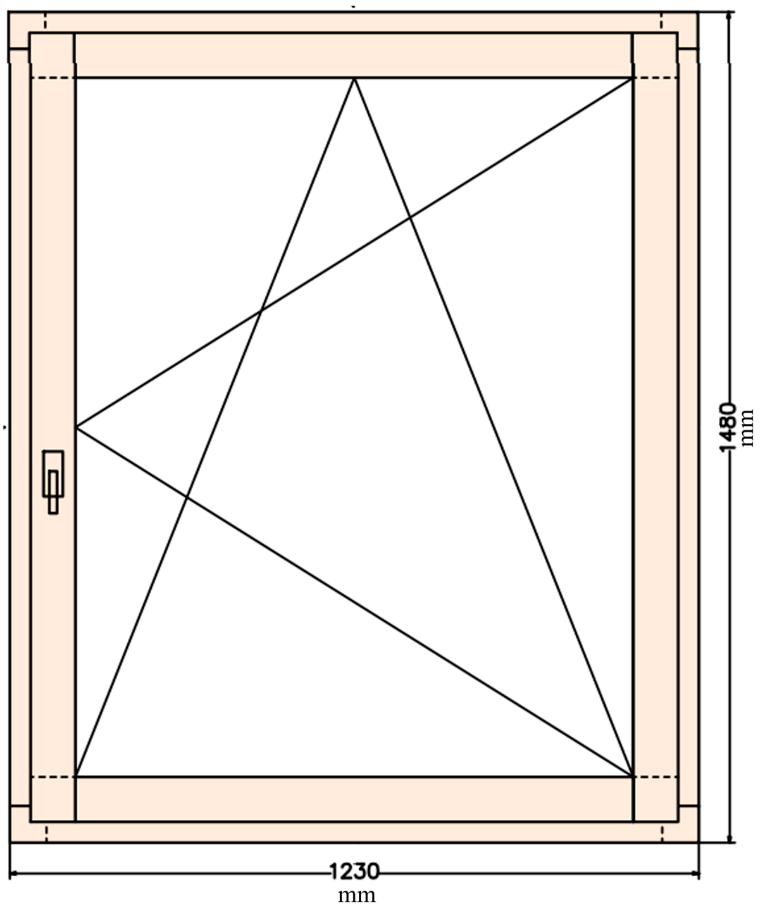

Figure 2. View of reference window from inside the building [16].

Each material for the production of the window is imported separately from the suppliers. These materials and distances were determined from manufacturer. The main materials and distances are indicated in Table 1.

Table 1. Main materials used and distance of transportation.

Material	Distance (km)
Hardware	1119
Screws	913
Gaskets	803
Triple glazing	474
Extruded aluminum	330
Plastic clips	330
Window scantlings	116

Window scantlings are made from spruce lumber dried to 12–13% moisture. Window scantlings consist of three layers of wood glued together. Triple glazing is used in the window. The function of the insulating glass used in a window is to provide thermal insulation properties. It retains the heat generated by heating and is characterized by a heat transfer coefficient through the glazing Ug = 0.53 $W/(m^2{\cdot}K)$. The lower the value of the heat transfer coefficient, the lower the heat loss. This is the most important characteristic of insulating glass [16].

Inside-lying hardware is used, operated by a single handle, locking in the tilted position. The handle is composed of aluminum, plastic and steel and has a positional locking and invisible attachment. Mechanism is certified according to RAL-RG 607/3, STN 16 60 11, and STN 16 60 10 [16–19]. Extruded aluminum is used to cover the exterior of the window. The window surface treatment consists of 3 layers [16]:

1. The soaking base is applied to the sanded wood. It prepares the surface for the second surface treatment, binds directly to the wood and carries the protective substance. Thanks to this base, the windows are protected against mold, fungi, pests and even UV rays.
2. The glaze (Intermedio) guarantees the resistance of the wood and the base against moisture. Intermedio is applied by dipping or pouring on the base, where it also reaches the joints and where moisture penetrates the wood the most. Intermedio protects the wood of the entire perimeter in contact with the external environment.
3. The thick layer of glaze is the last layer and is applied by spraying. It is resistant to moisture, it must be soft enough to withstand hail. It is flexible enough to withstand small dimensional changes caused by changes in wood moisture.

2.3. Life Cycle Impact Assessment

The used software was updated to the latest versions at the time of the research (SimaPro 9.5.0.0 and GaBi 2024.1), along with the life cycle impact assessment (referred to as LCIA) method. All processes and flows included in the system boundaries were the same for both SimaPro and GaBi from the Ecoinvent database v3.10, except for transport. Transport was modeled in SimaPro from the Ecoinvent database and in GaBi from the GaBi database 2024.1 edition. The differences in the transport results are discussed later in the study. The software offers several world-recognized methods and methodologies to classify inputs and outputs into impact categories for characterization and normalization. The Environmental Footprint 3.1 (adapted) V1.00/EF 3.1 normalization and weighting set midpoint method was used for the analysis because the European Commission proposed the Product Environmental Footprint and Organisation Environmental Footprint methods as a common way of measuring environmental performance. The Product Environmental Footprint and Organisation Environmental Footprint are the EU recommended LCA-based methods to quantify the environmental impacts of products and organizations [20].

2.3.1. GaBi

Developed by Sphera (formerly thinkstep), Sphera LCA for Experts, formerly known as GaBi, is a popular LCA tool. It adheres to ISO standards for LCA studies and provides various environmental assessments like carbon footprint, product and organizational environmental footprints and water footprint. GaBi offers its own extensive databases (around 17,000 processes) alongside compatibility with popular options like Ecoinvent. The software excels in compliance with international standards, making it a strong choice for industries like automotive and electronics. However, its industry focus might limit its usefulness compared to SimaPro in other sectors. It covers everything from defining project goals and system boundaries to conducting a full LCA study, including custom process creation and interpreting results. GaBi uses sequential computing. It gradually analyses each process involved in the product system. That is, it considers the inputs required by each process, such as energy or materials, and calculates the environmental impact associated with obtaining those inputs. It then uses the outputs from one process as inputs to another, creating a chain of calculations that reflects the product's life cycle. This method offers a clear picture of how each individual process contributes to the overall environmental footprint [21].

2.3.2. SimaPro

SimaPro is a leading software tool for LCA. Developed by PRé Sustainability, it allows users to conduct LCA studies following ISO standards. Paid licenses unlock access to extensive databases like Ecoinvent, US input/output, US LCI, Dutch input/output, Swiss input/output, LCA food, industry data, Japanese input/output and IVAM. Additionally, some licenses include add-on modules SimaPro Collect, SimaPro Share and SimaPro Explore. Users can customize the database, impact assessment methods and data points. The software even allows for adding new processes and materials for specific research needs. It also supports the creation of complex models based on additional parameters. SimaPro takes a different approach to calculation, using a powerful technique called matrix inversion. Instead of following a step-by-step process, it addresses the entire product system as a whole. SimaPro creates a mathematical representation of the entire life cycle, considering all processes and their connections. Using matrix inversion, it can solve this complex equation at once and simultaneously calculate the impact of all processes on the environment. This method is particularly effective for complex models with many processes, potentially handling thousands of calculations at once [21].

2.4. Interpretation

Factors that can affect LCA results of this study are discussed in this section. One of them is the location of the manufacturer where window is produced in connection with the transport of materials needed, and the second is the electricity supply mix at that location. Transport distances can significantly affect LCIA results. In 2022, national energy mix in Slovakia was largely made up of nuclear energy sources. Energy generated from nuclear power plants in Slovakia accounts for up to 60.11% of the total energy generated. Hydropower comes second with a share of 14.79% and energy from natural gas comes third with a share of 8.56%. Energy production from lignite and hard coal accounts for 3.28% and 2.55%, respectively. Petroleum products and other fossil resources account for 3.61% in addition to the above. Biomass energy production accounts for 4.14%, solar energy for 2.57% and other renewable energy sources for 0.39%. In total, Slovakia produced 24.68 TWh of energy [22].

3. Results

In general, the results regarding the system boundaries of this study point to the similarities and differences in the software tools. The most similar results were achieved for the following impact categories: Photochemical Ozone Formation, Human Toxicity, cancer (total), Climate Change, Resource Use, fossils and Eutrophication. On the other hand, the results were most different in the following impact categories: Ozone Depletion, Resource Use, minerals and metals, Ecotoxicity, freshwater—inorganics and Ecotoxicity, freshwater (total). Only processes that had a difference greater than 5% were discussed in more detail (if they were the processes with the biggest impact for the given impact category, then those were also discussed).

The results indicate that for almost every impact category, the GaBi software had a lower impact value than the SimaPro software. The SimaPro Acidification value was 0.732 mol H^+ eq and the GaBi value was 0.645 mol H^+ eq (11.9% difference). The difference in the impact on Climate Change was slightly smaller. The SimaPro value was 114.835 kg CO_2 eq and the GaBi value was 110.595 kg CO_2 eq (3.7% difference) (Figure 3).

The largest contributor to the Acidification impact category was glazing production (57.9% SimaPro; 64.1% GaBi). Even though these percentage values were significantly different for the given triple glazing production process, the values of the emissions themselves were very similar (0.43 mol H^+ eq SimaPro; 0.41 mol H^+ eq GaBi). The second largest contributor was hardware production (11.9% SimaPro; 11.1% GaBi). A difference of 17.2% between the software tools was observed (0.087 mol H^+ eq SimaPro; 0.072 mol H^+ eq GaBi). The third most impactful process was transport (10% SimaPro; 3.6% GaBi). In SimaPro, the transport value was 0.07 mol H^+ eq, and in GaBi it was 0.02 mol H^+ eq. The biggest difference in results in this case was connected with the use of different transport databases (55.6%).

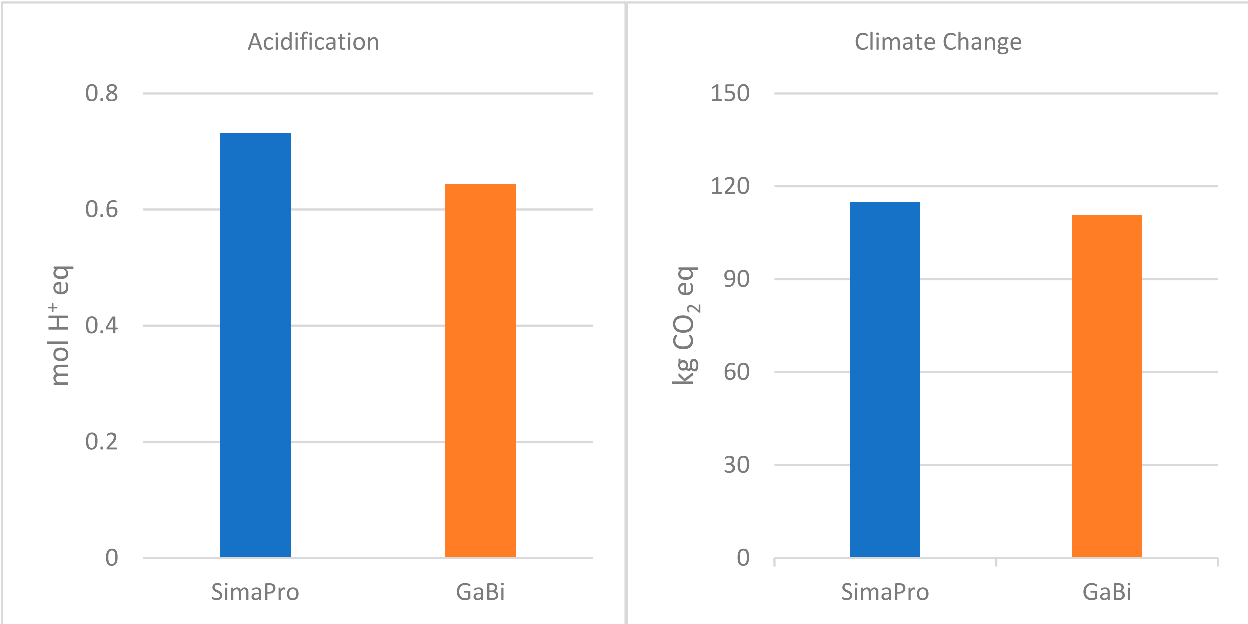

Figure 3. Acidification and Climate Change.

In the case of Climate Change, the production of triple glazing also had the largest impact on both software tools (42% in both). The triple glazing production process differed by only 0.2%. Hardware production was the second largest impact of Climate Change (20% for both software). The difference was 2.1%. The third largest impact was transport (19.5% SimaPro; 17.5% GaBi). The difference in transport between the software was 13.5%. This process represents the biggest difference in the emitted kg CO_2 eq within the processes involved. Other processes do not represent a significant margin of difference. In the case of Climate Change, these differences were due to the use of different databases for transport (72% of the difference).

According to the Environmental Footprint method, the impacts of ecotoxicity are divided into three impact categories—Ecotoxicity, freshwater (total) and Ecotoxicity, freshwater—inorganics and organics. The value of Ecotoxicity, freshwater was 1342.953 CTUe for SimaPro and 924.546 CTUe for GaBi (difference of 31.2%). For Ecotoxicity, freshwater—inorganics, the SimaPro value was 1052.059 CTUe and 677.769 CTUe for GaBi (difference of 35.6%). For Ecotoxicity, freshwater—organics, the SimaPro value was 290.894 CTUe and 246.777 CTUe for GaBi (difference of 15.2%) (Figure 4).

The largest contributor to the impact category Ecotoxicity, freshwater was the production of scantlings for the SimaPro software. In the case of SimaPro, this process had a value of 538.981 CTUe, and in the case of GaBi, the value was only 37.837 CTUe. This difference is caused by the fact that GaBi did not include all background processes (e.g., glue production), whereas SimaPro did. The biggest contributor was triple glazing for the GaBi software. The value of CTUe in the case of GaBi was 351.988, and in the case of SimaPro, it was 353.717 (minimal differences caused by the characterization calculation). The difference in the case of transport was also visible. SimaPro calculated a value of CTUe 121.596 and GaBi calculated a value of 186.188. The difference was caused by the use of different databases. In the case of hardware production, a significant difference was also found.

The difference was at the level of 66.2% (210.956 CTUe SimaPro; 71.371 CTUe GaBi). This difference was also caused by the fact that GaBi did not include all background processes.

The impact of Particulate Matter was 1.12×10^{-5} disease inc. in the case of SimaPro and 8.16×10^{-6} disease inc. in the case of GaBi (difference 27.2%). With Ionizing Radiation, the difference was a slightly smaller (20.5%). The SimaPro value was 13.452 kBq U-235 eq and the 10.697 kBq U-235 eq for GaBi (Figure 5).

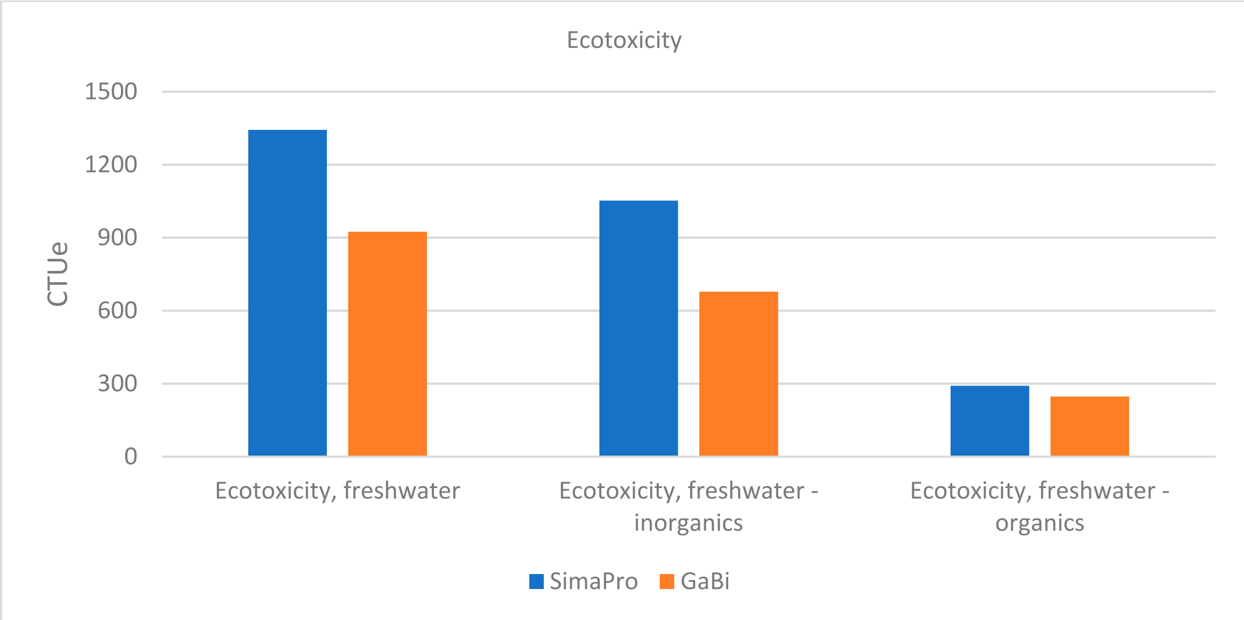

Figure 4. Ecotoxicity.

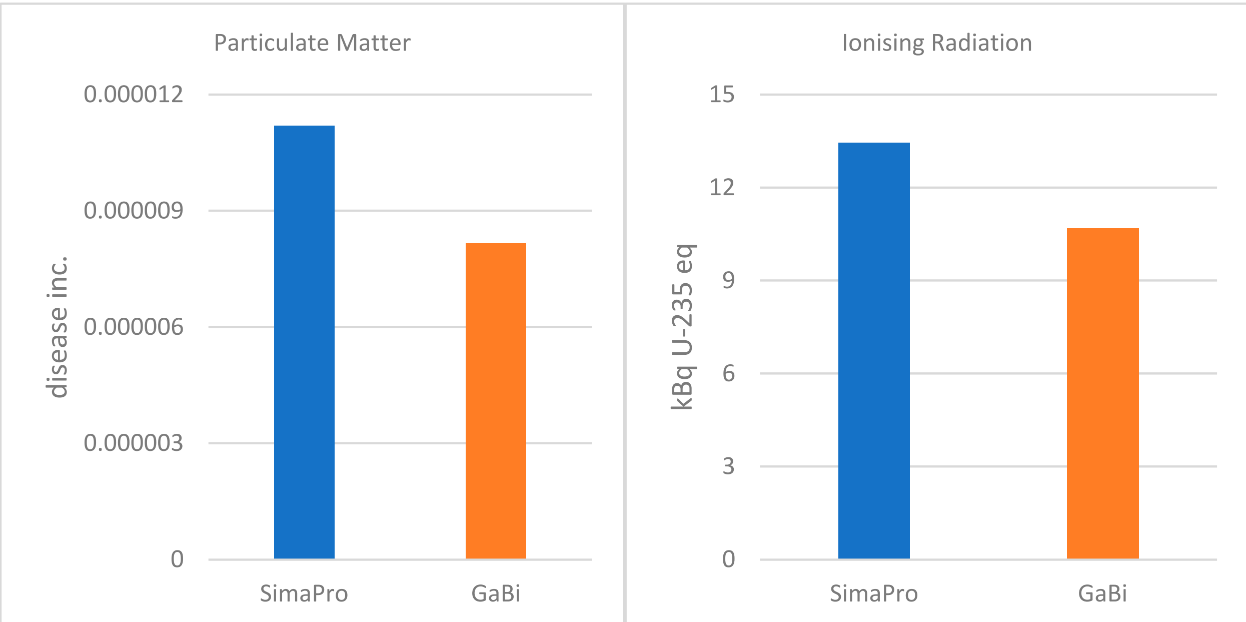

Figure 5. Particulate Matter and Ionizing Radiation.

The highest value for Particulate Matter impact category was in the glazing production process. The SimaPro value was 4.32×10^{-6} disease inc. and 4.12×10^{-6} disease inc. for GaBi. The difference is at the minimum level of 4.6%. The biggest difference was in the case of transport. SimaPro calculated a value of 2.63×10^{-6} disease inc. and GaBi only calculated a value of 1.66×10^{-7} disease inc. In the case of transport, this difference is caused by the use of a different database. The differences in all other processes were below 5%.

In the case of Ionizing Radiation, the biggest contribution was for the production of glazing. In the case of SimaPro, it was a value of 5.11 kBq U-235 eq, and for GaBi it was 4.42 kBq U-235 eq. These differences were caused by different characterizing factors for this impact category. The characterization factors were different in GaBi compared to SimaPro (for example Radium-222). The second largest impact for this impact category is the production of electricity. The electricity production value in SimaPro was 3.44 kBq U-235 eq and 3.36 kBq U-235 eq in GaBi. The differences for this process are minimal (2.3%). The biggest difference was transportation. In the case of transport, the value calculated by SimaPro was 1.86 kBq U-235 eq and 0.07 kBq U-235 eq by GaBi. The differences were caused by the use of a different database in the case of transport. The other processes had only minimal differences of <5%.

In this LCIA method, eutrophication is divided into three impact categories—Eutrophication, marine; Eutrophication, freshwater; and Eutrophication, terrestrial (Figure 6). Of these impact categories, the highest value was for Eutrophication, terrestrial with a value of 1.5 mol N eq for SimaPro and 1.36 mol N eq for GaBi (difference 9.3%). In Eutrophication, freshwater, the value for SimaPro was 0.042 kg P eq and 0.036 kg P eq for GaBi (difference 14.2%). The value of Eutrophication, marine was 0.137 kg N eq for SimaPro and 0.125 kg N eq for GaBi (difference 8.8%).

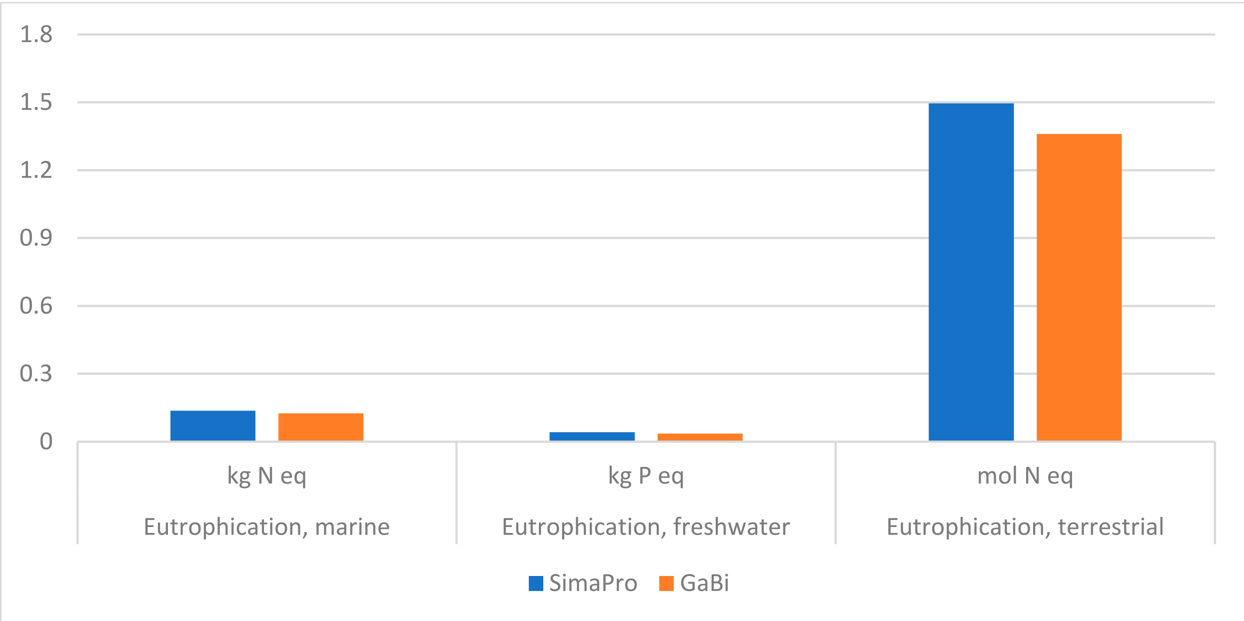

Figure 6. Eutrophication.

The biggest impact within the Eutrophication, marine impact category was the glazing production process with a value in both SimaPro and GaBi of 0.07 kg N eq. The biggest difference was in the case of transport (50%). The transport value calculated by SimaPro was 0.016 kg N eq and 0.08 kg N eq by GaBi. The difference was caused by the use of different databases. The other processes had only minimal differences of <5%.

In the case of Eutrophication, freshwater also had the greatest impact glazing production process. Both SimaPro and GaBi calculated the same value of 0.014 kg P eq. The biggest difference was in the production of scantlings. SimaPro had a value of 0.006 kg P eq and GaBi only had a value of 0.002 kg P eq. As already mentioned, this difference was also caused by the fact that GaBi did not include all background processes in the production of scantlings (glue production process). The other processes had only minimal differences of <5%.

For the impact category Eutrophication, terrestrial, the biggest contributor was glazing production with a value of 0.8 mol N eq calculated by both SimaPro and GaBi. The biggest difference was observed in transport (48.5%). SimaPro calculated the value of mol N eq 0.18 and GaBi calculated a value of 0.09. The difference was caused by the use of different databases. The other processes had only minimal differences of <5%.

Human Toxicity, cancer is also divided into three impact categories—Human Toxicity, cancer (total) and Human Toxicity, cancer—inorganics and organics (Figure 7). In Human Toxicity, cancer and Human Toxicity, cancer—organics, GaBi had a greater impact than SimaPro. For Human Toxicity, cancer (total), the SimaPro value was 2.054×10^{-7} CTUh and for GaBi it was 2.130×10^{-7} CTUh (difference 3.6%). For Human Toxicity, cancer—inorganics, the SimaPro value was 9.972×10^{-8} CTUh and for GaBi it was 7.596×10^{-8} CTUh (23.8%). For Human Toxicity, cancer—organics, the SimaPro value was 1.057 CTUh and for GaBi it was 1.370 CTUh (difference 22.8%).

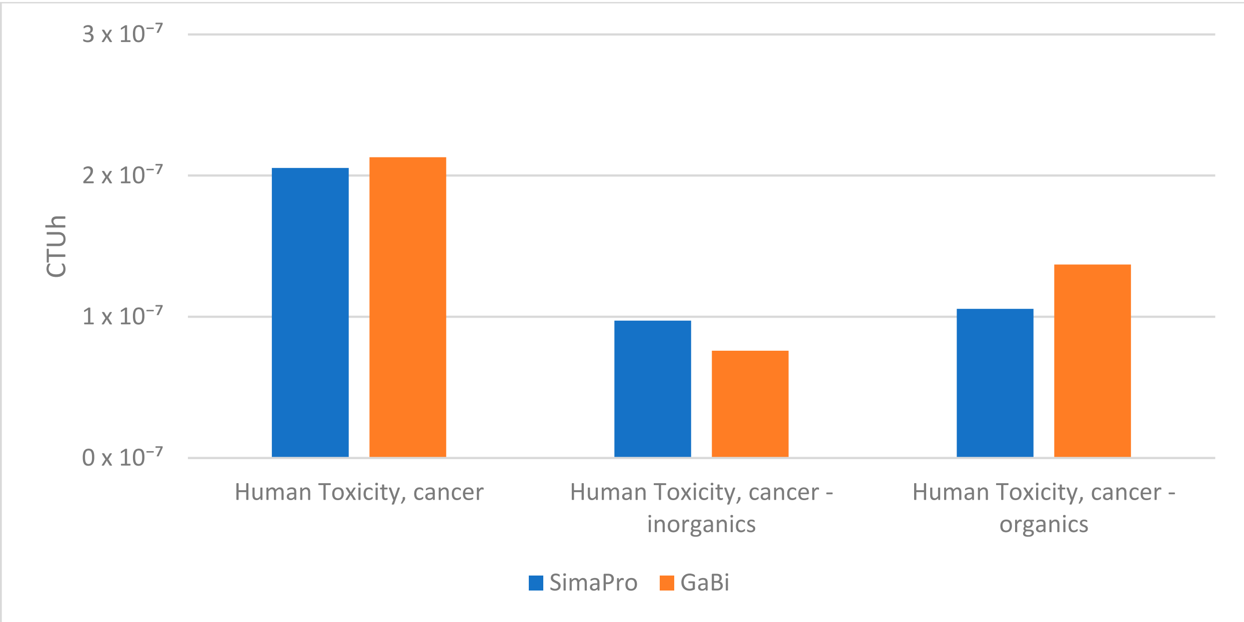

Figure 7. Human Toxicity, cancer.

The biggest impact and difference was in the case of Toxicity, cancer (total) hardware production. SimaPro calculated a value of 1.18×10^{-7} CTUh and GaBi calculated 1.46×10^{-7} CTUh. In this process, GaBi uses a greater characterization factor for the substance Benzo(a)pyrene. During the production of hardware, a difference was also found in the inventory of the substance Anthracene. In SimaPro software, the characterization factor was non-zero, but in the case of GaBi, it was zero. These differences also apply in the case of Toxicity, cancer—organics. There was also a difference in the production of glazing. SimaPro calculated a value of 3.25×10^{-8} CTUh and GaBi 3.41 calculated $\times 10^{-8}$ CTUh in the impact category Human Toxicity, cancer (total). During this process, a different characterization factor was found for the substance Chromium (+VI), where it was slightly smaller for SimaPro than for GaBi. This fact also applies to Toxicity, cancer—inorganics. The other processes had only minimal differences of <5%.

Human Toxicity, non-cancer is divided in the same way as Human Toxicity, cancer into the impact categories Human Toxicity, non-cancer (total) and Human Toxicity, non-cancer—inorganics and organics (Figure 8). Human Toxicity, non-cancer (total) together with Human Toxicity, non-cancer—inorganics had a greater impact in SimaPro than in GaBi. On the other hand, in Human Toxicity, non-cancer—organics, GaBi had a greater impact than SimaPro. In Human Toxicity, non-cancer (total), SimaPro reached a value of 1.425×10^{-6} CTUh and GaBi reached 1.130×10^{-6} CTUh (difference 20.7%). In Human Toxicity, non-cancer—inorganics, the value of SimaPro was 1.366×10^{-6} CTUh and 1.061×10^{-6} CTUh in GaBi (difference 22.3%). The Human Toxicity, non-cancer—organics value was 1.370×10^{-7} CTUh in GaBi and 1.057×10^{-7} CTUh in SimaPro (difference 22.8%).

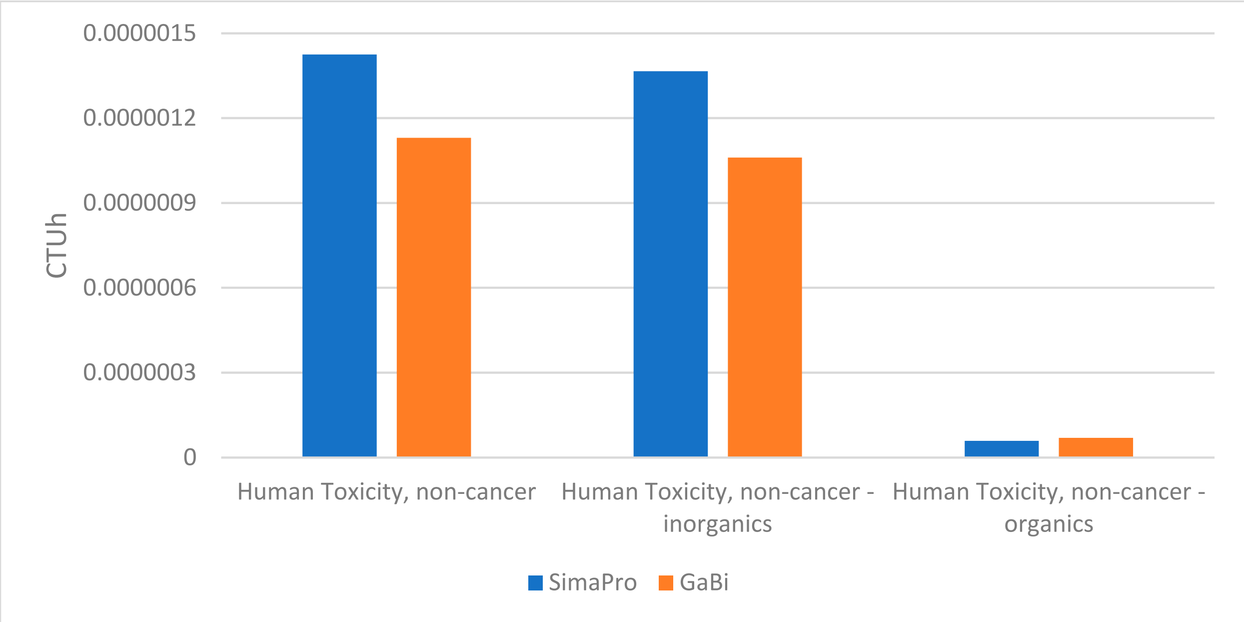

Figure 8. Human Toxicity, non-cancer.

The biggest contributor to the impact category Human Toxicity, non-cancer (total) was the glazing production process with a value of 5.1×10^{-7} CTUh for SimaPro and 5.32×10^{-7} CTUh for GaBi (a difference of 4.1%). The second biggest contribution was the scantlings manufacturing process. In the case of SimaPro, the value was 3.6×10^{-7} CTUh, and in the case of GaBi it was 7.7×10^{-8} CTUh. This process had the largest difference in all processes (78.5%). It was caused, like in the previous impact categories, due to the fact that GaBi did not include all background processes in the production of scantlings (glue production process). This is also the case with Human Toxicity, non-cancer—inorganics. In the case of transport, the value calculated by SimaPro was 2×10^{-7} CTUh, and for GaBi it was 1.7×10^{-7} CTUh. This difference is caused by the use of different databases. In the case of Human Toxicity, non-cancer—organics, the biggest impact and the most significant difference was in the case of glazing production. SimaPro calculated a value of 1.9×10^{-8} CTUh and GaBi calculated 2.6×10^{-8} CTUh. This difference is caused by different characterization factors for NMVOC unspecified (airborne emissions), where for GaBi, the value is non-zero (significant), and for SimaPro, it was zero. It should be noted that the second biggest impact was the production of the gasket (both SimaPro and GaBi calculated 1.2×10^{-8} CTUh). The other processes had only minimal differences of <5%.

In this case, in the impact category Land Use and Water Use, GaBi had a greater impact than SimaPro (Figure 9). The Land Use impact value for GaBi was 5429.204 Pt and for SimaPro it was 3822.573 Pt (difference 29.9%). For Water Use, the GaBi value was 34.143 m^3 depriv. and the SimaPro value was 28.776 m^3 depriv. (difference 15.7%).

The largest contributor to the Land Use impact category is the production of scantlings. In the case of SimaPro, it had a value of 3083.421 Pt, and in the case of GaBi, it had a value of 5041.581 Pt. The main differences are caused by different characterizing factors. The characterization factor in GaBi was significantly higher than in the case of SimaPro for Land Use, Occupation Forest Intensive. Also, the characterization factor for Land Use, Transformation, Forest Intensive, in the case of SimaPro, has larger negative values than in the case of GaBi (two orders of magnitude higher). The second largest impact was transport (420.361 Pt for SimaPro; 108.618 Pt for GaBi). This difference was caused by the use of different databases. The other processes had only minimal differences of <5%.

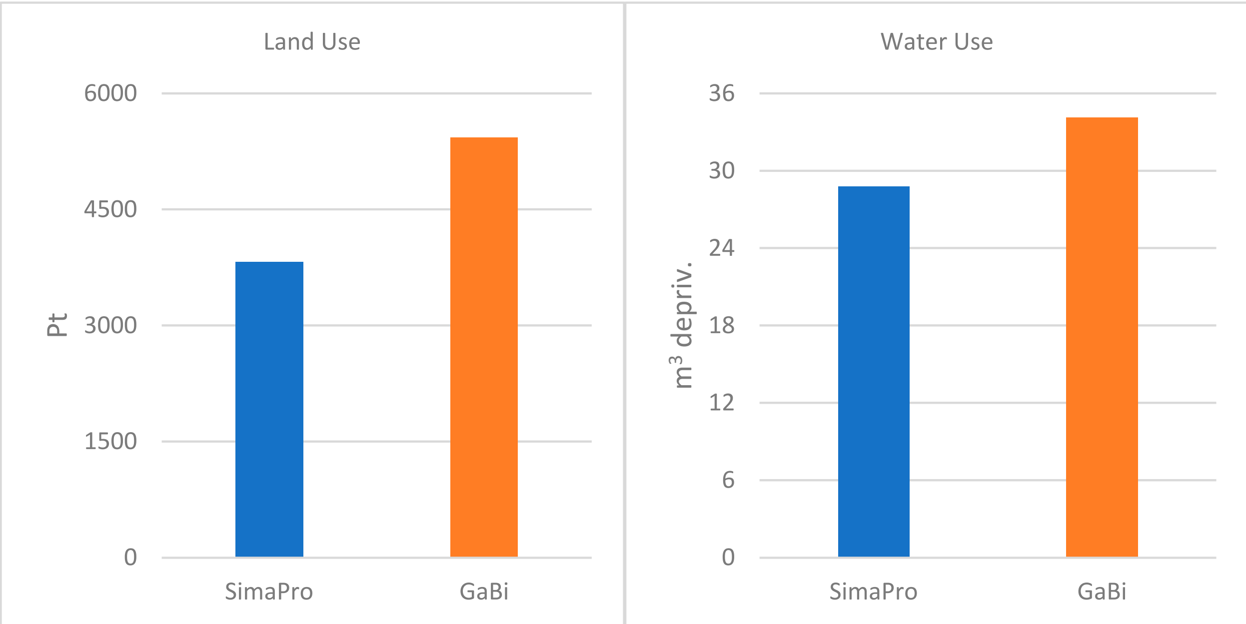

Figure 9. Land Use and Water Use.

For the Water Use impact category, the largest contributor was glazing production. SimaPro had a value of 12.129 m^3 and GaBi had a value of 16.289 m^3. The difference in this process is the fact that SimaPro also included negative characterization factors (positive influences) in the inventory, but GaBi did not. The second biggest influence was the production of hardware. But the differences were minimal (5.499 m^3 for SimaPro; 5.561 m^3 for GaBi). The other processes had only minimal differences of <5%.

For Photochemical Ozone Formation, the impact category values were approximately the same for both software (Figure 10). For SimaPro, the impact value was 0.626 kg NMVOC eq, and for GaBi it was 0.619 kg NMVOC eq (difference 1.1%). On the other hand, in the case of the impact category Ozone Depletion, the SimaPro software had a much greater impact. The Ozone Depletion value for SimaPro was 1.278×10^{-5} kg CFC11 eq, and for GaBi, it was 1.954×10^{-6} kg CFC11 eq (difference 84.7%).

Glazing production was the largest contributor for the Photochemical Ozone Formation impact category as well. SimaPro calculated a value of 0.205 kg NMVOC eq and GaBi calculated 0.229 kg NMVOC eq (10.5%). The difference was caused by a smaller difference in the characterization factor for NO_x. The second largest contributor was gasket production (0.170 kg NMVOC eq SimaPro; 0.172 kg NMVOC eq GaBi). The third process that had the greatest impact was transport. SimaPro calculated a value of 0.07 kg NMVOC eq and GaBi calculated 0.02 kg NMVOC eq. The difference was in the use of different databases. The other processes had only minimal differences of <5%.

In the case of Ozone Depletion, the biggest difference was in transport. In the case of SimaPro, the value was 5.63×10^{-6} kg CFC11 eq, and in GaBi, it was 2.483×10^{-12} kg CFC11 eq. The difference was caused by the use of different databases. Another significant impact was the production of glazing (4.50×10^{-6} kg CFC11 eq SimaPro; 1.06×10^{-6} kg CFC11 eq). These differences were due to different characterization factors for substances in this impact category. The hardware production process also had a visible difference. SimaPro calculated a value of 9.720×10^{-7} and GaBi had a value of 4.998×10^{-7}. This difference is caused by the fact that GaBi did not include all background processes, whereas SimaPro did. The other processes had only minimal differences of <5%.

In the case of Resource Use, the category is divided into two: Resource Use, fossils and Resource Use, minerals and metals (Figure 11). For Resource Use, fossils, the results were about the same, but GaBi had a slightly higher value. The value of GaBi was 1613.753 MJ, and for SimaPro, it was 1541.472 MJ (difference 4.5%). In Resource Use, minerals and metals, there was a greater difference and SimaPro had a higher value. The SimaPro value was 0.002 kg Sb eq, and for GaBi, it was 0.0005 kg Sb eq (75% difference).

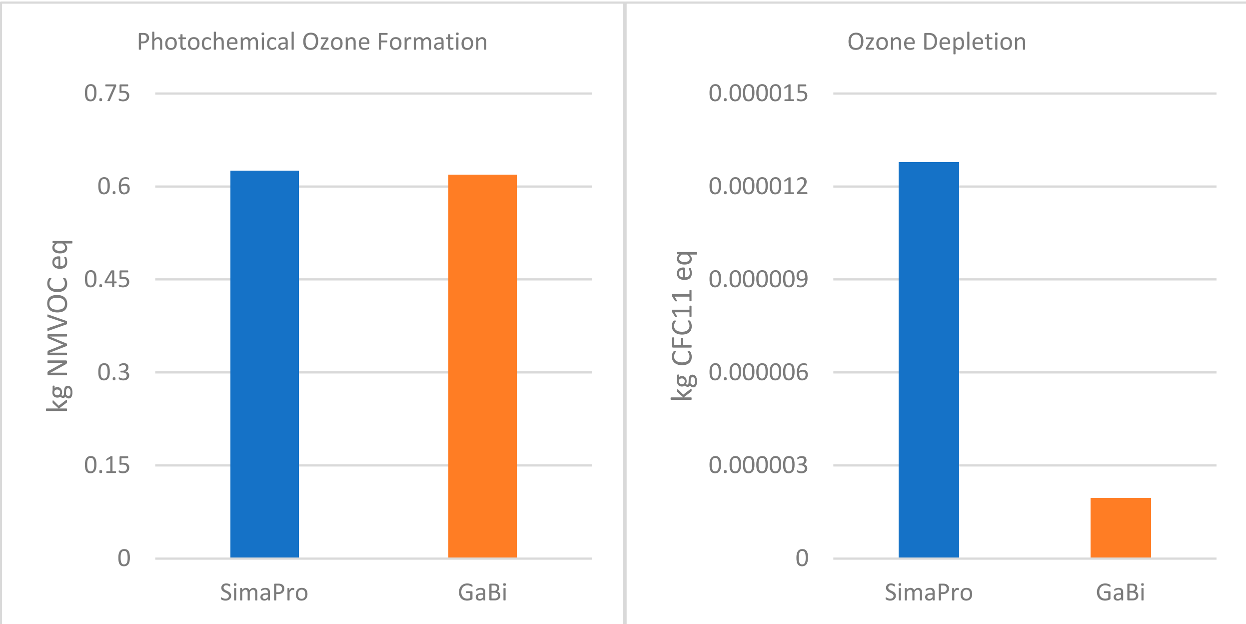

Figure 10. Photochemical Ozone Formation and Ozone Depletion.

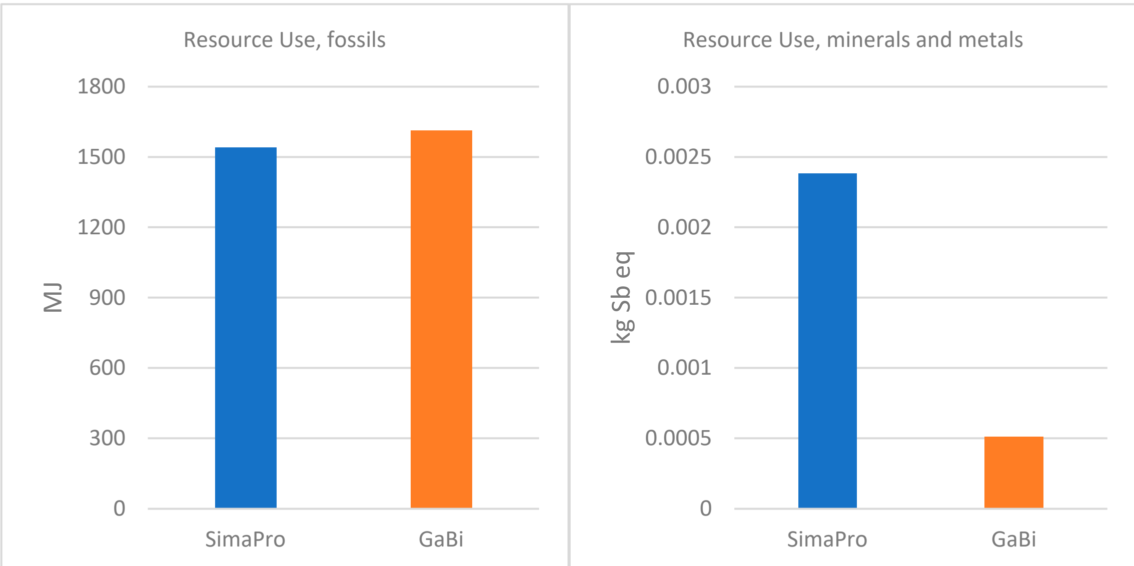

Figure 11. Resource Use, fossils and Resource Use, minerals and metals.

The biggest impact and difference in the case of the impact category Resource Use, fossils was the glazing production process. The glazing production process had a value calculated by SimaPro of 610.703 MJ and 673.770 MJ for GaBi. This difference was caused by different characterization factors for the use of fossil fuels. Some have larger characterization factories in the case of GaBi (Coal, hard; Lignite; Uranium). The other processes had only minimal differences of <5%.

For the impact category Resource Use, minerals and metals, the process of manufacturing scantlings had the largest contribution. SimaPro calculated a value of 0.0016 kg Sb eq and GaBi calculated 2.13×10^{-5} kg Sb eq. This difference is caused by the fact that GaBi did not include all background processes (glue production processes), whereas SimaPro did. The other processes had only minimal differences of <5%.

In the case of transport, a different process was used in each software. These results were obtained and calculated from selected software tools (SimaPro, GaBi) based on weight and distance, as shown in Table 1. As shown in Table 2, the differences in the values of the impact categories are in some cases very high (the most significant Ozone Depletion, Resource Use, minerals and metals, Human Toxicity, cancer—organics, Ionizing Radiation, Eutrophication, freshwater and Particulate Matter, respectively), which was also reflected in the overall difference in the impact categories.

The results of electricity production did not differ significantly for each impact category (<5%).

In practice, it is difficult to model the product system in various software tools during the LCA study due to limited time and resources. For this reason, it is essential that each LCA expert has a deep knowledge of the chosen software and is able to identify missing material flows and relevant differences in the impact assessment methodology. Regardless of the software chosen, it is necessary for LCA studies to inform the target audience of any limitations of the software and to specify how the author dealt with it.

Table 2. Differences in transport processes.

Impact Category	SimaPro	GaBi	Impact Category	SimaPro	GaBi
Acidification [mol H^+ eq]	0.071962204	0.023072	Human Toxicity, cancer [CTUh]	7.14×10^{-9}	3.78×10^{-9}
Climate Change [kg CO_2 eq]	22.43133305	19.41167	Human Toxicity, cancer—inorganics [CTUh]	4.26×10^{-9}	3.66×10^{-9}
Ecotoxicity, freshwater [CTUe]	121.5963485	186.1876	Human Toxicity, cancer—organics [CTUh]	2.87×10^{-9}	1.12×10^{-10}
Ecotoxicity, freshwater—inorganics [CTUe]	99.27048682	183.842	Human Toxicity, non -cancer [CTUh]	2.48×10^{-7}	1.68×10^{-7}
Ecotoxicity, freshwater—organics [CTUe]	22.3253124	2.345638	Human Toxicity, non-cancer—inorganics [CTUh]	2.38×10^{-7}	1.66×10^{-7}
Particulate Matter [disease inc.]	2.63129×10^{-6}	1.65×10^{-7}	Human Toxicity, non-cancer—organics [CTUh]	1.00×10^{-8}	1.55×10^{-9}
Eutrophication, marine [kg N eq]	0.015930564	0.00824	Ionizing Radiation [kBq U-235 eq]	1.87×10	7.31×10^{-2}
Eutrophication, freshwater [kg P eq]	0.00145078	6.98×10^{-5}	Ozone Depletion [kg CFC11 eq]	5.66×10^{-6}	2.48×10^{-12}
Eutrophication, terrestrial [mol N eq]	0.176334866	0.093935	Photochemical Ozone Formation [kg NMVOC eq]	6.92×10^{-2}	2.03×10^{-2}
Water Use [m^3 depriv.]	1.298615647	0.230719	Resource Use, fossils [MJ]	3.67×10^{2}	2.60×10^{2}
Land Use [Pt]	420.3608962	108.6179	Resource Use, minerals and metals [kg Sb eq]	5.00×10^{-5}	1.26×10^{-6}

4. Discussion

Given the gap in the literature for comparative analyses of complex case studies in the construction sector, this study was designed to investigate the impact of software selection on LCA results in the pre-use phase of a wood–aluminum window. The aim of the study was to test the output uniformity of two selected software tools. We consider the limitations of this study to be the use of a different database in the case of transport; manufacturer location in the case of transport; not including the use, maintenance and end-of-life phase; and the use of the Slovak energy mix. The authors are not aware of any publications that evaluate the differences between software tools in the case of windows only. Therefore, other publications are mentioned in the discussion, but mainly regarding the building sector.

Implementing a common methodology in different LCA software can give different results even if the inputs are as accurate as possible. The most common cause of differences between the implementation of LCIA methods in SimaPro and GaBi is that one software included characterization factors for substances that the other software excluded. There were also cases where both SimaPro and GaBi had non-zero characterization factors for the substance, but the factors were significantly different. Whenever there is a difference in characterization factors between software, there is a possibility that the impacts reported by the software will differ significantly in some comparisons and not in others [23].

In a study by Lopes Silva et al. [24], they studied the differences between four software tools (SimaPro, GaBi, openLCA and Umberto) on a simple example of particleboard manufactured in Brazil; they concluded that in each software, for each impact category, there is a different number of characteristics factors and subcompartments, which can generate different results. The authors state that the main sources of discrepancies are missing characterization factors in some software (characterization factors for chlorofluorocarbons (CFCs) and volatile organic compounds (VOCs) were only in SimaPro and openLCA) and different characterization factors for elementary flows. They also found that the root causes are based on the import process for the background datasets and the lack of rules or standards for implementing LCIA methods.

One of the biggest differences is in the type of dataset formats between the software and how the uncertainty and sensitivity of the results are assessed. The results of the Acidification and Photochemical Ozone Formation impact categories were up to 22.7% and up to 66.7% higher in SimaPro compared to other software tools (GaBi, Umberto and openLCA), respectively. In our study, the difference between the results of Acidification was 11.9%. Thus, depending on the software tool that the user chooses, LCA results can vary greatly. It should be noted that this study was conducted cradle-to-gate. When a cradle-to-gate or cradle-to-grave approach is modeled, the results are likely to have a larger variance due to the greater amount of uncertainty added from the use of background datasets [25]. As also shown in the results of our study, some impact categories have greater differences.

Sanjuan-Delmas et al. [26] studied surface mining and pyrometallurgical refining copper production in Europe using two software, SimaPro and GaBi, and two databases. They found that LCA results varied depending on the software and database used. For most impact categories, higher values were found using SimaPro software and the Ecoinvent database compared to GaBi. The biggest differences were in Abiotic Depletion, Human Toxicity and Ecotoxicity. They point out that deviations can be caused by differences in the databases used (environmental impacts that are considered to be avoided due to the substitution of raw material by recycled material); differences in the boundaries of the system (considering or not electricity imports and upstream impacts); the possibility that the combination of LCI and characterization factors might go wrong due to different names and/or CAS numbers; differences between emissions for specific substances and groups of substances; and additional characterization factors provided in the software.

A study by Emami et al. [27] studied the LCA of two residential buildings using two different LCA database–software combinations (SimaPro and GaBi). The authors found that the results of the ReCiPe LCIA method differ significantly between the two software in each impact category (compared to Pyry.). Only Climate Change (+16% for SimaPro), Photochemical Oxidant Formation (+2% for SimaPro) and Fossil Depletion (+9% for GaBi) achieved relatively similar results when comparing the two software, which was also the case in our study. The biggest difference was Water depletion (+4724% for GaBi). In our results, GaBi also had a significantly greater impact, but not to this extent (caused by using another LCIA method). Also, Ozone Depletion had a significant difference (+97% for SimaPro). In our study, the difference was at the level of 84.7%, which indicates very similar results (although their study is more complex than ours). In our case, with Particulate matter formation, the difference was 27.2%. The authors calculated a difference value of 40%, which is not a big difference considering the complexity of their study. Ionizing Radiation cannot be compared due to the use of a different energy mix and different units. In the case of Human Toxicity, Terrestrial acidification, Ecotoxicity, and Metal depletion, there were also different units. The results indicate that GaBi had a lower environmental impact than SimaPro (with a few exceptions such as Water Depletion and Fossil Depletion) overall, which also corresponds to the results in our study.

Pauer et al. [28] dealt with the influence of database selection on environmental impact results in the LCIA Environmental Footprint method. They examined the Ecoinvent database and the GaBi database. They found that these databases, together with the SimaPro and GaBi software, made a big difference in the LCA results. In the case of Climate Change, these differences are minimal, but in the case of other impact categories, these differences are more significant. They note that the results of the Ecoinvent database are, in most cases, significantly higher than those of the GaBi database. This fact was also shown in the results of our study. The authors cite the different system boundaries of some cases as reasons for these differences, with the Ecoinvent data containing significantly more background processes (e.g., infrastructure wear, maintenance work) than GaBi. In the case of the impact category Water Use, one of the reasons for the higher values is the use of a global characterization factor for water, which leads to inflated results if water is consumed in regions without water scarcity.

In the case of transport, GaBi has a significantly lower carbon footprint than SimaPro per tkm. In the case of a truck, GaBi has approximately 25% less impact on Climate Change. As in our study, GaBi has a much lower impact on Climate Change than SimaPro. It is further recommended that LCA-based studies focus on case-specific data and use a fit-for-purpose model [29].

5. Conclusions

This study was focused on the comparison of two LCA software tools in the production of a wood–aluminum window, and the goal was to test the output uniformity of the two selected tools. This study highlights the importance of databases used by LCA tools. The results can vary significantly depending on the databases used, highlighting the need for practitioners to verify the data sources used by the software. The LCA results typically cover multiple environmental impact categories. It is necessary to prioritize these impacts based on the scope of the study or regulatory requirements. Due to a gap in the literature, this study was designed to investigate the impact of software selection on the results of LCA in the pre-use phase of a wood–aluminum window. The results indicate that when using two different software for the same processes, the LCA results differed significantly for some impact categories. The study uses two different processes from two different databases only in the case of transport. The biggest difference (84.7%) was in the impact category Ozone Depletion, where the reason for the high difference was also the use of another process from the GaBi database, which had a significantly lower impact value for this category. The second biggest difference was in the case of the impact category Resource Use, minerals and metals, and the third biggest difference was in Ecotoxicity, freshwater—inorganics. The differences in LCIA results between SimaPro and GaBi primarily result from inconsistencies in the implemented characterization factors. This means that the software can assign different factors to specific impact categories, leading to potential variations in the calculated environmental impact profile. In the case of transport, however, the results show differences that correlate well with the overall results. These differences have been caused by different system boundaries in some processes, with the Ecoinvent data containing significantly more background processes. Regardless of the software chosen by the user, LCA studies alert the audience and decision-makers to any discrepancy regarding the software characteristics and declare how it was handled. An LCA from SimaPro and GaBi software should be interpreted with caution by practitioners and other interested parties. To achieve the reliability of LCA as a decision management tool, the cooperation of stakeholders, including software providers, to strengthen the transparency and consistency of LCA results is crucial. Future studies could extend the analysis to include the entire product life cycle, including the use and end-of-life phases, to provide a more comprehensive environmental assessment and should explore efforts to standardize databases and characterization factors used across LCA software to minimize differences in the results and ensure more consistent environmental assessments.

Author Contributions: Conceptualization: M.S. (Michal Sečkár); Formal analysis: M.S. (Michal Sečkár); Investigation: M.S. (Michal Sečkár) and A.P. (András Polgár); Methodology: M.S. (Michal Sečkár), M.S. (Marián Schwarz), and A.P. (András Polgár); Resources: M.S. (Michal Sečkár), M.S. (Marián Schwarz), and A.P. (András Polgár); Visualization: M.S. (Michal Sečkár); Writing—original draft: M.S. (Michal Sečkár); Project administration: M.S. (Marián Schwarz); Writing—review and editing: M.S. (Marián Schwarz), A.P. (András Polgár), and A.P. (Adam Pochyba); Supervision: M.S. (Marián Schwarz); Validation: M.S. (Marián Schwarz). All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the Internal Project Agency (IPA) of the Technical University in Zvolen, IPA 21/2024 Life Cycle Assessment of wood-aluminum window and Comprehensive Research of Determinants for Ensuring Environmental Health (ENVIHEALTH), ITMS 313011T721 supported by the Operational Programme Integrated Infrastructure (OPII) funded by the ERDF.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author/s.

Acknowledgments: Financial and non-financial interests: The authors declare no financial or non-financial interests. Employment: The authors declare no employment by an organization that may gain or lose financially. Declaration of generative AI and AI-assisted technologies in the writing process: During the preparation of this work, the authors did not use generative AI or AI-assisted technologies.

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

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