forests

Article

Environmental Assessment of Forest-Based Industry Products with CAD-Integrated LCA Tools: A Comparative Case Study of Selected Software

Katarina Remic [1,2,*], Leon Oblak [2], Manja Kitek Kuzman [2], Teja Bizjak Govedič [2] and Bojan Dolšak [1]

1 Faculty of Mechanical Engineering, University of Maribor, Smetanova ulica 17, 2000 Maribor, Slovenia; bojan.dolsak@um.si
2 Biotechnical Faculty, University of Ljubljana, Jamnikarjeva 101, 1000 Ljubljana, Slovenia; leon.oblak@bf.uni-lj.si (L.O.); manja.kitekkuzman@bf.uni-lj.si (M.K.K.); teja.bizjakgovedic@bf.uni-lj.si (T.B.G.)
* Correspondence: katarina.remic@bf.uni-lj.si

Abstract: The study evaluates how the environmental impacts of wooden products could be assessed in the early stages of product development using CAD-integrated life cycle assessment (LCA) tools. Focusing on a wooden chair design, the study compares the environmental impact results derived from LCA tools integrated in SolidWorks, NX and Fusion against a traditional LCA analysis performed using SimaPro. Methods involve analysing a chair model to measure the environmental impacts across different life cycle phases, such as material extraction and manufacturing. The results reveal that manufacturing processes, particularly electricity use, significantly contribute to environmental impacts, especially marine and freshwater ecotoxicity. Comparisons between LCA tools integrated into commercial CAD software and SimaPro 9.5.0.1. showed that while the tools deliver comparable results for global warming potential and other categories, they struggle with certain impact categories. The main distinguishing features of the results were methodological. Overall, the results aligned the most with the impact values calculated in Solidworks Sustainability. The study concludes that CAD-integrated tools are useful for early-stage environmental assessments but have limitations, particularly in their material databases and life cycle scope. For a comprehensive assessment, combining these tools with more detailed analysis methods may be necessary. The research suggests improvements for CAD-based tools to enhance their effectiveness in evaluating the environmental impact of wooden products.

Keywords: life cycle assessment; environmental impact assessment; wooden products; SimaPro; SolidWorks Sustainability; NX Sustainability; Fusion 360 Makersite; sustainable design

Citation: Remic, K.; Oblak, L.; Kitek Kuzman, M.; Bizjak Govedič, T.; Dolšak, B. Environmental Assessment of Forest-Based Industry Products with CAD-Integrated LCA Tools: A Comparative Case Study of Selected Software. *Forests* **2024**, *15*, 1909. https://doi.org/10.3390/f15111909

Academic Editor: Michela Nocetti

Received: 1 October 2024
Revised: 24 October 2024
Accepted: 27 October 2024
Published: 29 October 2024

1. Introduction

As the pressure on the environment has never been greater than in recent years and has led to various social and climatic crises [1], the European Union has adopted various strategies, such as the European Green Deal [2], to mitigate the threats. It emphasises the goal of reducing global warming and greenhouse gas emissions and making Europe a climate-neutral continent. The Net Zero Industrial Plan [3] is a companion document to the European Green Deal and focuses on the development of industry to achieve a sustainable, circular (bio)economy. However, it was recognised that the current industrial development strategy is not sufficient to achieve the EU's environmental goals. Therefore, the new concept of Industry 5.0 [4] was introduced, which focuses on the transition to a sustainable, people-centred and resilient industry. Sustainability is closely linked to the choice of materials and processes, while resilience can be achieved through digitalisation and automation.

In countries and regions with large forest areas, such as Slovenia, lignocellulosic biomass and wood-based industries are seen as a pathway to bio-circularity and a thriving economy [5,6]. Wood is seen as a promising substitute for many fossil fuel-based materials and could reduce dependence on them [7]. As wood-based industries are demonstrably more environmentally friendly than comparable fossil-based industries [2,3,8], they represent a solution for an industry that emits fewer greenhouse gases (GHGs) [9,10]. However, GHG emissions and other environmental impacts such as resource consumption or freshwater eutrophication caused by the production of wood products still need to be carefully monitored to avoid environmental trade-offs [11]. Life cycle assessment (LCA) is widely used to monitor the environmental footprint as it allows the assessment of the various impacts throughout the life cycle of a product—from raw material sourcing to waste treatment and final disposal [11,12]. The LCA analysis is a standardised method [13,14] and consists of four phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation. The method is often used for strategic planning, as a regulatory tool for legislation, for marketing purposes and for product development. It can be particularly useful for the latter, as most production processes with their environmental aspects of a product are already largely defined in the design phase and can be predicted, evaluated and partially avoided with the LCA [15,16]. However, carrying out a full LCA analysis is very time-consuming and therefore often not a suitable solution for product development in the manufacturing industry, where resources are limited. According to Delaney and Liu [17], only 18% of designers and engineers currently use LCA studies within their design processes. To make environmental impact assessment and regulations in the manufacturing industry easier, faster and more accessible, many leading computer-aided design (CAD) and computer-aided engineering (CAE) software companies have integrated LCA-like tools with supporting databases into their software [18,19]. With the digitalisation and automation of the industry, digital twins and virtual prototypes have become an important and widely used tool to study product performance, simulate the manufacturing process, evaluate the cost and check the overall feasibility of the design [18,20,21]. Therefore, the ecological assessment of already created virtual 3D models is the most logical, time-saving and economical solution. In addition, by adapting the 3D model, more environmentally friendly alternatives for a product can be evaluated in real time during the design/development phase.

Different software integrations offer different possibilities for impact assessment and are supported by different databases, so the results may vary depending on the tool used. The most commonly used CAD-integrated LCA tools are SolidWorks Sustainability [22–25], NX Sustainability impact analysis [19,26] and 3DEXPERIENCE Platform [27]. Researchers have already conducted a series of environmental tests on various product examples. SolidWorks Sustainability has been used for the evaluation of a raised floor system [28], a storage box [29], the design of a drone [30], the development of a solar tricycle [31], the evaluation of a plastic cap, a pinion shaft and a carter [32], the environmental assessment of steel pipes [33] and for the comparison of different battery packaging [34]. NX Sustainability impact assessment was used to evaluate the environmental performance of the engine hood and the possibility of environmental assessment for machined parts [35,36]. The possibilities of assessing the machining process with a CAD-integrated LCA tool were also discussed in a case study by Winter et al. [37] using the NX software. The 3DEXPERIENCE platform was used to evaluate the robotic arm [38] and in studies comparing different tools. For example, it was used in comparison to Eco Materials Adviser (Autodesk Inventor) and SolidWorks Sustainability [39]. Eco Material Adviser was also used in comparison to SolidWorks Sustainability to evaluate a plastic box [40]. Ren and Su [41] compared CES EduPack, SolidWorks Sustainability, Sustainable Minds, SimaPro and GaBi, while Dervishaj and Gudmundsson [42] presented a holistic comparison of the most common LCA-like plugins that are mainly intended for Building Information Modelling (BIM) but can also be used in some way for product design, such as plugins for Autodesk Revit, plugins for Grasshopper or the applications of One Click LCA. The G.EN.ESI Ecodesign platform was tested on a practical example of a cooker hood [43], while Top et al. [44] emphasised the advantages and possibilities of using LCA-like tools for additive manufacturing and compared the

ECO-it tool with more complex LCA software. Although the environmental impacts in architecture and construction can be predicted relatively well by using BIM [45–47], the adaptation of LCA-like tools for product assessment is more complex in some aspects because the variability of products is much greater and the supporting databases do not contain sufficient data. Therefore, some researchers focus exclusively on developing new methodological aspects of LCA analysis in CAD, CAE and CAM software [48–51].

Although there are some studies dealing with the use and comparison of CAD-integrated LCA tools, there is a lack of studies focusing on the assessment of wood-based materials using such tools. Adeyi et al. [52] compared the LCA results of SolidWorks Sustainability for a simple chair. The comparison was done for three different materials—mahogany wood, epoxy resin and galvanised steel—and the wooden chair was found to be the most environmentally friendly option. To the best of our knowledge, there are no studies comparing different LCA tools for wood products, although wood manufacturing is considered an important industry for the development of the circular economy. Wood as a raw material is very heterogeneous and wood products differ greatly in terms of manufacturing processes, (secondary) materials used and overall complexity. Therefore, the software and integrated LCA tools, which were not originally developed for the wood processing industry, may not be sufficient to assess the environmental impacts of wood products.

The aim of this study is therefore to evaluate and compare the LCA tools of selected CAD software specifically for the environmental assessment of wood products. In contrast to previous studies on various materials, this study provides unique insights into the capabilities of these sustainability assessment extensions specifically for wood products, which have not been investigated in the existing literature. In addition, the calculated impacts of each CAD software are compared with the environmental impacts calculated in the LCA software. In this way, the study introduces a new approach to evaluating the performance and accuracy of CAD-integrated LCA tools by directly comparing the results of the integrated tools with the results of the LCA software in a realistic scenario that also includes the entire life cycle, as opposed to previous studies that at best rely on comparing the environmental impacts of material inputs. The study also emphasizes the benefits of this approach, which simplifies environmental impact assessment at an early stage of the design process and has practical implications for sustainable product development.

2. Materials and Methods

In a theoretical case study on the 1960 wooden chair named Rex (Ljubljana, Slovenia), designed by a pioneer of Slovenian industrial design Niko Kralj [53], the results of the environmental analysis using various CAD-integrated LCA tools are compared with the results of the LCA carried out in the SimaPRO 9.5.0.1. software. Firstly, LCI was created based on a 3D model analysis of the parts (volume, mass, etc.) and an approximation of the chair's manufacturing processes. Secondly, the LCA analysis was performed using SimaPRO software and LCA-like tools in SolidWorks 2024, NX 2306 and Autodesk Fusion 2.0.20476. The LCA analysis was performed according to EN ISO 14040:2006 [13] and EN ISO 14044:2006 [14]. The chair used in this study is particularly suitable for such an evaluation and comparison as it is made of bent veneer (plywood), solid hardwood and some metal elements, thus combining a variety of materials used in the wood industry in a single product.

2.1. LCA Study

2.1.1. Goal and Scope Definition

The aim of the LCA analysis presented in this paper is to assess the environmental impact of a designer wooden chair so that the results of the calculated emissions can be compared with the results of various CAD-based LCA tools. The functional unit of the LCA study is defined according to the objective as the production and functionality of one wooden chair for its life cycle.

As different tools include different life cycle phases, e.g., the cradle-to-gate or the cradle-to-grave approach, the original LCA is split into three parts: impacts of the raw materials, cradle-to-gate approach and cradle-to-grave approach. The choice of life cycle approach for comparing the results therefore depends on the capabilities of the software in question. The cradle-to-gate approach covers the phases and processes from material acquisition to the end of production, while the second additionally includes the use phase and the end-of-life scenario. The LCA analysis serves as a reference point for the evaluation of selected LCA-like tools. In addition, a Monte Carlo uncertainty analysis is performed for the LCA analysis, which enables a better comparison of the results.

The data used in the study is secondary and comes from other studies and/or the Ecoinvent 3.9.1 database. The calculations were carried out using SimaPro 9.5.0.1 software. The system boundaries (Table 1) include (1) production of the seat and backrest mouldings; (2) production of the seat and backrest; (3) preparation of the wood; (4) legs and aprons production; (5) surface treatment of the parts; (6) assembling; (7) use phase; and (8) disposal scenario. The system boundary data for points (1) to (6) are identical for the cradle-to-gate and cradle-to-grave approaches, while points (7) and (8) are only included for the cradle-to-grave approach. The impact assessment (LCIA) is calculated and evaluated on the basis of the ReCiPe 2016 [54] method. This method was chosen because it allows a wide range of different categories to be analysed, but still has a manageable scope. Moreover, it is widely used and therefore allows the results to be compared with other studies [54]. It describes emissions at midpoint level with the following impact categories: climate change, stratospheric ozone depletion, ionizing radiation, fine particular matter formation, photochemical oxidant formation (ecosystem quality), photochemical oxidant formation (human health), terrestrial acidification, freshwater eutrophication, human toxicity (cancer), human toxicity (non-cancer), terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, land use, water use, mineral resource scarcity and fossil resource scarcity. The influencing factors of an individual midpoint category on the endpoint results depend on the chosen perspective (individualistic, hierarchical, egalitarian). For our study, the hierarchical (H) perspective was chosen, which is the standard perspective and takes into account the time frame of 100 years. In addition, the system was analysed using the Centre for Environmental Studies (CML) [55] and Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) [56] methods to ensure a better comparison with the results of the CAD tools, as some, such as SolidWorks Sustainability, use special calculation methods and/or different units of impact measurement than ReCiPe.

2.1.2. LCI

The LCI for the Rex 1960 wooden chair (Figure 1) contains the system parameters listed in Table 1. The total energy consumption associated with the manufacturing processes is based on the installed power of the machine and the estimated time required for processing with each machine. Wood residues, e.g., sawdust, trimmings, etc., are defined as avoided products in the system and are not considered, for example, as energy recovery potential. The study is geographically limited to Slovenia, so it is assumed that all transport is regional. All wood and glue are purchased directly from the manufacturer, so no market activities are taken into account. For the metal materials, on the other hand, only market activities and no production processes are taken into account, as they are made from recycled metals. Table 1 shows the parameters for a set of mouldings. However, it is assumed that the moulds for bending plywood for the seat and backrest are sufficient for a hundred thousand chairs, so that only one-hundred-thousandth of the impacts were included in the final calculations for a single chair. The use phase does not include maintenance work such as touching up the paint or replacing the screws. It is assumed that 30% of the chair is disposed of in a landfill and 70% is incinerated [65,66].

Table 1. LCI for Rex 1960 wooden chair.

LCA Section	Parameters	Specification	Quantity [57–64]
1	Transport of the wood	Lorry 16–32 metric ton, EURO 6	45 km
	Transport of the glue	Lorry 16–32 metric ton, EURO 6	80 km
	Sawn wood (Ljubljana, Slovenia)	Hardwood, dried	0.121 m^3
	Glue (Sežana, Slovenia)	Urea formaldehyde	0.188 kg
	Stainless-steel plate (Ljubljana, Slovenia)	Market activity	6 kg
	Electricity	SI mix, for CNC milling	36.25 kWh
	Recycling of the stainless steel	For the plate production	6 kg
2	Plywood (Ljubljana, Slovenia)	Production	0.02 m^3
	Electricity	SI mix, for bending in a hydraulic press and for CNC milling	8.58 kWh
	Water	For cleaning the glue residues, SI origin	0.001 m^3
	Wastewater treatment	From plywood production	0.001 m^3
	Transport of the plywood	Lorry 16–32 metric ton, EURO 6	45 km
3	Sawn wood (Ljubljana, Slovenia)	Hardwood, dried	0.005 m^3
	Electricity	SI mix, for cutting to size and planning	9.4 kWh
	Transport of the wood	Lorry 16–32 metric ton, EURO 6	45 km
4	Electricity	SI mix, for CNC milling, drilling and planning	19.41 kWh
5	Transport of the paint	Lorry 16–32 metric ton, EURO 6	45 km
	Paint (Domžale, Slovenia)	Water-based	0.12 l
	Electricity	SI mix, for spray painting and sanding	12.23 kWh
	Water	For cleaning varnish residues, SI origin	0.001 m^3
	Wastewater treatment	From spray-painting	0.001 m^3
	Volatile organic compounds (VOC)	Emissions to air	0.6 kg
6	Screws (Ljubljana, Slovenia)	Recycled iron scrap	59.52 g
	Market for screws	Market activity	59.52 g
	Electricity	SI mix, for assembling	0.065 kWh
7	Transport of the chair	To the household, passenger car, diesel	45 km
8	Transport (Ljubljana, Slovenia)	To the disposal site, lorry 16–32 metric tons, EURO 6	60 km

2.2. SolidWorks Sustainability

Depending on the software licence, the SolidWorks (SW) software is supplied either with SustainabilityXpress or with the Sustainability tool. The latter offers the option of evaluating assemblies, while the Xpress version only allows the evaluation of parts made from a single material. The integrated tool is supported by the GaBi database and also allows the setup data of a product to be exported directly to the GaBi LCA software. In addition to exporting to GaBi, the results, which include the carbon footprint (measurement of the equivalent of emitted CO_2 in kg), energy consumption (measurement in MJ), water eutrophication (measurement of the equivalent of emitted PO_4 in kg) and air acidification (measurement of the equivalent of emitted SO_2 in kg), can be calculated using the CML or TRACI method.

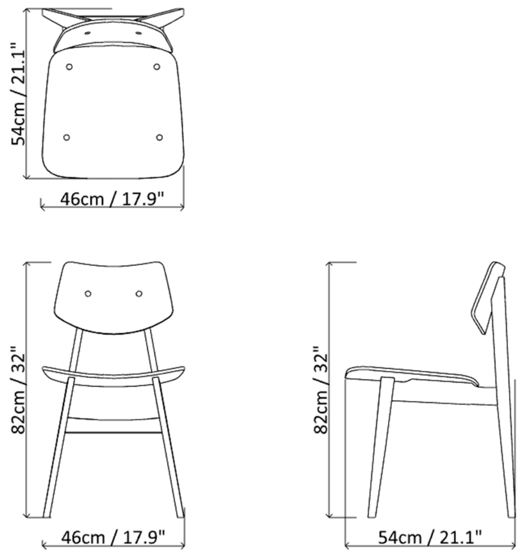

Figure 1. Technical drawing of Rex 1960 wooden chair. Adapted from Rex [53].

The tool makes it possible to define the entire life cycle of a product, including the input materials, production, use phase, transport and end-of-life scenario. The materials for each part are defined at the beginning. The integrated database includes the following wood materials: balsa, beech, cedar, mahogany, maple, oak, pine, teak, particleboard, KLH, OSB, particleboard and wood flooring laminate. Oak was chosen for the legs and aprons, and particleboard was chosen for the seat and backrest, as plywood is not available. The surface of all wooden parts was treated with water-based paint. The electricity consumption was specified in the Custom Process option for each part according to the calculated consumption (Table 1). The screws were defined as stainless steel (AISI 304) and milling was chosen as the production process, leaving the setting for the process at standard. Europe was defined as the region of production and use for all materials in the assembly. All parts (as well as the assembly) were designed for a service life of 100 years. Secondly, the assembly process was defined. Here too, Europe was defined as the area of application. The electricity requirement for the assembly process was determined, as was the transport of the assembled chair, which includes both transport to the household and transport at the end of the service life. By determining the duration of use, the software calculates the quality factor by which it then multiplies all environmental impacts. For this study, the service life was set at 15 years, as studies show that the average lifespan of furniture is around 10–15 years [67].

2.3. NX Sustainability Impact Analysis

The sustainability module for NX offers a wide range of analysis options. One of them is the environmental impact assessment, which enables the evaluation of the following categories: climate change (measurement of the equivalent of emitted CO_2 in kg), total consumption of non-renewable primary energy (measurement in MJ), freshwater consumption (measurement in m^3), human toxicity (cancer and non-cancer, measurement in CTUh), freshwater eutrophication (measurement of the equivalent of emitted P or N in kg). The results of the analysis can be calculated for default assigned materials (A), nominal values; for recycled materials (RC), the designed product is considered to be made from recycled materials; or for renewable materials (RN), the calculations assume that the designed product is made from materials that can and will be reused.

Sustainability scores are calculated based on the assigned materials from the connected library. The library provided by NX can be extended by either creating new materials in NX or uploading the library with defined third-party materials, which is by far more accurate. The standard library for sustainability includes the following wood-related materials: paper, cardboard and wood. We wanted to test the default option of the software and therefore used "wood" to describe the legs and aprons as well as the seat and backrest. To also account for the glue in the plywood, we assigned phenol-formaldehyde resin to an additionally modelled, box-shaped element that represented the proportion of glue in our model. AISI 304 was chosen for the screws.

2.4. Fusion Makersite

Fusion 360 enables the integration of various add-ons. In addition, the SimaPro API supports the assessment of 3D models from Fusion via an online platform based on the Ecoinvent database. However, direct environmental assessment is possible with the Makersite add-on. Based on the predefined materials from the integrated material library in Fusion, Makersite enables the creation and export of the bill of materials (BOM). The Fusion library includes the following wood materials: ash, birch, cherry, maple, jarrah, lauan, mahogany, white oak, red oak, poplar, spruce, teak, walnut, redwood, Douglas fir, Scots pine, radiata pine, Scots pine, southern pine, LVL, MDF, particleboard, plywood, softwood, construction timber and wood flooring. Depending on the selected materials, the AI-based tool finds corresponding materials from the external database. It also recommends more environmentally friendly substitute materials based on the analysed category—the carbon footprint (measurement of the equivalent of emitted CO_2 in kg).

White oak (*Quercus alba* L.) was chosen for the legs and aprons, while plywood was selected for the seat and backrest. AISI 304 was chosen for the screws. Although the plywood is included in the Fusion library, the Makersite did not recognise the plywood when the bill of materials was exported and the calculations were therefore not possible. For this reason, particleboard was chosen instead of plywood.

3. Results and Discussion

3.1. LCA Results

The results of LCA analysis using SimaPRO software for the entire life cycle of the 1960 Rex chair were calculated and normalized according to the global average, which enabled us to compare the results from different impact categories (with different units). The highest values of impacts were found for marine ecotoxicity, following freshwater ecotoxicity and human carcinogenic toxicity (Figure 2). The most influential contribution to these categories turned out to be the electricity consumption for the manufacturing processes, more precisely, pollution with heavy metals due to the production of electricity from the coal-fired power plant [68], which accounts for a significant share—21% [69,70]—of the electricity mix in Slovenia. Other processes and material inputs in the system account for a much smaller share of the impact on the environment and generally represent an insignificant proportion of the impact categories.

Figure 3 shows a comparison of the normalized results, taking into account the different life cycle aspects (impact of raw materials, cradle-to-gate approach and cradle-to-grave approach). The share of raw material impacts in the overall life cycle is up to 5%. Particularly low impacts from raw materials (less than 1% of total life cycle impacts) were found in the categories of ionizing radiation, freshwater eutrophication, freshwater ecotoxicity, marine ecotoxicity, carcinogenic human toxicity and non-carcinogenic human toxicity, and the highest impacts were found for land use (4.6%), mineral resource scarcity (3.7%) and stratospheric ozone depletion (3.6%). On the other hand, the manufacturing processes of the product were responsible for more than 80% of the total life cycle impacts in the following categories: ionising radiation, particulate matter formation, soil acidification, freshwater eutrophication, carcinogenic human toxicity, land use, depletion of mineral resources and water consumption. The use phase and end-of-life scenario proved to be the most influential in the freshwater and marine ecotoxicity categories (around 55%). In the other categories, the impacts were significantly lower. The results on the most influential processes and the impact categories with the highest values are consistent with the studies focusing on the environmental assessment of wooden products [71–73].

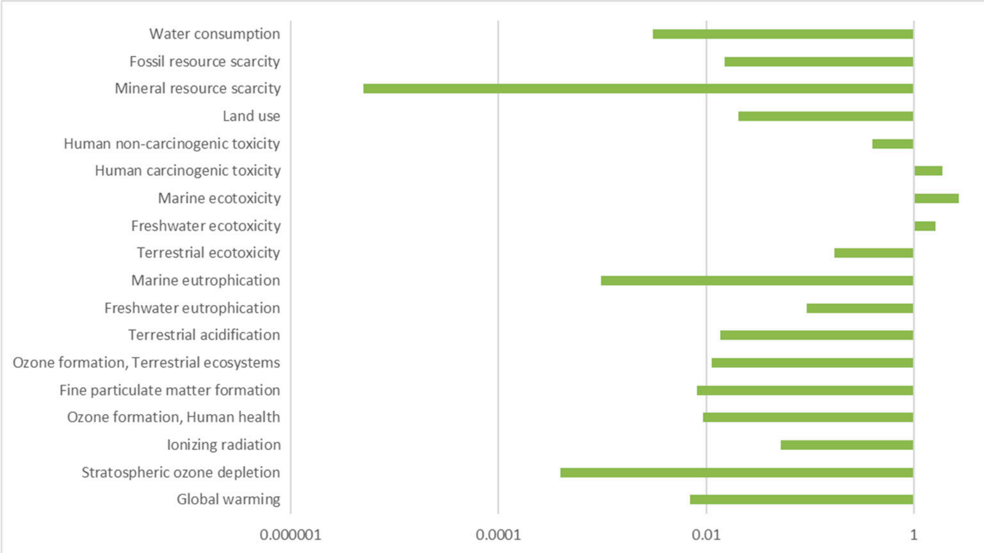

Figure 2. Normalized values of the impact categories on the logarithmic scale.

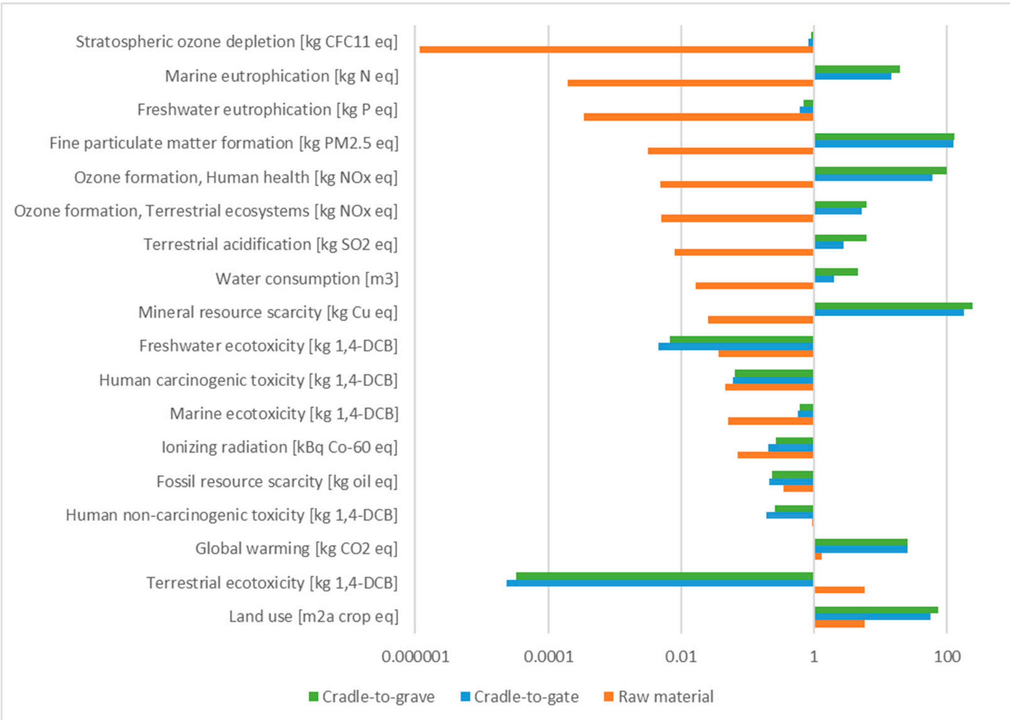

Figure 3. Characterized values of the impact categories for impacts of raw materials, cradle-to-gate approach and cradle-to-grave approach on the logarithmic scale.

3.2. Results of CAD-Integrated LCA-like Tools

3.2.1. Raw Material Impacts

Table 2 shows the midpoint results of the comparison of the linked categories (global warming, acidification, freshwater eutrophication, human toxicity) for the impacts of raw materials. Not all categories could be linked or assessed with all selected methodological approaches, either because the LCA-like tool does not allow the assessment of a specific category or because different units of measurement are used. However, for the impacts of raw materials, the Global Warming (GW) category can be linked for all programmes assessed. The impact category Freshwater Eutrophication (FWE) can be linked in SimaPRO, SW and NX, but the possibility of eutrophication calculations is not included in Fusion. In addition, the ReCiPe method calculates FWE in other units (kg P to freshwater). Therefore, only the CML and TRACI methods can be compared as they present the results in the same unit as the CAD tools (kg N to freshwater). The acidification category (AC) can be linked between SimaPRO and SW. NX and Fusion, on the other hand, do not allow calculations in this category. Human toxicity (HT) is not provided as a calculation option in SW and Fusion. However, the introduction of the TRACI method in SimaPRO means that human toxicity (HT) can be compared with the results from NX. Again, the ReCiPe method calculates HT in different units (kg 1,4-DCB to urban air) than NX and/or TRACI (CTUh).

Table 2. Comparison of raw material impacts calculated in SimaPRO and selected software.

Impact Category	SimaPRO			SW	NX			Fusion
	ReCiPe	CML	TRACI	CML	A	RC	RN	
GW [kg CO_2 eq]	1.291	1.274	1.266	1.256	0.313	−0.914	−0.533	1.36
FWE [kg N eq]	-	0.0022 [1]	0.004	0.0022 [1]	0.0039	0.001	0.0031	-
AC [kg SO_2 eq]	0.0079	0.0096	0.0095	0.06	-	-	-	-
HT [CTUh]	-	-	15×10^{-8}	-	9×10^{-8}	7×10^{-8}	9×10^{-8}	-

[1] The unit for CML methodology is kg PO_4 eq.

The global warming results in SimaPRO for the impacts of raw materials provided us with similar values for all methods. The Monte Carlo simulations for a 95% confidence level gave a range of values between 1.202 and 1.382 kg for the ReCiPe method, a range between 1.191 and 1.359 kg for CML and a range between 1.188 and 1.357 kg for TRACI. The SW results showed similar values to the median values of the SimaPRO software, while the Fusion Makersite results were at the upper end—around the 97.5th percentile of the values of the SimaPRO calculations. In both CAD programs mentioned, plywood was not available in the material library and had to be replaced by an alternative—particleboard. LCA studies dealing with the environmental impact of the production of wood-based materials such as plywood [74], particleboard [75], MDF [76], etc., can confirm that the production impacts of the different composites are generally quite similar, especially in the global warming category. Therefore, the expansion of wood-based materials in libraries, while urgently needed, is not an absolute barrier to rapid environmental assessment of designs using wood-based materials.

The results of NX Sustainability gave us negative values for the scenarios with recycled and renewable material and a positive value for the material assigned as default, which was, however, much lower compared to SimaPRO, SW or Fusion. The material »wood« is defined in the NX library with a negative carbon footprint as it takes into account the carbon neutrality (carbon negativity) of wood, which can be considered due to the ability of wood to absorb CO_2 during the growth phase. The absorbed biogenic carbon then remains almost completely integrated into the cell walls throughout the life cycle of the wood until combustion or decay. Taking this into account, a considerable amount of CO_2 emissions can be avoided by using wood instead of other materials that already release significant amounts of CO_2 in the raw material extraction phase. On the one hand, this is a major advantage of NX for the assessment of wood products, as carbon storage is already taken into account and no further calculations are required. On the other hand, however, the calculations in SimaPRO (Figure 3, Table 3) have shown that for wood products, the manufacturing processes have the greatest influence on the emissions during the entire life cycle and that the consideration of the raw material alone can therefore be misleading. It is methodologically correct to consider carbon neutrality, but this should always be done within a certain time frame, as the choice of wood as a raw material does not completely avoid CO_2 emissions, but postpones them until the wood is burnt or decomposes.

Table 3. Comparison of impacts from cradle-to-gate and cradle-to-grave life cycle approaches calculated in SimaPRO and Solidworks Sustainability.

Impact Category	SimaPRO		SW	SimaPRO		SW
	ReCiPe	CML	CML	ReCiPe	CML	CML
	Cradle-to-gate			Cradle-to-grave		
GW [kg CO_2 eq]	56.27	55.68	56	73.82	72.766	65
FWE [kg PO_4 eq]	-	0.2238	0.0208	-	0.290	0.027
AC [kg SO_2 eq]	0.5672	0.6798	0.204	0.616	0.741	0.227

The calculations of freshwater eutrophication resulted in similar values for the material impacts in NX and SimaPRO (TRACI method). The values calculated in NX as assigned values are consistent with the 95% confidence interval, which ranged from 0.0037 to 0.0042 kg (TRACI). The values considering the recycling or renewable materials scenario were significantly lower. The results from SW showed identical values to the results calculated using the CML method, which otherwise ranged from 0.0020 to 0.0023 kg.

The results for acidification showed slightly higher values in SimaPRO than in SW, and the SW results did not fall within the range of the values calculated with Monte Carlo simulations, which were between 0.007 and 0.008 kg for ReCiPe, between 0.009 and 1.03 kg for CML and between 0.009 and 0.01 kg for TRACI. In contrast to the global warming category, the differences in acidification can be explained by the choice of alternative material to plywood, as the comparison of the studies by Puettmann et al. for plywood [74] and particleboard [75] production showed higher values for the acidification category for particleboard. Therefore, for categories where not only global warming is assessed, the inclusion of more wood-based materials in the library is crucial.

The human toxicity results were similar for SimaPRO (TRACI method) and NX but were not within the uncertainty interval (14×10^{-8}–16.2×10^{-8}), but well below it. Considering that the materials for the chair were simplified and defined as wood and phenol-formaldehyde resin, the electricity otherwise required for the production of wood composites was not considered and there is no way to account for it. For otherwise health-compatible products and production systems, electricity is usually the most influential factor for the human toxicity categories [77], hence the difference. This also shows the need to expand the material libraries.

3.2.2. Cradle-to-Gate and Cradle-to-Grave Approaches

The results for the comparison of the cradle-to-gate approach and the entire life cycle of the chair are shown in Table 3, whereby only a comparison of the results from SimaPRO and the results from SolidWorks Sustainability was possible.

The results of the cradle-to-gate approach are almost identical for the GW median values calculated with SimaPRO and the values calculated with SW. For the entire life cycle (cradle-to-grave approach), the results vary slightly and are lower in SW. However, taking into account the uncertainty of the SimaPRO results, the value is within the 95% confidence interval, as the range of impacts for ReCiPe is 65.17–83.77 kg CO_2 eq and for the CML method is 64.29–81.29 kg. The results of FWE and AC are significantly lower in SW for both the cradle-to-gate and cradle-to-grave approaches. However, it must be emphasized that SolidWorks Sustainability calculates emissions based on the quality factor, which is determined by the durability of the product and the actual lifespan. In practice, this is an extremely useful solution for calculating the impact, as no additional calculations are required regarding the multiple inputs of the product within our time frame (functional unit). However, it has a considerable impact on the results if only a "theoretical" LCA is carried out. The LCA tool is therefore more suitable for the sustainable product development of a single product than for comparisons with other products, especially if their lifespan is different.

SimaPRO also found that the most influential factor for eutrophication (and most other categories) throughout the chair's life cycle is electricity consumption. All impacts strongly depend on the chosen electricity mix, which we cannot determine exactly for each country in the SW software. However, we can select the continent/region, such as Europe or Asia, where the manufacturing or assembly takes place and consequently where the energy is consumed. The differences in the impact values can therefore also be partly explained by differences in the electricity mix used for the assessment.

The applicability of the results for the future development of sustainability assessment and sustainable design can be seen in many dimensions. Firstly, the methodology for testing the suitability of the linked databases and the calculation results in the CAD tools should be based on the comparison of environmental impact values for actual product scenarios, also in the context of just the raw material impacts, in order to avoid unexpected trade-offs and burdens of not taking into account significant impacts (e.g., some extraction processes or initial transport). As for the LCA-like tools themselves, the biggest shortcoming seems to be that most software programmes can only calculate the impacts of raw material inputs. This is a major limitation in the calculations, especially for wood products. Therefore, not only the material libraries should be expanded, but also the databases linked to the tools with the processes that are already described in the intended LCA databases. Another challenge in calculating emissions from production processes is electricity consumption. The LCA results show that electricity consumption has a large influence on the impact, which varies depending on the source or mix of electricity. As the industry develops sustainably, the software should be adapted accordingly to provide the ability to define the source of electricity consumption—either the national (regional) electricity mix or other sources, e.g., many companies have their own solar installations or other renewable power plants. If these tools are developed to assess products more holistically, they could be better integrated into the industry and ultimately used to promote sustainability policies, as the reference data would be much easier and quicker to obtain compared to conducting a full LCA. In the context of wood product development, in addition to general impact assessment, such a tool could be used primarily to highlight the weak points of industrial processes that have the greatest impact compared to raw material extraction, thus helping to improve the sustainability of the processing industry as a whole, e.g., in the wood industry.

4. Conclusions

The study provided a comprehensive comparison of environmental impacts using three CAD-integrated LCA tools—SolidWorks Sustainability, NX Sustainability Impact Analysis and Auto-desk Fusion 360 Makersite—based on a practical case study of the 1960 Rex wooden chair. The effectiveness of these tools in assessing the environmental impact of a wood product was compared with the results of a traditional LCA conducted using SimaPro software. The aim was to evaluate whether and to what extent these CAD extensions are suitable and reliable to assess the environmental footprint of wood products in the categories of global warming/GWP), freshwater eutrophication (FWE), acidification (AC) and human toxicity (HT).

The LCA of the wooden chair, carried out using the SimaPro software (cradle-to-grave approach), has shown that the greatest environmental impact is due to marine ecotoxicity, followed by freshwater ecotoxicity and human carcinogenic toxicity. The main contributor to these impacts is electricity consumption during the manufacturing process, which accounts for more than 80% of the total life cycle impact. In contrast, the environmental impact of raw material extraction accounts for less than 1% of the total life cycle impact. GWP results were consistent across SimaPRO, SolidWorks and Fusion 360, while NX had a negative carbon footprint for wood, indicating carbon neutrality. The results for freshwater eutrophication were most consistent in SimaPRO and SolidWorks, while the results for acidification were slightly higher in SimaPro. A cradle-to-gate and cradle-to-grave comparison was only possible between SimaPRO and SolidWorks, highlighting the limitations of the other tools for complete LCAs. Overall, the GWP results of the different approaches were similar, but SolidWorks Sustainability provided significantly lower impacts for eutrophication and acidification.

It is important to note that categories such as marine and freshwater ecotoxicity, which had the highest values in the SimaPRO calculations, are not considered in the LCA-like tools. For wood products, however, the inclusion of energy consumption in the manufacturing phase would be even more necessary, as the main environmental impacts of wood products, unlike metal products, occur in the manufacturing phase and not in material sourcing. This would also solve the dilemma of carbon negativity, which is taken into account in NX sustainability. Finally, more wood-based materials should be included in the material libraries, especially if categories other than GW are included, as this has proven to be influential. We can therefore conclude that all tested CAD programmes are suitable for environmental impact assessment in the early stages of product development, but currently have some limitations that should be considered. Therefore, for each project, it is necessary to predict which specific environmental impacts are most important for the particular project and adapt the calculation and choice of software accordingly.

In conclusion, the study has provided several important insights. The need for expanded material libraries, especially for wood-based products, to ensure accurate LCA results for a wider range of impact categories. More detailed mapping of production processes, especially electricity consumption, is essential for improving the accuracy of LCAs in CAD-integrated tools. While NX's consideration of the carbon neutrality of wood is valuable, it needs to be balanced by a full life cycle approach to avoid misleading conclusions. The tools assessed have the potential for rapid environmental assessment at the design stage but need to be further developed for wider and more reliable use, especially in industries with complex production processes such as wood product manufacturing. This could lead to a more comprehensive assessment that provides a better basis for sustainable design practices. In addition, the clarity of the calculations, methodology and entities behind the results of the respective software should be presented upfront and in more detail.

These findings contribute to the growing field of sustainable product design by providing practical recommendations for improving life cycle assessment methods and the integration of CAD tools, ultimately improving the accuracy and usability of environmental impact assessments in industrial applications.

Author Contributions: Conceptualization, K.R. and B.D.; methodology, K.R., T.B.G., M.K.K. and L.O.; software, K.R. and B.D.; validation, B.D., M.K.K. and L.O.; formal analysis, K.R., T.B.G. and B.D.; investigation, K.R. and B.D.; resources, B.D., M.K.K. and L.O.; data curation, K.R. and B.D.; writing—original draft preparation, K.R. and T.B.G.; writing—review and editing, K.R., B.D., T.B.G., M.K.K. and L.O.; visualization, K.R. and T.B.G.; supervision, B.D., M.K.K. and L.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Public Agency for Scientific Research and Innovation of the Republic of Slovenia (ARIS), within the framework of the program Wood and lignocellulosic composites (P4-0015).

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

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

References

1. UN General Assembly. Transforming Our World: The 2030 Agenda for Sustainable Development. 2015. Available online: https://sdgs.un.org/2030agenda (accessed on 12 April 2024).
2. EC. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions The European Green Deal. *Publications Office of the European Union.* 2019. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2019:640:FIN (accessed on 13 April 2024).
3. EC; Net Zero Industry Act. *Commission Staff Working Document for a Regulation of the European Parliament and of the Council on Establishing a Framework of Measures for Strengthening Europe's Net-Zero Technology Products Manufacturing Ecosystem*; Publications Office of the European Union: Luxembourg, 2023.
4. EC. *Industry 5.0, a Transformative Vision for Europe—Governing Systemic Transformations Towards a Sustainable Industry*; Publications Office of the European Union: Luxembourg, 2021. [CrossRef]
5. EC. *A Sustainable Bioeconomy for Europe: Strengthening the Connection Between Economy, Society and the Environment*; Publications Office of the European Union: Luxembourg, 2018. [CrossRef]
6. Juvančič, L.; Osojnik Črnivec, I.G.; Berne, S.; Oven, P.; Mihelič, R. Povzetek Strokovnih Izhodišč za Strategijo Razvoja Biogospodarstva v Sloveniji. 2023. Available online: https://www.daes.si/storage/post-content/qb3NGrBnNyykTFfCy8gmJSeGR8k9jhYXYnIaEklQ.pdf (accessed on 12 April 2024).
7. Reyes, L.; Abdelouahed, L.; Mohabeer, C.; Buvat, J.-C.; Taouk, B. Energetic and exergetic study of the pyrolysis of lignocellulosic biomasses, cellulose, hemicellulose and lignin. *Energy Convers. Manag.* **2021**, *244*, 114459. [CrossRef]
8. EC. *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions*; A New Industrial Strategy for Europe; Publications Office of the European Union: Luxembourg, 2020.
9. D'Amato, D.; Gaio, M.; Semenzin, E. A review of LCA assessments of forest-based bioeconomy products and processes under an ecosystem services perspective. *Sci. Total Environ.* **2020**, *706*, 135859. [CrossRef] [PubMed]
10. Klein, D.; Wolf, C.; Schulz, C.; Weber-Blaschke, G. 20 years of life cycle assessment (LCA) in the forestry sector: State of the art and a methodical proposal for the LCA of forest production. *Int. J. Life Cycle Assess.* **2015**, *20*, 556–575. [CrossRef]
11. Sinkko, T.; Sanyé-Mengual, E.; Corrado, S.; Giuntoli, J.; Sala, S. The EU Bioeconomy Footprint: Using life cycle assessment to monitor environmental impacts of the EU Bioeconomy. *Sustain. Prod. Consum.* **2023**, *37*, 169–179. [CrossRef]
12. Sala, S.; Amadei, A.M.; Beylot, A.; Ardente, F. The evolution of life cycle assessment in European policies over three decades. *Int. J. Life Cycle Assess.* **2021**, *26*, 2295–2314. [CrossRef]
13. *ISO 14040:2006*; Environmental Management—Life Cycle Assessment—Principles and Framework. ISO: Geneva, Switzerland, 2006.
14. *ISO 14044:2006*; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. ISO: Geneva, Switzerland, 2006.
15. Delaney, E.; Liu, W.; Zhu, Z.; Xu, Y.; Dai, J. The investigation of environmental sustainability within product design: A critical review. *Des. Sci.* **2022**, *8*, e15. [CrossRef]
16. Hegab, H.; Shaban, I.; Jamil, M.; Khanna, N. Toward sustainable future: Strategies, indicators, and challenges for implementing sustainable production systems. *Sustain. Mater. Technol.* **2023**, *36*, e00617. [CrossRef]
17. Delaney, E.; Liu, W. Insights into environmental sustainability implementation during the design stage of New Product Development: An industry perspective. *J. Eng. Technol. Manag.* **2024**, *71*, 101803. [CrossRef]
18. Assad, F.; Konstantinov, S.; Rushforth, E.J.; Vera, D.A.; Harrison, R. Virtual engineering in the support of sustainable assembly systems. *Procedia CIRP* **2021**, *97*, 367–372. [CrossRef]
19. Chen, Z.; Tao, J.; Yu, S. A Feature-based CAD-LCA Software Integration Approach for Eco-design. *Procedia CIRP* **2017**, *61*, 721–726. [CrossRef]
20. Kent, L.; Snider, C.; Gopsill, J.; Hicks, B. Mixed reality in design prototyping: A systematic review. *Des. Stud.* **2021**, *77*, 101046. [CrossRef]
21. Lo, C.K.; Chen, C.H.; Zhong, R.Y. A review of digital twin in product design and development. *Adv. Eng. Inform.* **2021**, *48*, 101297. [CrossRef]
22. Ko, N.; Graf, R.; Buchert, T.; Kim, M.; Wehner, D. Resource Optimized Product Design—Assessment of a Product's Life Cycle Resource Efficiency by Combining LCA and PLM in the Product Development. *Procedia CIRP* **2016**, *57*, 669–673. [CrossRef]
23. Ozden, B. Incorporating sustainability in material science education: Adapting computer aid programs in teaching materials sustainability. *MRS Commun.* **2021**, *11*, 685–691. [CrossRef]
24. Tseng, T.L.B.; Rahman, M.F.; Chiou, R.; Ho, J.C. Sustainable Green Design and Life Cycle Assessment for Engineering Education. In Proceedings of the ASEE Virtual Annual Conference Content Access, Virtual, 26–29 October 2021.
25. Zeid, A. CAD tools for sustainable design. In Proceedings of the 2015 International Conference on Industrial Engineering and Operations Management (IEOM), Dubai, United Arab Emirates, 3–5 March 2015; IEEE: Piscataway, NJ, USA, 2015; pp. 1–5. [CrossRef]

26. Tao, J.; Chen, Z.R.; Yu, S.R.; Peng, Q.J. Study on ugnx-lca integration for sustainable product development. In Proceedings of the ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Charlotte, NC, USA, 21–24 August 2016; ASME: New York, NY, USA, 2016; Volume 4.
27. Hultgren, P.; Smärgel, P. CAD-Integrated Life Cycle Assessment in Product Development: Evaluation in a Technical Development Context. Master's Thesis, Jönköping University, Jönköping, Sweden, 2023.
28. Wu, Y.; Su, D.; Peng, W.; Zhang, Q. Application of lifecycle assessment and finite element analysis in the design of raised access floor products. In Proceedings of the Computational Plasticity Xiv: Fundamentals and Applications, Barcelona, Spain, 5–7 September 2017; Volume 1, pp. 806–814.
29. Popa, L.; Popa, V. Products eco-sustainability analysis using CAD SolidWorks software. *MATEC Web Conf.* **2017**, *112*, 06002. [CrossRef]
30. Zhafri, Z.; Effendi, M.S.M.; Rosli, M.F. A review on sustainable design and optimum assembly process: A case study on a drone. *AIP Conf. Proc.* **2018**, *2030*, 020071.
31. Paudel, A.M.; Kreutzmann, P. Design and performance analysis of a hybrid solar tricycle for a sustainable local commute. *Renew. Sustain. Energy Rev.* **2015**, *41*, 473–482. [CrossRef]
32. Morbidoni, A.; Favi, C.; Germani, M. CAD-Integrated LCA Tool: Comparison with dedicated LCA Software and Guidelines for the Improvement. In *Glocalized Solutions for Sustainability in Manufacturing, Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, Technische Universität Braunschweig, Braunschweig, Germany, 2–4, May 2011*; Springer: Berlin/Heidelberg, Germany, 2011; pp. 569–574.
33. Dovramadjiev, T.; Mrugalska, B. Real-time planning and monitoring of the steel pipes towards life cycle sustainability management. *Ann. Oper. Res.* **2023**, *324*, 1485–1499. [CrossRef]
34. Adriyanti, A.L.; Sahroni, T.R. Design Sustainability for Battery Packaging to Increase Customer Satisfaction. *J. Eng.* **2023**, *2023*, 9916084. [CrossRef]
35. Tao, J.; Li, L.; Yu, S. An innovative eco-design approach based on integration of LCA, CAD/CAE and optimization tools, and its implementation perspectives. *J. Clean. Prod.* **2018**, *187*, 839–851. [CrossRef]
36. Tao, J.; Yu, S. Development of LCA module integrated with cad for eco-assessment of machined products. In Proceedings of the ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Quebec City, QC, Canada, 26–29 August 2018; Volume 4.
37. Winter, S.; Quernheim, N.; Arnemann, L.; Anderl, R.; Schleich, B. Approach to Reduce the Environmental Impact of a CNC Manufactured Product in the CAD Phase. In *Manufacturing Driving Circular Economy, Proceedings of the 18th Global Conference on Sustainable Manufacturing, Berlin, Germany, 5–7 October 2022*; Springer: Cham, Switzerland, 2023; pp. 749–756.
38. Fontana, A.; Corti, D.; Alge, M.; Petrucciani, M.; Calvo, L.; Marangi, L. Integrating a LCA tool with a design platform towards a sustainable-aware PSS design: Application in a FabLAB environment. *IFAC-Pap.* **2018**, *51*, 1125–1130. [CrossRef]
39. Dudkowiak, A.; Grajewski, D.; Dostatni, E. Analysis of Selected IT Tools Supporting Eco-Design in the 3D CAD Environment. *IEEE Access* **2021**, *9*, 134945–134956. [CrossRef]
40. Radzki, M.; Diakun, J. Comparative Analysis of the Environmental Assessment of an Exemplary Product in Selected IT Tools. In *Advances in Manufacturing III*; Springer: Cham, Switzerland, 2022; pp. 61–75.
41. Ren, Z.; Su, D. Comparison of different life cycle impact assessment software tools. *Key Eng. Mater.* **2013**, *572*, 44–49. [CrossRef]
42. Dervishaj, A.; Gudmundsson, K. From LCA to circular design: A comparative study of digital tools for the built environment. *Resour. Conserv. Recycl.* **2024**, *200*, 107291. [CrossRef]
43. Favi, C.; Germani, M.; Mandolini, M.; Marconi, M. Implementation of a software platform to support an eco-design methodology within a manufacturing firm. *Int. J. Sustain. Eng.* **2018**, *11*, 79–96. [CrossRef]
44. Top, N.; Sahin, I.; Mangla, S.K.; Sezer, M.D.; Kazancoglu, Y. Towards sustainable production for transition to additive manufacturing: A case study in the manufacturing industry. *Int. J. Prod. Res.* **2023**, *61*, 4450–4471. [CrossRef]
45. Ajtayné Károlyfi, K.; Szép, J. A Parametric BIM Framework to Conceptual Structural Design for Assessing the Embodied Environmental Impact. *Sustainability* **2023**, *15*, 11990. [CrossRef]
46. Fan, H.; Goyal, B.; Ghafoor, K. Computer-aided architectural design optimization based on BIM Technology. *Informatica* **2022**, *46*, 323–332. [CrossRef]
47. Hollberg, A.; Agustí-Juan, I.; Lichtenheld, T.; Klüber, N. Design-integrated environmental performance feedback based on early-BIM. In *Life-Cycle Analysis and Assessment in Civil Engineering: Towards an Integrated Vision*; CRC Press: Boca Raton, FL, USA, 2019; pp. 433–439.
48. Gaha, R.; Yannou, B.; Benamara, A. A new eco-design approach on CAD systems. *Int. J. Precis. Eng. Manuf.* **2014**, *15*, 1443–1451. [CrossRef]
49. Gaha, R.; Benamara, A.; Yannou, B. Proposition of Eco-Feature: A New CAD/PLM Data Model for an LCA Tool. In *Design and Modeling of Mechanical Systems—III, Proceedings of the 7th Conference on Design and Modeling of Mechanical Systems, CMSM'2017, Hammamet, Tunisia, 27–29 March 2017*; Springer: Cham, Switzerland, 2018; pp. 763–770.
50. Gaha, R.; Yannou, B.; Benamara, A. Selection of a green manufacturing process based on CAD features. *Int. J. Adv. Manuf. Technol.* **2016**, *87*, 1335–1343. [CrossRef]
51. Russo, D.; Rizzi, C. Structural optimization strategies to design green products. *Comput. Ind.* **2014**, *65*, 470–479. [CrossRef]

52. Adeyi, A.J.; Adeyi, O.; Isola, B.F.; Areghan, S.E.; Oke, E.O.; Ogunsola, A.D.; Adetunji, M.O. Sustainability of Forest Resource Utilization: A Life Cycle Assessment Study. In Proceedings of the International Conference the International Society of Tropical Foresters, Ibadan, Nigeria, 14–16 February 2023; pp. 221–227.
53. Rex. 1960 Wood Chair, Dining Chair, Design Niko Kralj. 1960. Available online: https://rex-kralj.com/product/1960-wood-chair/ (accessed on 22 May 2024).
54. Huijbregts, M.A.J.; Steinmann, Z.J.N.; Elshout, P.M.F.; Stam, G.; Verones, F.; Vieira, M.; Zijp, M.; Hollander, A.; van Zelm, R. ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *Int. J. Life Cycle Assess.* **2017**, *22*, 138–147. [CrossRef]
55. Guinee, J.B. Handbook on life cycle assessment operational guide to the ISO standards. *Int. J. Life Cycle Assess.* **2002**, *7*, 311–313. [CrossRef]
56. Bare, J. TRACI 2.0: The tool for the reduction and assessment of chemical and other environmental impacts 2.0. *Clean Technol. Environ. Policy* **2011**, *13*, 687–696. [CrossRef]
57. Severles. Available online: https://www.severles.si/o-nas.html (accessed on 3 March 2024).
58. Mitol. Mekol. Available online: https://www.mitol.si/sl/products/mekol/ (accessed on 3 March 2024).
59. Belinka. Interier. Available online: https://www.belinka.com/sl/izdelki/interier/ (accessed on 5 March 2024).
60. Tisa d.o.o. Available online: https://www.tisa.si/ (accessed on 3 March 2024).
61. Lesstroj. Available online: https://www.lestroj.si/si/ (accessed on 6 March 2024).
62. Stahlhandel Gröditz GmbH. AISI 304. Available online: https://www.stahlportal.com/en/stainless-steel/aisi-304/ (accessed on 3 March 2024).
63. Ou, R.; Chang, C.; Zeng, Y.; Zhang, X.; Fu, M.; Fan, L.; Chen, P.; Ye, D. Emission characteristics and ozone formation potentials of VOCs from ultra-low-emission waterborne automotive painting. *Chemosphere* **2022**, *305*, 135469. [CrossRef]
64. Lu, J.; Zhuo, Q.; Ren, X.; Qiu, Y.; Li, Y.; Chen, Z.; Huang, K. Treatment of wastewater from adhesive-producing industries by electrocoagulation and electrochemical oxidation. *Process Saf. Environ. Prot.* **2022**, *157*, 527–536. [CrossRef]
65. Goldhahn, C.; Cabane, E.; Chanana, M. Sustainability in wood materials science: An opinion about current material development techniques and the end of lifetime perspectives. *Philos. Trans. Ser. A Math. Phys. Eng. Sci.* **2021**, *379*, 20200339. [CrossRef]
66. Garcia, C.A.; Hora, G. State-of-the-art of waste wood supply chain in Germany and selected European countries. *Waste Manag.* **2017**, *70*, 189–197. [CrossRef]
67. Cooper, T.; Furmston, K.; Cutts, A.; Kaner, J. Furniture lifetimes in a circular economy: A state of the art review Cooper. In Proceedings of the 4th PLATE, Limerick, Ireland, 26–28 May 2021.
68. Ćujić, M.; Dragović, S.; Đorđević, M.; Dragović, R.; Gajić, B. Environmental assessment of heavy metals around the largest coal fired power plant in Serbia. *CATENA* **2016**, *139*, 44–52. [CrossRef]
69. RS. Domestic Energy Production Down, Energy Dependancy Up. 2022. Available online: https://www.stat.si/StatWeb/en/News/Index/11405 (accessed on 5 May 2024).
70. IEA. Energy System of Slovenia. Available online: https://www.iea.org/countries/slovenia (accessed on 5 May 2024).
71. Lao, W.-L. Assessing environmental burdens of China's wooden flooring production based on life-cycle assessment. *J. Clean. Prod.* **2024**, *446*, 141341. [CrossRef]
72. Pokhrel, G.; Gu, H.; Gardner, D.; O'Neill, S. Life Cycle Assessment (LCA) of Wood Flour and Pellets for Manufacturing Wood-Plastic Composites (WPCs). *Recent Prog. Mater.* **2021**, *4*, 3. [CrossRef]
73. Pommier, R.; Grimaud, G.; Prinçaud, M.; Perry, N.; Sonnemann, G. LCA (Life Cycle Assessment) of EVP—Engineering veneer product: Plywood glued using a vacuum moulding technology from green veneers. *J. Clean. Prod.* **2016**, *124*, 383–394. [CrossRef]
74. Puettmann, M.; Oneil, E.; Wilson, J.; Johnson, L. *Cradle to Gate Life Cycle Assessment of Softwood Plywood from the Pacific Northwest*; Corrim: Seattle, WA, USA, 2013. [CrossRef]
75. Puettmann, M.; Oneil, E.; Wilson, J. *Cradle to Gate Life Cycle Assessment of U.S. Particleboard Production*; Corrim: Seattle, WA, USA, 2013. [CrossRef]
76. Piekarski, C.M.; de Francisco, A.C.; da Luz, L.M.; Kovaleski, J.L.; Silva, D.A.L. Life cycle assessment of medium-density fiberboard (MDF) manufacturing process in Brazil. *Sci. Total Environ.* **2017**, *575*, 103–111. [CrossRef] [PubMed]
77. Treyer, K.; Bauer, C.; Simons, A. Human health impacts in the life cycle of future European electricity generation. *Energy Policy* **2014**, *74*, S31–S44. [CrossRef]