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Streamlined Life Cycle Assessment of an Innovative Bio-Based Material in Construction: A Case Study of a Phase Change Material Panel

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Abstract: Research Highlights: This is the first study that analyzes the environmental performance of wood-based phase change material (PCM) panels. Background and Objectives: Life cycle assessment (LCA) is a powerful environmental management tool. However, a full LCA, especially during the early design phase of a product, is far too time and data intensive for industrial companies to conduct during their production and consumption processes. Therefore, there is an increasing demand for simpler methods to demonstrate a company's resource efficiency potential without being data or time intensive. The goal of this study is to investigate the suitability of streamlined LCA (SLCA) tools and methods used in the building material industry, and to assess their robustness in the case study of a wood-based PCM panel. Materials and Methods: The Bilan Produit tool was selected as the SLCA tool and a matrix LCA was selected as the most commonly used SLCA method. A specific case study of a wood-based PCM panel was selected with a focus on its application in building construction in the province of Québec. Results: As a semi-quantitative LCA method, the matrix LCA provided a quick screening of the product life cycle and its hotspot stages, i.e., life cycle stages with high impact. However, the results of the full LCA and SLCA tools were quantitative and based on scientific databases. The use of the PCM panel and heating energy had the highest environmental impacts as compared to other inputs. The results of the full LCA and SLCA also identified energy consumption as a hotspot. Insufficient material or processes in the SLCA databases was one of the reasons for the difference between the results of the SLCA and full LCA. Conclusions: The examined SLCA methods provided proper explanations for the bio-based material in construction, but several limitations still exist, and the methods should be improved to make them more robust when implemented in such a specific sector.

Keywords: life cycle assessment; simplified LCA; matrix LCA; building; bio-based material; phase change material

1. Introduction

Wood is one of the most important building construction materials [1]. Regarding its high strength and reasonable cost, wood is one of the most common sources of construction material with "low specific weight, ease of working, good insulation properties, attractive appearance, and adequate life if protected from moisture and insects" [1]. Owing to a wide range of potential applications, it often competes with other materials such as steel, concrete, or plastics [2,3]. Wood products usually have a low embodied energy with low water and air pollution. Compared to other building material, wood products have a smaller carbon footprint [4–6].

The lack of information on the environmental performance of wood products does not allow customers and decision makers to understand the environmental impacts of their choices [7]. Environmental management programs in organizations are shifting to more proactive and strategic approaches, as opposed to static ones [8]. Life cycle assessment (LCA) is an internationally accepted approach that assists in quantifying the environmental impacts of the entire life cycle (i.e., material extraction, production, use phase, and end of life stage) of products and services (e.g., construction materials). An LCA also aids in determining where environmental improvements can be made during a product's life cycle and contributes toward the design of new products [9].

Since a full LCA (traditional LCA that is in accordance with the International Organization for Standardization (ISO) 14040/14044 [10]) is far too time and cost intensive for industrial companies to implement during their production and consumption processes during the design stage [11], there is an increasing demand for simpler methods to demonstrate a company's resource efficiency potential without being data or time consuming [12]. There are two different SLCA approaches that include streamlining at the level of life cycle inventory (LCI) and the life cycle impact assessment (LCIA). Streamlining at the LCI level reduces data collection efforts and simplifies the model (e.g., using surrogate data as a proxy: surrogate data are secondary data sources, e.g., using data on a similar process in the absence of a particular process.), whereas streamlining at the LCIA level simplifies the communication of the results and reduces the number of impact categories [13]. The literature review on streamlined/simplified LCA shows an increase in publications mostly in the building and construction (e.g., [14–17]), automobile and vehicle development (e.g., [18–21]), transport (e.g., [22]), electronics (e.g., [23]), renewable energy (e.g., [24]), agricultural and food products (e.g., [25–30]) sectors, among others.

Phase Change Materials (PCMs) are substances that have a high fusion temperature. They are solidified and melted at a certain temperature and have the capacity to store and release large amounts of energy. These substances, when incorporated into building materials, lead to reductions in the building's energy consumption [31–33]. PCMs can be incorporated into air conditioning systems [34], solar thermal storage systems [35], and wallboards, or they can be placed between walls, in ceilings, and in floors to reduce temperature fluctuations within a building [36].

A literature review has revealed that an LCA of bio-based products has previously been conducted with respect to medium-density fiberboard (MDF) [37,38], oriented strand board (OSB) [39], particleboard [40], and laminated veneer lumber [41]. The environmental performance of PCM has been analyzed in several products including solar thermal systems [32,33], root zone heating systems [42], air conditioning systems [34], and solar thermal storage systems [35]. PCMs incorporated in building envelopes are widely studied in order to increase their thermal energy storage capacity [31,43–45]. Rincón et al. [46] studied the environmental impact from all the phases of experimental buildings using various constructive systems. They found that the operational phase had the highest environmental impact. Other research on the use of PCM in building envelopes did not consider all the phases of the building life cycle. Three types of stabilized rammed earth doped with microencapsulated PCM were investigated during the manufacturing phase by Serrano et al. [47]. They reported that the environmental impact of the material increased by incorporating microencapsulated PCM into the rammed earth. De Gracia et al. [43] analyzed the inclusion of PCM in experimental buildings for the manufacturing and operation phases and showed that the impact of conventional bricks with PCM was more than 35% lower than that of the reference cubicles without insulation. The study by Castell et al. [48] analyzed the manufacturing and operation impact of PCM with the alveolar brick construction system, using the same methodology employed by De Gracia et al. [43]. They determined that the impact of PCM-incorporated alveolar bricks was slightly higher than that of the cubicles with polyurethane and PCM. De Gracia et al. [49] investigated the environmental impact of the PCM-incorporated ventilated double skin facades from the manufacturing and disposal phases. They indicated that the environmental impact of PCM-incorporated ventilated double skin facades (VDSF) was three times that of the alveolar bricks. There are few studies on the application of PCM in wood-based panels [50–54]; however, the environmental performance of PCM in wood-based panels is yet to be evaluated.

LCA and SLCA methods can be viewed as parallel subjects and the use of SLCA does not prevent LCA practitioners from applying a full LCA. It should be considered that a full LCA and a SLCA have different scopes, and comparing the two approaches is a logical way of analyzing the accuracy of the results of an SLCA method. The goal of this study is to analyze the environmental impacts of the production and application of PCM in a wood-based panel, using SLCA tool and methods. In order to investigate the suitability of SLCAs for the building material industry, and to assess their robustness in the case study of a PCM panel, the results of the SLCA are compared to those of a full LCA. This study has also highlighted the potential shortcomings that currently limit the wider application of the streamlined approach in this industry.

2. Materials and Methods

One PCM panel made to lab-scale (0.00153 m^3) was selected as the functional unit for this study. The system boundary for the panel that was considered for the study was primarily from materials extraction, transportation, electricity, fuels, and chemicals. An SLCA tool (Bilan Produit) and SLCA method (matrix LCA), versus a full LCA were conducted. The following section outlines the procedure that was followed for the methods under review.

2.1. PCM Panel

The objective of this study is to analyze the environmental impact of including PCM within the wall of a building as a PCM wood-based panel. The PCM panel produced by the Industrial Research Chair on Ecoresponsible Wood Construction (CIRCERB) was chosen for this case study. This panel consists of three layers including an MDF and a high-density fiberboard (HDF) panel, as well as a plastic bag of PCM (Figure 1) [54].

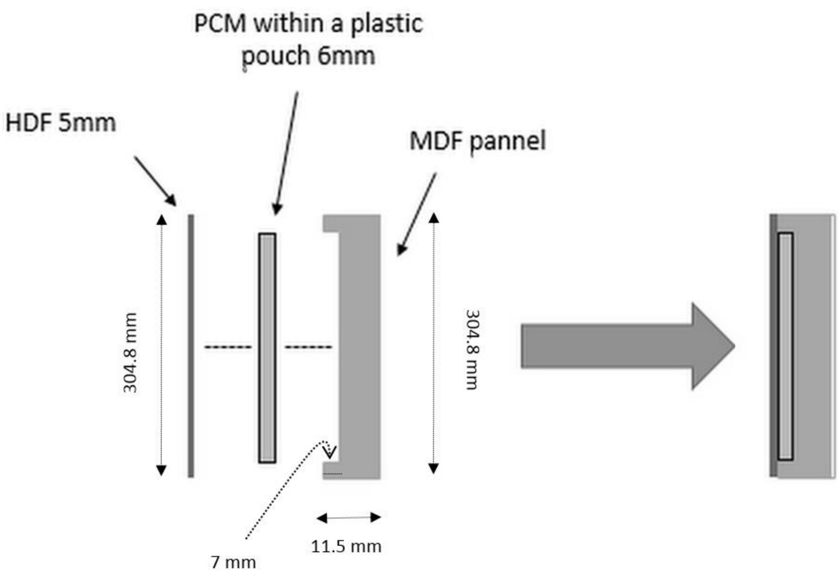

Figure 1. Sketch of a wood-based PCM panel [54].

The properties of the functional units are listed in Table 1 [54,55].

Table 1. Properties of wood-based PCM panels [54,55].

Property	Unit	Value
Width	m	1.65×10^{-2}
Length	m	3.05×10^{-1}
Height	m	3.05×10^{-1}
Volume	m^3	1.53×10^{-3}
Density	Kg/m^3	889.90
Melting point onset	°C	20.6
Heat of fusion	J/g	47.5
Solidifying point	°C	20.5
Heat of solidification	J/g	49.8

2.2. Full LCA

The traditional LCA (full LCA) utilized in this study is in accordance with the International Organization for Standardization (ISO) 14040/14044 [10], which is an international standard framework for conducting LCAs. The functional unit was defined as a wood-based PCM panel, which was 0.00153 m^3 and made from the three layers identified in Section 2.1. The study included the material extraction, manufacturing, and end of life stages of all inputs used to produce a PCM panel to laboratory-scale; the transport stage was excluded from the analysis. The background information on the production of MDF, HDF, the plastic bag, and glue were obtained by referring to the Ecoinvent 3.3 database (using the recycled content system model) [56]. A summary of the inventory data collected is listed in Table 2.

Table 2. Inventory data for one PCM panel *.

Component	Name in the Database Ecoinvent Corresponding to the Component	Unit	Value
MDF	Medium density fibreboard	m^3	5.19×10^{-4}
HDF	Fibreboard, hard	m^3	4.65×10^{-1}
PCM	Fatty acid	kg	0.336
Glue	Vinyl acetate	kg	0.0140
Plastic bag	Polyethylene, high density, granulate	kg	0.018
Electricity	Electricity, medium voltage	kWh	1.420
Heat	Heat, district or industrial, other than natural gas	MJ	9.960

* Functional unit is a PCM panel of 0.00153 m^3.

The environmental performance of the PCM panel was analyzed at both the midpoint and endpoint levels using the IMPACT 2002+ [57], ReCiPe Midpoint (H), and ReCiPe Endpoint (H) [58] methods, as well as SimaPro 8.4.1.4 software [59]. At the midpoint level, IMPACT 2002+ uses 15 impact categories and ReCiPe uses 18 impact categories, which are given along with their units in the Supplementary Materials (Table S1). At the endpoint level, these midpoint impact categories are multiplied by damage factors and aggregated into three to four endpoint damage categories (three damage categories in the ReCiPe method and four damage categories in the IMPACT 2002+ method) (See Supplementary Materials, Table S1).

2.3. Matrix-Based LCA/Environmentally Responsible Product Assessment (ERPA)

The environmentally responsible product assessment (ERPA) or matrix LCA was introduced as a semi-quantitative method by [60,61]. The main feature of this method is a 5×5 assessment matrix. The horizontal dimension comprises environmental concerns including materials chosen, energy used, as well as liquid, solid, and gaseous residues. The vertical dimension of the matrix addresses the life cycle phases including pre-manufacturing, product manufacturing, packaging and transport, use, and disposal. According to Graedel and Allenby et al. [61], each cell of the matrix is given an environmental performance score that is identified from the highest impact (score 0) to the lowest impact (score 4). The practitioner is assisted by reliable checklists, experience, a design and manufacturing survey, and other information to rate each cell with an environmental performance score.

Tables S2–S6 in the Supplementary Materials demonstrate the checklists, environmental factors, and scoring guides developed for the environmental concerns at each life cycle stage in the PCM panel system [31,37,49,62,63].

The procedure used in the ERPA method is presented in Figure 2.

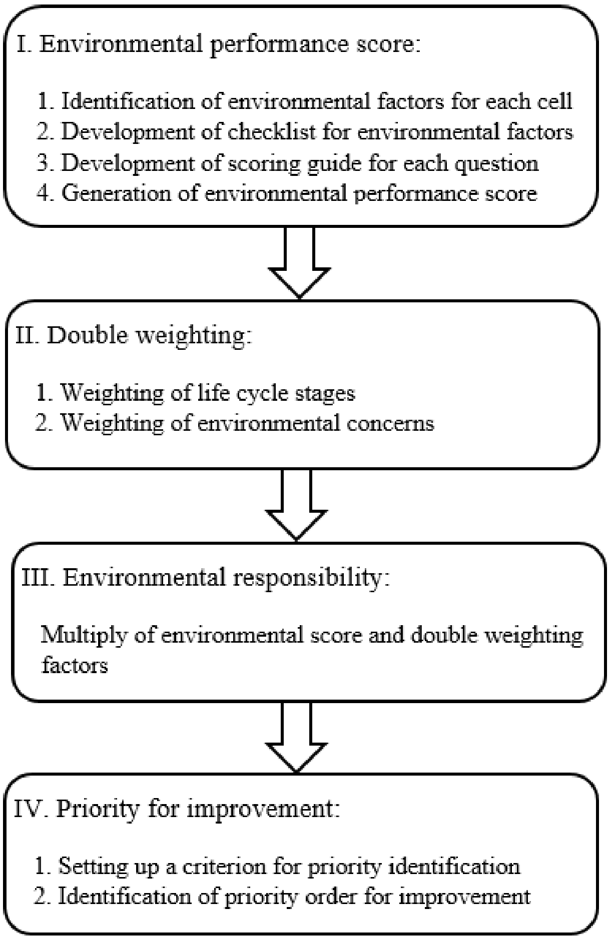

Figure 2. Procedures used in the ERPA method [61].

As the environmental categories and environmental concerns at each life cycle stage differ in terms of relative significance, a double-weighted matrix results [64,65], as described below in Equation (1):

$$R_{ERP} = \sum_{i}\sum_{j} w_{i,j} M_{i,j} \quad (1)$$

Here R_{ERP} is the environmentally responsible product rating, $w_{i,j}$ is a set of weighting factors, $M_{i,j}$ is each cell of the matrix, and i and j are the number of matrix rows and columns, respectively. In the weighting stage (step 2), the life cycle phases with lower weights lead to more severe environmental impacts. In order to obtain a double weighting factor, the two forms of weighting factors are multiplied for each cell. In step 3, the double weighting factors for each cell are multiplied by the environmental performance score to calculate the environmental responsibility (ER). The total ERPA score for each product is calculated as the sum of the ER for all cells. The significant environmental aspects associated with the product system and its improvement priority are identified in view of the ER value of each cell (step 4, Figure 2).

Since the case study of the PCM panel was at a lab-scale and there was no data for usage, the use and delivery phases (cells 3.1, 3.2, 3.3, 3.4, 3.5, 4.1, 4.2, 4.3, 4.4 and 4.5) were not considered in this study.

2.4. Bilan Produit Tool

There are several SLCA tools (e.g., Athena and Bilan Produit) that cover different impact categories. Bilan Produit considers the life cycle stages of a product. Based on this point and because it covers similar environmental impact categories as the ReCiPe and IMPACT 2002+ methods, it was selected for this study. Bilan Produit is an SLCA tool that applies simplification at the LCI level [66]. An online version [67] designed by the French Environment and Energy Management Agency (ADEME) comprises six specific tabs: general, manufacturing, distribution, usage, end of life, and results. The general tab is where the necessary goal and scope related information can be given. The second tab allows for the selection of inventories related to the manufacturing of the product (e.g., input materials and manufacturing processes). In the distribution tab, the user can select inventories related to the transportation of the inputs (unit for this step is t·km). The usage tab is where the use scenario(s) for the product (e.g., power consumption of an electronic device and use of washing product) can be defined. In the end of life tab, the user can describe the end of life scenario(s) for each product material. The results tab provides for the selection of the desired impact categories and damage assessments, and the tool calculates the results based on the selected items. This tab presents the summary of the impacts for the entire life cycle of the product, as well as the results of each impact category based on each product life cycle stage. Since the online version of the Bilan Produit tool still does not include a complete database (e.g., organic chemicals), the old version [67], which was on a Microsoft Excel file and only available in French, was used.

Table 3 shows the main characteristics of the full LCA and SLCA tool and method [13,26,57,58,61,64,66].

Table 3. Main characteristics of the full and streamlined LCAs.

Approach/Tool	Full LCA	Matrix LCA	Bilan Produit *
Results type (Quantitative/Qualitative)	Quantitative	Semi-quantitative	Quantitative
Streamlining level	Both LCI and LCIA level	LCIA level	LCI level
Indicators	15–18 midpoint and Three to four endpoint impact categories	Five environmental concerns: 1. Material Choice 2. Energy Use 3. Solid Residue 4. Liquid Residue 5. Gaseous Residue	Eight impact categories: 1. Acidification 2. Aquatic Ecotoxicity 3. Climate Change 4. Energy consumption 5. Eutrophication 6. Human Toxicity 7. Photochemical pollution 8. Resources consumption
Comparison of products	Yes	Yes	No
Database	Agri-footprint Ecoinvent v3.3 ELCD EU and Danish Input Output Industry data v.2 Swiss Input Output US LCI	No database	Ecoinvent v2
Free access Online software Time requirements ** Cost	No No Long Expensive	Yes No Short Inexpensive	Yes Yes Short Inexpensive

* Online version of Bilan Produit; ** Time requirement covers the time of data collection and analysis time.

3. Results and Discussion

In this section, the results of carrying out LCAs for the PCM panel are presented and discussed. Specifically, the application of the full LCA is presented first, followed by the streamlined versions using the matrix LCA and Bilan Produit tools.

3.1. Full LCA Results

Table 4 shows the endpoint results for the PCM panel based on different life cycle stages using two impact assessment methods (IMPACT 2002+ and ReCiPe).

Table 4. Damage assessment results of a PCM panel (0.00153 m^3) for different life cycle stages based on two impact assessment methods.

	Damage Category	Material Extraction	Manufacturing	Use	End of Life
IMPACT2002+	Human health (DALY)	0.00	0.00	—*	5.7×10^{-10}
	Ecosystem quality (PDF.m^2.y)	4.69	0.28	—	1.7×10^{-4}
	Climate change (kg CO_2-eq)	2.08	1.23	—	4.8×10^{-3}
	Resources (MJ primary)	26.38	11.21	—	6.5×10^{-3}
ReCiPe	Human Health (DALY)	0.00	0.00	—	1.8×10^{-8}
	Ecosystems (PDF.m^2.y)	2.59	0.46	—	1.5×10^{-3}
	Resources ($)	0.15	0.03	—	5.7×10^{-5}

* No available data for use phase.

Table 5 provides the endpoint results for the PCM panel based on inputs using two impact assessment methods. The results of midpoint impact categories are displayed in Tables S7–S8 in the Supplementary Materials.

Table 5. Damage assessment results of a PCM panel (0.00153 m^3) for materials based on two impact assessment methods.

	Damage Category	MDF	HDF	PCM	Plastic Bag	Electricity	Heat	Waste Scenario
IMPACT2002+	Human health (DALY)	6.1×10^{-7}	4.9×10^{-7}	1.9×10^{-6}	2.8×10^{-8}	2.0×10^{-7}	9.8×10^{-7}	5.7×10^{-10}
	Ecosystem quality (PDF.m^2.y)	0.3	0.3	4.0	0.0	0.1	0.3	0.0
	Climate change (kg CO_2-eq)	0.4	0.3	1.1	0.0	0.3	1.2	0.0
	Resources (MJ primary)	6.7	5.1	10.4	1.4	7.4	10.9	0.0
ReCiPe	Human Health (DALY)	1.1×10^{-6}	1.4×10^{-6}	3.7×10^{-6}	5.6×10^{-6}	1.1×10^{-7}	2.9×10^{-6}	1.8×10^{-8}
	Ecosystems (PDF.m^2.y)	0.3	0.5	1.8	0.0	0.0	0.4	0.0
	Resources ($)	0.0	0.0	0.1	0.0	0.0	0.0	0.0

With respect to the damage to human health, the phase change material (in this case, lauric and capric acids) had the biggest share, followed by the heating energy. Lauric acid and capric acid are PCMs with a low temperature latent heat storage owing to their low carbon chains and are used in the walls of buildings to store energy. Among the inputs, the PCM, HDF, and heating energy had the highest impact on the ecosystem quality. Regarding climate change and resource damage categories, the heating energy and PCM were the hotspots, i.e., life cycle stages with a high impact, along with other materials.

3.2. Matrix-Based LCA Results

The environmental responsibility results of the PCM panel were assessed using the ERPA method. The scoring results for each life cycle stage and each environmental concern are shown in Figure 3.

Given that this case study with the PCM panel was to lab-scale and the product delivery and product use stages were not considered, the overall rating of 39 is much lower than that of similar studies. The results are displayed in Table S9, in the Supplementary Materials as well. The product life cycle stages with lower scores had a higher environmental impact. The results of the ERPA matrix show that energy use was the hotspot environmental concern, which is consistent with the results of the full LCA. The ERPA results create a complete outline of the environmental characteristics of a product's life cycle. One of the difficulties with the matrix LCA is assessing a fair rate for life cycle stages and their corresponding environmental concerns. Rating the cells with the matrix LCA method requires that the practitioner be familiar with the performance of the processes along the life cycle of the product. The practitioner should have information regarding environmental considerations linked to how the processes are made. However, this kind of information is not always available. Streamlining with qualitative and semi-quantitative approaches like the ERPA risks overlooking environmental information [68].

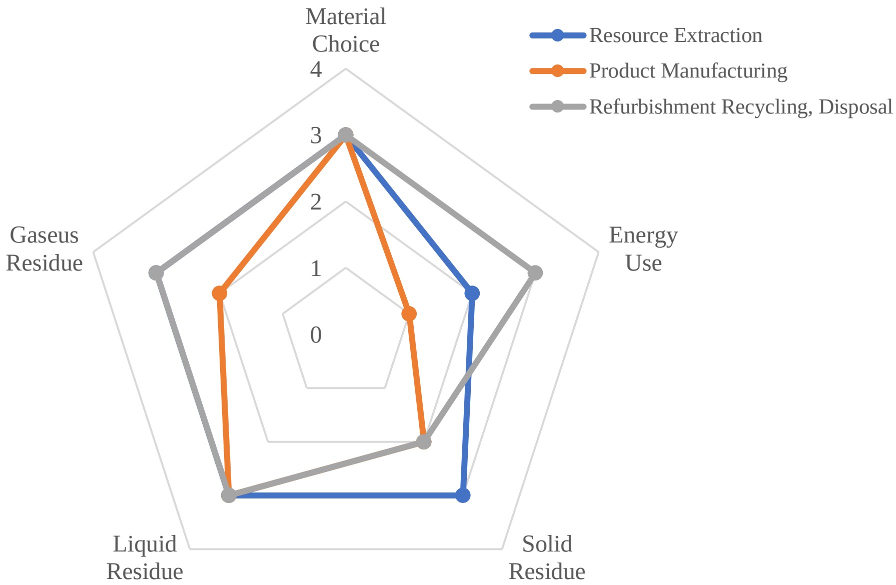

Figure 3. Environmental Responsible Product Assessment for the PCM panel. The use stage was not considered for this study due to missing data.

When working with streamlined LCAs, such as the matrix LCA, a designer can consider possible design improvements for each hotspot. The rating scale has a range from 0 to 4, with 4 (lowest environmental impact) indicating that there is no option for any potential improvement, and 0 (highest environmental impact) representing many options for a feasible potential improvement. By comparing the current situation and potential for improvement of a product or service, the design team can determine various improvement options, i.e., those life cycle steps where little improvement has been already applied but more improvement could likely be achieved. This method will allow the user to exclude the life cycle stages with lower impacts and focus on life cycle stages with higher impacts. With the ERPA method, the user can easily specify the hotspots and the most important environmental concerns (in this case, energy use). The results of the ERPA suggest a focus on energy use as the main environmental concern for determining improvement options.

Previous studies that applied the ERPA matrix reported several advantages as well as limitations of the method [65,69]. A matrix-based LCA was used to analyze the environmental impacts of several cars with different power sources [65]. The results of the matrix LCA demonstrated that there was no difference between two selected cars. At the product use stage, the type of fuel or material choice caused the difference between an ethanol car and a petrol car, with the latter having more environmental impacts than the former [65]. In the ERPA matrix, all stages of the product's life cycle, from manufacturing to end-of-life, have been considered. This helps in the identification of the product's key life cycle stages where environmental improvements are needed [70]. The ERPA matrix method can be applied for existing products, as well as for the development of new products during the design phase. Lee et al. investigated the environmental impacts of a vacuum cleaner and of cellular phone systems using the matrix LCA [69]. Based on their results, material use and use of energy in the pre-manufacturing phase was reported as the issues with the highest potential for improvement.

3.3. Bilan Produit Tool Results

Bilan Produit was used as the SLCA tool for this study. Table 6 shows the results of the Bilan Produit tool for the PCM panel.

Table 6. Results of the SLCA Bilan Produit tool.

Indicators	Unit	Wood	PCM	Plastic Bag	Glue	Energy
Non-Renewable Energy	MJ-eq	11.0558	19.3987	1.3638	1.2125	14.6172
Resource consumption	kg Sb-eq	0.0047	0.0086	0.0006	0.0005	0.0070
GWP, 100 years	kg CO_2-eq	0.5290	0.2780	0.0343	0.0271	0.8638
Acidification	kg SO_2-eq	0.0018	0.0017	0.0001	0.0001	0.0011
Eutrophication (air, water, soil)	kg PO_4-eq	0.0011	0.0003	0.0000	0.0000	0.0004
Photochemical pollution	kg C_2H_4	0.0001	0.0001	0.0000	0.0000	0.0001
Aquatic ecotoxicity	kg 1,4-DB-eq	0.1440	0.0414	0.0005	0.0057	0.0893
Human Toxicity	kg 1,4-DB-eq	0.2822	0.1523	0.0014	0.0256	0.3647

The utilization of fatty acid phase change material had the highest impact in this study, with respect to the non-renewable energy and resource consumption impact categories. Energy consumption for electricity and heat had the largest share for global warming potential and human toxicity. MDF and HDF wood were the main contributors to acidification, eutrophication, and aquatic ecotoxicity. Even though Bilan Produit is a simplified LCA tool, it provides the use phase in a separate tab. It can therefore model several usage scenarios, in terms of any materials or energy consumed throughout the use phase, by creating a different life cycle model.

Arzoumanidis et al. used Bilan Produit as a simplified LCA tool for four different agri-food products including roasted coffee, lemon juice, olive oil, and red wine, to assess the robustness, suitability, and shortcomings of the simplified approach in the agri-food industry. Their findings showed that, because agriculture-related processes and emissions were absent in the database of the simplified tool, this did not always agree with the implementation of the full LCA [26].

Figure 4 compares the results of Bilan Produit as a quantitative SLCA tool with the full LCA. The comparison of results of the full LCA and simplified LCA tool are displayed in Table S10, in the Supplementary Materials as well.

In this case study, the SLCA tool analyzed the results with less data than the full LCA. Regarding the required time for the LCA application between the SLCA and full LCA, when the data were available, the analysis time was equal for both approaches. However, the data collection for the full LCA required more time than that for the Bilan Produit SLCA tool, because a full LCA requires detailed information for all processes. When comparing the results of the SLCA tool with the full LCA (Figure 4), the life cycle stages with a higher environmental impact (i.e., hotspot) in the two approaches were the same for similar impact categories. The results regarding GWP (Figure 4a) and non-renewable energy (Figure 4d) showed that the energy was the most impacting one, due to electricity (1.42 kWh/FU) and heat (9.95 MJ/FU) consumption. Regarding the results of eutrophication (Figure 4c), the phosphate emission to water and phosphorous emission to soil are the main contributors, and their characterization factors are different in the full LCA and in the SLCA. The results regarding acidification (Figure 4b) and eutrophication (Figure 4c) showed that the PCM (64% capric acid and 36% lauric acid) was a hotspot. As certain flows and processes were lacking in the SLCA tool database, its results did not always agree with those from the full LCA application. These differences exist because the SLCA tool did not consider the same environmental impact categories that the full LCA methods did. Insufficient material or processes in the SLCA tool's databases could be another reason for these differing results, especially when it comes to chemicals. Although the results of the SLCA and full LCA were not always equal, they did exhibit the same hotspots for environmental improvement. Therefore, it can be concluded that if the goal of the study is to have a screening view of a product's environmental performance, the SLCA is preferable because it requires less data, especially for the early design stage (e.g., eco-design).

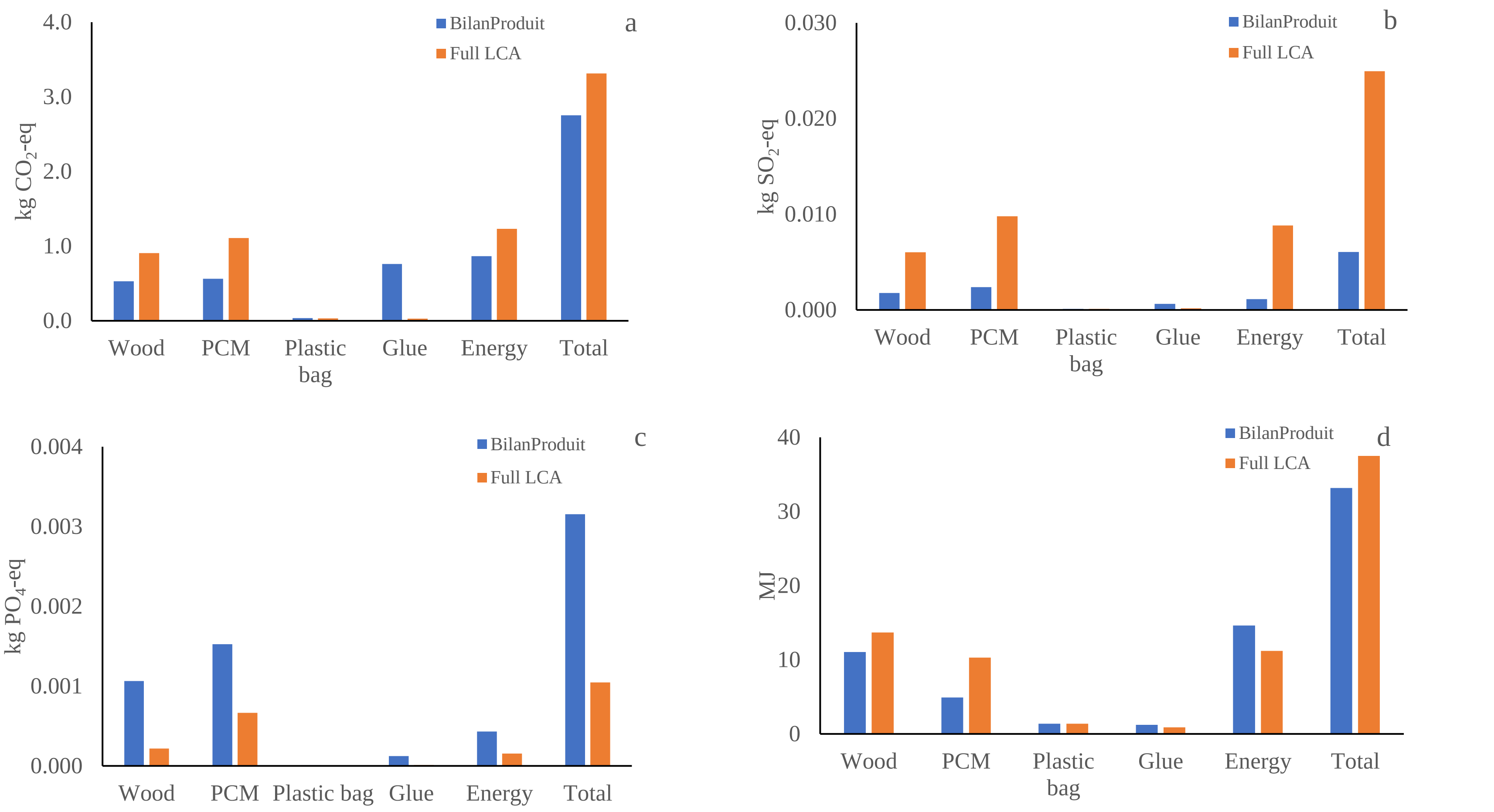

Figure 4. Results comparison of the full LCA and Bilan Produit tool based on four similar impact categories, (**a**): Global Warming Potential (GWP); (**b**): Acidification; (**c**): Eutrophication; and (**d**): Non-Renewable Energy.

3.4. Challenges With the Streamlined Life Cycle Assessment

Usability may be increased for LCA users by including a special set of impact categories, such as water scarcity and climate change, and by reducing the number of life cycle impacts. Huijbregts et al. implemented a regression analysis between the impact categories and fossil cumulative energy demands (CED) of 498 products [71]. They reported a correlation between fossil cumulative energy demands and most environmental impacts including the global warming potential (GWP). They concluded that CED can be used as a single indicator for screening the environmental assessment. Lasvaux et al. [72] studied 40 low-energy houses in France and identified LCA guideline values that describe a range of environmental impacts for new houses.

Data availability is another critical aspect of an environmental assessment, and collecting all detailed inventories is a difficult step. The ERPA was used as an effective method in this study to deal with this problem. Since the matrix-based LCA determines life cycle stages where environmental improvements are needed and the areas where improvements can be made, the ERPA method can be applied in eco-design to determine possible improvements and reduce environmental impacts. One of the problems associated with qualitative and semi-quantitative approaches is how precisely to compare different processes. As there is no quantitative dimension for this approach, a comparison is avoided and the practicality of this approach is also limited. Another weakness of qualitative methods is that the scoring of environmental concerns is subjective and it is very difficult to find data to support the estimated scores [69].

To select the most appropriate SLCA method, the reliability and accuracy of the results should be balanced. Considering all criteria, there is no method for streamlining that is superior to all the others. Selecting an SLCA method and/or tool requires an equilibrium between the type of results that the industry is seeking and the simplification of the method. When a decision should be supported by an SLCA method, it is important to identify which kind of information to use and if the method can provide it [73]. The type of streamlining is one the most important points that should be considered when choosing an SLCA method or tool. Streamlining approaches could be applied at LCIA or LCI levels. Strategies at the LCIA level aim to reduce the number of impact categories, whereas strategies at the LCI level reduce data collection efforts and assist with streamlining the model [26]. Based on the time, cost, and availability of data, the designer can decide to apply streamlining at LCI or LCIA levels or to exclude life cycle phases and limit impact categories.

The distinction between the goal of streamlined and full LCA applications should also be considered. Several researchers have employed SLCA methods in order to solve the limitations of the full LCA, such as data availability and complexity [65,74]. However, the development of the SLCA approach did not only result from these constraints. For instance, for certain projects there is available data for all detailed process, but the goal of the project is to perform a screening environmental assessment of a product at the design phase. Therefore, conducting an SLCA could be a necessary step in decreasing the environmental impacts of this product along its life cycle. Eco-design, which is the aggregation of environmental attention into the product and into its service design and development, is one the main applications of the SLCA methods that aims to improve the environmental performance along the life cycle of a product or service. The best time to improve a product's environmental impact is during the design phase, and most impact categories can be effectively decreased by addressing them early on. Product designers require accurate and clear information about the relative quality of the available options in order to make design-related decisions that improve sustainability.

4. Conclusions

Given that the data-consuming full LCA is difficult to implement at the design phase of a product, streamlined LCA methods that require less data and effort can address this problem. The environmental impact analysis presented in this paper is the result of a full LCA, a semi-quantitative LCA method, and an SLCA tool for a PCM wood-based panel. The Bilan Produit tool was selected as the SLCA tool, and a matrix LCA was selected as the most commonly used SLCA method. In order to investigate the suitability of streamlined LCAs for the building material industry, the results of the SLCA were compared to those of a full ISO-based LCA, using the IMPACT 2002+ and ReCiPe methods. Heating energy and PCM were the hotspots, among other materials, for most of the impact categories. The results of the SLCA show that energy use was the hotspot environmental concern, which is consistent with the results of the full LCA. In comparing the results of the SLCA tool and method with a full LCA as a reference, we concluded that the matrix LCA, as a semi-quantitative LCA method, provided a quick screening of the product life cycle and its hotspot stages. However, the results of the full LCA and SLCA tool were quantitative and based on scientific databases. When considering global warming potential, acidification, eutrophication and non-renewable energy as similar impact categories among the SLCA tool and the full LCA, the life cycle stages with a higher environmental impact were the same for both approaches. The SLCAs simplified the use of the LCA at the design phase but did not always agree with the implementation of the full LCA in the assessed environmental impacts (e.g., eutrophication for the PCM panel). One of the shortcomings of the methods was that the SLCA and full LCA did not take into consideration the same characterization factors for environmental impact categories. Another drawback was the lack of databases for certain processes in the SLCA tool, in particular in relation to chemicals. Despite the limitations of SLCAs, the examined methods provided proper explanations for the PCM panel as a bio-based material in the construction, and we can conclude that if the goal of the study is to have a screening view of a product's environmental performance, the SLCA is preferable because it requires less data, especially for the early design stage of a product.

Future research should analyze more case studies of bio-based materials in the construction sector using SLCA methods to find the most appropriate methods for this field. Efforts to develop comprehensive databases including sector-specific inventories in bio-based materials, such as chemical components and forestry operations, are necessary for the sector, for both full and streamlined LCAs. The characterization of uncertainty related to applied streamlined LCA methods should also be investigated, as well as the development of a comprehensive streamlined LCA tool for projects with time and cost limitations.

Supplementary Materials: The followings are available online at http://www.mdpi.com/1999-4907/10/2/160/s1. Table S1: Midpoint and endpoint impact categories based on IMPACT 2002+ and ReCiPe methods, Table S2: The guideline of the environmental performance scoring for the environmental concerns at resource extraction stage in the PCM panel system, Table S3: The guideline of the environmental performance scoring for the environmental concerns at manufacturing stage in the PCM panel system, Table S4: The guideline of the environmental performance scoring for the environmental concerns at product delivery stage in the PCM panel system, Table S5: The guideline of the environmental performance scoring for the environmental concerns at use stage in the PCM panel system, Table S6: The guideline of the environmental performance scoring for the environmental concerns at end of life stage in the PCM panel system, Table S7: Midpoint assessment of a PCM panel, considering IMPACT 2002+ method, Table S8: Midpoint assessment of a PCM panel, considering ReCiPe H, method, Table S9: Environmental Responsible Product Assessment for PCM panel, Table S10: The comparison of results of the full LCA and simplified LCA tool (BilanProduit) for a PCM panel.

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