Circular Economy Practices on Wood Panels: A Bibliographic Analysis

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Abstract: The scarcity of natural resources and the generation of waste without adequate disposal are a worldwide concern related to the linear production model. These characteristics are present in the wood panel production. Faced with this problem, the present study aimed to identify in the literature, circular economy (CE) practices in the waste management of wood panel production processes and the possibilities for implementing new practices that incorporate circularity concepts. A systematic search was conducted to select the most relevant work on the theme. A search was done using the ScienceDirect, Web of Science, and Scopus databases by combining the following keywords: “Circular Economy” (and its possible variations), “Wood-based Panel”, and “Wood Waste”. The results evidenced circular economy practices on waste management already being used by the wood panel industry, besides potential practices to increase circularity. The changes go towards sustainable manufacturing and responsible consumption, which aims to “ensure sustainable consumption and production patterns”. Opportunities range from the extraction of raw materials to the disposal of wood panel waste at the end-of-life. The circular economy model is still recent and the process of transitioning is in its initial phase, as well as scientific research on the theme, mainly regarding the wood panel industry. Studies addressing the circular economy and wood panels are not yet widespread, pointing to a gap yet to be explored. The bibliographic review allowed identifying the existence of potential applications of circular economy in the wood panel industry; yet, this piece of research points to a broad field of exploration.

Keywords: circular economy; wood panel; waste

1. Introduction

Wood is the most abundant biodegradable and renewable material available [1]. However, some factors need to be taken into consideration when optimizing its utilization, and attention must be paid to economic, social and, mainly, environmental issues, such as emissions of greenhouse gases (GHGs) and threats to forests, which have been effectively fought by the increase in the use of wood waste [1]. Wood waste is a versatile resource generally used for producing materials and energy [2]. Reusing and replacing virgin wood with recycled wood aims to reduce costs and the externalities associated with extraction, transportation and disposal [3]. Moreover, the recycling of wood waste has the environmental effect of reducing the use of materials such as water and energy used in the timber production process [3].
According to Ruishenget al. [4], there are several ways to manage wood waste, including the recycling of wood composites and biofuel production. The use of wood panels, such as particleboards, can reduce environmental threats to the consumption of resources; however, it adds many variables to the environmental equation as a whole.

Wood panels are structures formed by wood in different disaggregation stages, compacted by pressure, temperature and the use of synthetic resins [5]. These products have become substitutes for solid wood in the furniture (see References [6–8]) and construction (see References [9–11]) industries. This was greatly motivated by the scarcity of virgin raw materials. One major concern on this issue is the production strategies used in countries of vast extension, which are able to grow and harvest great amounts of wood to produce panels, and with a low level of technology development, which is the case of some developing countries, where Brazil stands out.

According to the report of the Brazilian Industry of Trees Association (IBÁ), in the first trimester of 2018 it was observed a consumption of 1,640 million m$^3$ of wood panels by the furniture industry. In the same period of 2017, the consumption had reached 1,591 million m$^3$, thus it can be noted an increase of 3.1% in 2018 compared to the previous year, only in Brazil.

The world production of wood panels has been increasing over the last decades. Analyzing the period 2007–2017, it can be observed that between 2008 and 2009 there was a decrease in the demand of wood panels. However, from 2010 on, it rose again and there have not been any drops since, which totals, in 2017, a figure of 420,361,171 m$^3$ of wood panels produced. Among all wood panels, the highlights are the high density fiberboard (HDF) (101,073,401 m$^3$ produced), medium density fiberboard (MDF) (93,177,474 m$^3$) and the oriented strand board (OSB) (30,636,646 m$^3$ produced), adding up to approximately 54% of the world wood panel production [12].

The production of wood panels is based on a linear process and there is excessive waste generation, from the extraction of raw materials to the disposal of the final product. In this context, the importance of the circular economy (CE) in this process looms, as it is an economic model that enables changes to the relation society–nature, preventing resource depletion, aiming to maintain materials and products in cycles, allowing potential waste to go back to production processes and recapturing value [13].

Besides all the environmental advantages of CE in the wood panel industry, it is believed that the adoption of circular practices can improve financial performance as well. Companies have the legal obligation of managing all generated waste. Engaging in CE practices, instead of spending money on waste management, they might even profit from selling the respective waste to a company that can use it as input, or yet find ways to reuse or recycle the waste themselves. Moreover, relationships can be built and networks might be the starting point for new businesses.

To the best of the authors’ knowledge, there are no studies in the existing literature that investigate the incorporation of CE in the production process of wood panels aimed at waste minimization. The motivation for the present study comes from the referred gap. Therefore, this study aims to answer the following research question: What are some CE practices in the waste management of wood panel production processes and what are some possibilities for implementing new practices that incorporate circularity concepts?

To answer such research questions, the present study aimed to investigate the existing literature in search of reported existing practices and present alternative practices for the gaps encountered. The scope of this study seeks to cover all life cycle phases of wood panels. Thus, it comprises the extraction of raw materials (i.e., wood) and all implications and relationships that all related activities might have (production and use of necessary material and equipment for wood production, transport, etc.) while going through the manufacturing phase (again, including all related material and equipment, such as the use of binding agents, energy use, etc.), distribution, use phase and end-of-life (including many possible paths such as direct disposal, reuse, remanufacturing, recycling, etc.).

To that end, this study is structured as follows. This first section presents the initial considerations around the theme. Section 2 will provide a brief theoretical background on wood panels, circular economy, wood waste, and issues on a transition from a linear to a circular economy. Section 3 will
present the methods used to conduct this piece of research. Section 4 will present the main considerations on this study’s findings. Lastly, Section 5 will draw the conclusions of this research, followed by the cited literature.

2. Theoretical Background

This section intends on providing a brief background on the main topics addressed in this paper, aiming to enable a proper understanding of the research, based on the concepts and definitions that are taken as basis.

2.1. Wood Panels

The great versatility of wood products has put them under a spotlight. Therefrom, many products have been created to supply the great demand in the furniture sector (mainly) and the construction industry. Forestry products, such as wood panels, have been developed bearing in mind the best use of wood [14].

Wood-based panels are produced from fragmented wood and synthetic resins, which act as the components’ binding agent. Wood panels are manufactured according to the desired uses, which include panels for furniture, structural and non-structural applications, as well as decorative panels [15].

According to Thoemen [16], wood panels can be classified into two types:

- Solid wood—made of mechanically processed solid wood, represented by plywood, panel constituted of layers of bound blades, and present good mechanical properties. This group also includes laminated veneer lumber (LVL) and the glued laminated timber (GLT), often used in the civil construction industry.
- Reconstituted wood—industrialized wood panels made from the disaggregation of wood in the form of particles or fibers, with MDF, OSB, and HDF being the main agglomerate particle products. This category encompasses all panels using lignocellulosic materials in their composition;

Furthermore, according to Youngquist [17], the panels can be divided into three main groups. These are:

- Blades—plywood, sawn veneer and LVL;
- Particles—particleboard, waferboard, OSB, oriented strand lumber (OSL) and laminated strand lumber (LSL);
- Fibers—fiber wood, insulating fiberboard, hardboard (HB) and MDF.

Although there are a number of panels, used with different purposes, in this segment a few panels can be highlighted [5], as follows:

- Medium density particleboard (MDP)—panels formed by wood particles (small wood chips) bound by a synthetic resin, usually urea-formaldehyde, under the action of heat and pressure (see Figure 1).

![Medium density particleboard (MDP)](image-url)

*Figure 1. Medium density particleboard (MDP). Source: Reference [18].*
Medium density fiberboard (MDF): The production process is similar to that of the MDP, however, the wood utilized (usually pine) has a greater segregation level, also bound by the use of synthetic resin under heat and pressure (see Figure 2).

![Medium density fiberboard (MDF). Source: Reference [18.]](image)

High density fiberboard (HDF): high-density panels, therefore, thinner. The raw-material used is the same as for the MDF (see Figure 3).

![High density fiberboard (HDF). Source: Reference [18.]](image)

Oriented strand board (OSB): panel of wood chips oriented perpendicularly in several layers, produced under high heat and pressure, with the addition of a synthetic resin [5] (see Figure 4).

![Oriented strand board (OSB). Source: Reference [19.]](image)

Sellers [20] highlights that the demand for these wood composites has grown substantially all over the world, due to their versatility. With such increase in demand, it is necessary to pay even greater attention throughout the life cycle of such panels, giving them a correct destination and aiming to reduce the waste load to the environment, a view supported by CE.

2.2. Circular Economy

CE is a model that aims at maintaining components, materials, and products at their maximum value of utility and time, with the intent to eliminate waste [13]. It is a regenerative method in which raw material input, waste generation, emissions, and energy are minimized by promoting the circularity of material and energy; being reached by repair, reuse, remanufacture, refurbishing and recycling [21].

CE is related to the reuse of materials, components, and products, because these are designed for a longer life cycle [22]. This model provides multiple mechanisms of value creation that are decoupled
from the consumption of finite resources [23]. Besides increasing the efficiency of resource utilization, its goal includes reaching a significant balance between economy, environment, and society [24].

According to the Ellen MacArthur Foundation [23], the CE model encompasses three basic principles:

1. **Preserve and enhance natural capital**, controlling finite reserves and balancing renewable resource flows;
2. **Optimize resource production**, making products, components and materials cycle at the highest level of utility, fulltime, both at the technical and biological levels;
3. **Foment the system’s efficacy** by revealing and excluding negative externalities since the beginning of the project.

The concept of CE has been gaining notoriety in the last years, both at national and international domains, aiming to optimize the way organizations have been producing and consuming [24].

On the national (Brazilian) scope, CE is still little spread, however, it presents great potential in the market, bringing economic sustainability and innovation to productive chains.

2.3. Waste

The wood panel industry stands out when waste is regarded, because panel manufacturing consists of several production stages, from log debarking to panel finishing, generating a considerable volume of waste, which is not given the correct destination. Hence, there is a need to understand the relationship between the industry and the environment and identify which measures can be considered to minimize waste.

In the wood panel production process, the generation of wood solid waste, the emissions of toxic gases, and the generation of residual water can be considered. Giving such waste the correct destination aims at avoiding possible environmental contamination and as gives the company financial return [25].

The wood waste can return to the production process to add value to the composite material (see Reference [26]), such as becoming wood panels at the end-of-life, which aims to bring economic and environmental advantages to the industry, instead of being inadequately disposed of [27]. The reduction of raw material and waste leaving the system can be correlated, once the waste output is strongly related to the raw material input. The reusage and recycling of waste reduces the use of virgin materials and seeks to use renewable materials and, thus, reduce environmental impacts [28].

2.4. Transition from a Linear to a Circular Economy

The linear model has for a long time led the production and consumption of products. These being manufactured with virgin raw materials, benefited by industries, consumed and disposed of as waste after use [29]. The linear model has been reaching a significant advance in resource management by means of implementing new technologies. However, it is known that a system based on consumption and disposal results in great losses throughout production, bringing negative impacts, such as the volatility of raw material prices, the degradation of natural systems due to constant extraction, and economic losses [13]. The circular economy is a model that addresses the entire industrial sector, allowing circular possibilities. Thus, the wood panel industry is an attractive area for the development of industrial practices for the following reasons: (i) The industry has based its activities on virgin raw materials; (ii) there are toxic components in the production of wood panels that if replaced might increase the possibilities for circularity, for allowing end-of-life panels to be used for the production of new products; (iii) there are also many issues at the end-of-life (besides toxic components) regarding correct destination.

The wood panel manufacturing process is considered a linear production, evident in waste without a correct disposal, the irresponsible use of natural resources, and the use of toxic chemicals, for which a more efficient regulation is necessary to reduce the risks to more acceptable levels [30].
Considering the need to reduce the consumption of virgin resources, waste recycling and reusing are indispensable, for they are of great importance to reduce environmental impacts [28]. Industrial wood waste (e.g., small logs) can be used to produce wood-based panels. In general, the panels have a relatively long life, approximately 10 years. Thus, it is necessary to understand the dynamics related to storage and the emission of toxic gases at the use and disposal phases [15].

For the transition from a linear to a CE in industries, such as the wood panel one, CE production methodology must be considered: Aiming to eliminate waste generation, adopt renewable resources, use systemic thinking, and non-externalize costs. This new model is a valid and feasible alternative when compared to the current, linear, economic system [31].

The Ellen MacArthur Foundation [31] assessed and identified four building blocks that envision stimulating the transition to a circularly economic model.

1. **Circular economy design**: The main characteristics of the CE model are to be regenerative and restorative, having as objective the recovery of components and materials since the design. Thus, companies will have to develop design strategies that allow reusing, recycling and cascading.

2. **New business models**: The introduction of new models that replace and prioritize access instead of property, where the product utilization will be given on a lease, having the total conscience of the costumer that after the use they must return the product to be reused or recycled. These models guide the transformation of customers and users.

3. **Reverse cycles**: To create value from used materials and products it is necessary to collect them and take them back to their origins. Reverse logistics and the treatment methods allow the return of such materials to the market.

4. **Enablers and favorable system conditions**: The effective collaboration between value chains and sectors is essential to the establishment of a large-scale circular system, such as partnerships in product development, transparency, information sharing, and sectoral standards.

Considering CE steps and principles, it is possible for the wood panel industry to make the transition from the linear to the CE.

3. Methods

This section presents the methods used for conducting the present research, including the workflow sequence (as the search and analysis were conducted in steps) and the activities in each step. The steps and major activities in each step are illustrated in Figure 5. Thereafter, a detailed description of the procedures used in the literature search, selection and filtering of the retrieved articles, as well as the issues considered during full analysis of the articles comprising the final portfolio are provided.

**Step 1: Definition of keywords and keyword combinations**

The set of keywords and combinations to be used in the search was defined by means of a preliminary investigation following no systematic procedures, in the Web of Science, ScienceDirect and Scopus databases. The documents returned were randomly screened and their content used to establish the final set of keywords and their combinations. Only the keywords and combinations found suitable were, then, used in the final search. Table 1 presents the keywords and combinations used in the final search. The final search was conducted on January 16, 2019.

**Step 2: Final search**

The final search was conducted in the ScienceDirect, Scopus and Web of Science databases and returned the number of documents shown in Figure 2, comprising a raw portfolio. The queries shown in Table 1 were adjusted to the particularities of each database accordingly. From the raw portfolio, a series of filters was applied to find only the relevant studies to be fully analyzed, as described in Step 3.

**Step 3: Selection of documents (filters)**
The selection of the studies to comprise this study’s final portfolio was conducted based on the following filters:

- Duplicates and gray literature: All duplicates and documents other than research and review articles from journals with a peer-review system were excluded. These documents were managed using the reference management software tool EndNote. From the raw portfolio of 45 articles, 30 remained;
- Title, keywords, and abstract: All titles, keywords, and abstracts were read and articles showing no relevance to this study for not being related to the topics addressed were excluded. Therefore, 17 articles remained;
- Full reading: The 17 remaining articles were read in full to verify the existence of examples of CE practices or gaps revealing opportunities to implement them. Articles found not suitable or not related to this study’s topics were ruled out. The reasons to rule out articles in this step included: Not presenting a strong relationship with the present study’s topics, having blurred or (recognizably) mistaken interpretations, presenting at times overly shallow approaches and/or not presenting significant contributions to the investigated literature body taking into consideration the previously existing literature. During the full reading of the articles Step 4 was conducted;

Step 4: Analysis

During the analysis of the articles a series of issues were taken into consideration, including:

- Article type (research or review);
- Objective of the study;
- Topics addressed (e.g., circular economy, waste management, relevant issues on the wood panel industry);
- Gap that motivated the study;
- Methods applied in the study;
- Location to which the study was applied;
- Environmental practices addressed in the study;
- Circular economy practices addressed by the study;
- Sector to which the study was applied;
- Contribution of the study to the present piece of research.

### Table 1. Keywords and combinations—final search.

<table>
<thead>
<tr>
<th>Query</th>
<th>Database</th>
<th>Number of Articles</th>
</tr>
</thead>
<tbody>
<tr>
<td>(“circular economy” OR “industrial ecology” OR “industrial symbiosis”) AND “wood-based panel”</td>
<td>Web of Science</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Science Direct</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Scopus</td>
<td>2</td>
</tr>
<tr>
<td>(“circular economy” OR “industrial ecology” OR “industrial symbiosis”) AND “wood waste”</td>
<td>Web of Science</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Science Direct</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Scopus</td>
<td>1</td>
</tr>
<tr>
<td>“circular economy” OR “industrial ecology” OR “industrial symbiosis”) AND (“wood-based panel” AND “wood waste”)</td>
<td>Web of Science</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Science Direct</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Scopus</td>
<td>0</td>
</tr>
<tr>
<td>“wood waste management”</td>
<td>Web of Science</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Science Direct</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Scopus</td>
<td>12</td>
</tr>
<tr>
<td>OVERALL TOTAL</td>
<td></td>
<td>45</td>
</tr>
</tbody>
</table>
The Ellen MacArthur Foundation assessed and identified four building blocks that envision stimulating the transition to a circularly economic model.

1. **Circular economy design:** The main characteristics of the CE model are to be regenerative and restorative, having as objective the recovery of components and materials since the design. Thus, companies will have to develop design strategies that allow reusing, recycling and cascading.

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**Figure 5. Procedures for retrieval and selection of articles.**

The full reading of the articles was given along with the filling out of a reading form (Table A1 in Appendix A provides all the referred information to each article on the final portfolio), identifying all the documents’ relevant data. The final portfolio comprised 11 articles. For the analysis, no particular approach from the articles in the final portfolio (on the topics addressed) was taken as basis, so as to avoid potential biased conclusions.

Aside from the described search and selection of documents, the supporting literature is seldom not peer-reviewed. It must be noted that no systematic search was undertaken for non-peer-reviewed documents. However, a highlighting strategy was that the authors used cross referencing from a snowballing approach from the final portfolio. Thereby, most of non-peer-reviewed documents were observed in the peer-reviewed articles.

Notwithstanding, the authors would like to highlight that this study does not claim to be exempt from any limitations or, by any means, exhaustive, as it was based on the particular topics, databases, and filters aforementioned. However, the authors believe it to be representative of the addressed body of literature.

### 4. Analysis and Discussion

After the search, it was concluded that the number of published articles that contribute to this study is yet small. Therefore, it can be said that there is no clear evidence of CE in the wood panel industry; however, the existing studies bring alternatives, based on CE characteristics, for waste reuse and supporting methods for extending product life. The alternatives for circularity are identified in Figure 6.

The alternatives to increase circularity found in the existing literature are presented in Section 4.1, whereas Section 4.2 draws on further circularity opportunities identified by the authors.
Emission of toxic gases, sawdust, water steam

4.1. Existing Circular Practices in the Wood Panel Industry

Some laboratory-scale studies are presented in Table 2. Those attribute wood waste or wood panel waste to the manufacturing of “new” products or by-products, which aim at establishing cleaner production methods and increasing product life cycle.

Table 2. Studies showing examples of circular economy practices.

<table>
<thead>
<tr>
<th>Title</th>
<th>Reference</th>
<th>Examples of CE Practices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental impacts of wood-based products under consideration of cascade utilization: A systematic literature review</td>
<td>[32]</td>
<td>Recycling. Production of new products, such as the panels, can derive from recycling of solid wood or even wood panels. Utilization of wood-based products for cascading.</td>
</tr>
<tr>
<td>Wood–plastic composites as potential applications of recycled plastics of electronic waste and recycled particleboard</td>
<td>[33]</td>
<td>Reuse. Manufacture of a wood-based composite, which shows a new form of use, for the product comes from wood particles.</td>
</tr>
<tr>
<td>Wood-based composite made of wood waste and epoxy-based ink-waste as adhesive: A cleaner production alternative</td>
<td>[27]</td>
<td>Reuse. Manufacture of a wood-based composite totally produced from wood waste and epoxy-based paint waste, to obtain a cleaner production and contribute to CE.</td>
</tr>
<tr>
<td>Environmental and technical feasibility study of upcycling wood waste into cement-bonded particleboard</td>
<td>[34]</td>
<td>Recycling. The authors studied the technical feasibility of environmental sustainability of particle and cement clusters made of recycled wood aggregates and alternative binders.</td>
</tr>
<tr>
<td>Small objects manufactured with wood panel residues generated by the furniture industry</td>
<td>[35]</td>
<td>Recycling, Reuse. Manufacture of small objects from a mixture of wastes of OSB, MDF and MDF.</td>
</tr>
<tr>
<td>Environmental performance assessment of the melamine-urea-formaldehyde (MUF) resin manufacture: a case study in Brazil</td>
<td>[36]</td>
<td>Substitution of UF (urea-formaldehyde) resin by MUF (melamine-urea-formaldehyde)</td>
</tr>
</tbody>
</table>

Based on Table 2, some studies consider the cascaded use of waste (e.g., cascading of wood), having as an end the extension of the life cycle and reduction of waste disposal [37]. The wood waste can also make it to the production process of wood particle panels or fiber panels [37], reaching 40% of the use of recycled wood [38].
However, according to Table 2, there are “reuse” practices, which aim at the recovery of products with several possibilities of use. When reusing a product, it might have the same function or not, either way it helps avoid waste and reduce the exploitation of natural resources for the production of new products. This step can be applied to wood panels, when they do not adequately exert the function for which they were designed or if they are at the last stage of their life cycle. Abreu, Mendes and Silva [35] developed small decoration objects from wood panel reuse, such as OSB, MDF, and MDF, thereby avoiding the inadequate disposal of such panels. Moreover, according to Garcia and Hora [38], 25% of wood waste can be utilized in reuse scenarios.

For a plywood panel, when a new material is added to its composition, for reinforcement (e.g., glass fiber polymer), it tends to present better physical-mechanical properties. This results in a set of ecological gains, for it will allow for an increase in reuse, a decrease in the extraction of virgin materials, and an increase in economic gains [39].

(3) Replacing Resin to Increase Circularity Potential

Another point to consider is the study proposal of Reference [36], who conducted an evaluation of the environmental performance of melamine-urea-formaldehyde resin (MUF) (a case study in Brazil). The study showed that the MUF resin, when compared to the UF presents a lower contribution to photochemical oxidation and human toxicity, was considered a great replacement. Therefore, it can be said that this approach aims to contribute to the circular economy, since it is known that one of the greatest environmental impacts of wood panels is present in resin [40–42]. Furthermore, replacing resin can allow for a more efficient recovery of materials at the end-of-life, which can lead to reuse opportunities and, thus, might diminish virgin material input.

The adoption of natural resins is a way towards environmental improvement, regarding the circularity of panels. For resources and materials to be used in a circular way, the frequent presence of toxic chemicals is a critical obstacle, and the chances of reaching a CE may vary. It depends on our capacity to identify flow of hazardous waste, separate them from other flows and, in the long term, find ways to detoxify them before their recycling [30].

There are a few studies addressing the use of wood waste in some production processes, mainly considering the manufacturing of wood panels. These studies are shown in Table 3.

<table>
<thead>
<tr>
<th>Title</th>
<th>Reference</th>
<th>Study Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparative LCA of wood waste management strategies generated from building construction activities</td>
<td>[43]</td>
<td>The goal of this study was to assess and compare the environmental impacts of wood waste management generated from building construction activities using different alternative management scenarios in Hong Kong. The study’s goal was to assess the Global Warming Potential - GWP (IPCC, 2013) of alternative scenarios for post-consumer wood waste management and to compare them against current practices. This paper aimed to advise the SMEs of the Australian wooden furniture manufacturing sector on how to integrate wood waste reduction and recycling into their current value added production system and to consider surplus wood as a resource rather than a problem. The goal of the research was to develop new CCA-treated wood waste management and recycling options. The objective of the study was to evaluate the environmental impacts of wood waste recycling systems, particleboard production and combined heat and power (CHP) generation.</td>
</tr>
<tr>
<td>Dynamic accounting of greenhouse gas emissions from cascading utilisation of wood waste</td>
<td>[2]</td>
<td></td>
</tr>
<tr>
<td>Wood waste management practices and strategies to increase sustainability standards in the Australian wooden furniture manufacturing sector</td>
<td>[1]</td>
<td></td>
</tr>
<tr>
<td>Optimization of a chemical leaching process for decontamination of CCA-treated wood</td>
<td>[44]</td>
<td></td>
</tr>
<tr>
<td>Analysis of the global warming potential for wood waste recycling systems</td>
<td>[3]</td>
<td></td>
</tr>
</tbody>
</table>

From the studies in Table 3 one can identify the various wood waste management activities that have been considered when taking many areas within the wood panel manufacturing into consideration.
Many studies have demonstrated the technical efficacy of particle panels produced from recycled material (recycled wood waste) (see Reference [45–48]). These studies assessed the mechanical characteristics of composites produced from recycled wood waste, comparing the results to those made of virgin raw materials. It is, therefore, possible to identify opportunities for companies that do not yet adopt such practices to contribute to lowering the impacts of related activities. Moreover, besides the environmental gains, companies may gauge cost and image-related benefits. However, further studies are yet to be conducted on the economic and brand image benefits of wood waste recycling to the production of wood panels.

In the environmental sphere, Hossain and Poon [43] conducted a life cycle assessment considering:

- Scenario 1: Environmental impacts of polymer-based particleboard produced from recycled wood waste instead of virgin sources (recycling facility located in Hong Kong and Japan; particleboard manufacturing facility located in the province of Guangdong, China);
- Scenario 2: Cement-based particleboard (CPB) produced from recycled wood waste instead of virgin sources (recycling facility located in Hong Kong and Japan; CPB manufacturing facility located in the province of Guangdong, China);
- Scenario 3: Energy generation from biofuel produced from waste residue instead of coal (recycling facility located in Hong Kong and Japan; fuel used in Hong Kong and Japan).

As the present study focuses on improvements to wood panel industries, especial attention is given to the first and second scenarios. The results showed that those scenarios achieve environmental benefits for reducing GHG emissions and energy consumption during manufacturing. For instance, approximately 70 kg and 29 kg of CO2 may be spared with the management of 1 ton of wood waste in Scenario 1 and Scenario 2, respectively. The wood waste can be used in different scenarios based on its quality. For example, good quality wood waste would preferably be used in Scenario 1, while lower quality wood waste can be used in Scenario 2. The use of recycled material resulted in the greatest positive environmental impacts. From this piece of evidence, it can be affirmed that the use of recycled wood by the wood panel industry can contribute beneficially to the environment, characterizing one of the main CE goals for the sector.

Another study, conducted by Faraca, Tonini and Astrup [2], address the use of wood waste in “cascade” in the European Union (optimized use of resources by sequential use). The cascaded use of wood waste can be in either time or value: Cascaded in time, the wood waste is remanufactured for the same product type iteratively, as many times its quantity allows; cascaded in value, the wood waste is recycled in different applications as its quality decreases. According to Faraca, Tonini and Astrup [2], panels produced from wood chips, under heat and pressure and the use of resin as binding agent, can consume a great deal of post-consumption wood waste—up to 100% of the wood waste, depending on the country (in Denmark, for instance, it represents 80%). This practice greatly contributes to a CE, as what would be disposed of in ordinary landfills becomes input to a new product, adding value to (so-regarded) “garbage”. To the particleboard industry, it represents an opportunity to participate in a more sustainable chain, involving several wood manufacturing companies and companies that collect post-consumption wood waste.

The study of Daian and Ozarska [1], aimed to advise small and medium enterprises (SMEs) of the Australian furniture industry on how to integrate wood waste reduction and recycling to their current system and consider end-of-process-wood surplus as a resource and not a problem. The study contextualizes the main aspects of potential markets for recovered wood, quality standards for the use of recovered wood waste, the current and future scenarios related to wood waste, as well as waste management plans that could be implemented by SMEs in the wood furniture sector.

In the engineered wood sector, such as the wood panels, the waste goes to the production of particleboards, instead of fiberboards, for the fiberboard process requires critical control of contaminants, as any impurities may affect the binding process.
Even for the particleboards, the Australian engineered wood manufacturers seek to meet the following criteria when it comes to wood waste:

- The recycled raw materials for the manufacture of particleboards are—pallets, boxes, clean shavings, sawdust (particles larger than 1 mm), particleboards. Solid or chemical contaminants require the use of segregation and cleaning technologies;
- The allowed percentage of wood waste used in the manufacture of particleboards is limited, for the mechanical properties have to be maintained. In Australia, it is required that the rupture module value be 12 or 13 MPa depending on the width, which is higher than the ones found in Europe, where the value for a “standard” board would be 11 MPa.
- The humidity content of residual material used in the manufacture of particleboards must be approximately 15%.

From Daian and Ozarska [1] it is still noted that many Australian companies already incorporated environmental responsibility to their businesses, taking selective practical measures to reach waste minimization. A few examples of wood waste reduction are:

- Use of automated cut equipment, resulting in specified dimensioning for furniture pieces;
- Wood panels ordered to specific sizes;
- Whenever possible, furniture design is simple, with shapes that do not require excessive machining;
- Most processing operations that generate considerable amounts of scrap are outsourced (turning, finishing, woodwork, lamination).

Answering to future issues related to wood waste, the furniture industry will soon be forced to restructure their business models, oriented to wood waste recycling, which can be developed around one of two streams:

1. Recycling waste, partnering with disposal and recovery centers along the supply chain of wood waste.
2. Turning wood waste into profit, by on-site processing them into value-added products and direct sale to the end consumer, particularly focusing on market niches.

In Daian and Ozarska [1], it can be seen a new stream in CE practices in the wood panel industry, which can be incorporated, established, aiming reuse and recycling of wood and wood products, which become raw materials for producing new panels.

In the study developed by Janin [44], the main objective was to develop new options for the waste recycling of wood treated with CCA (Chromated Copper Arsenate). This study focused on the design of an inexpensive and operational acid leaching process to remove arsenic, chromium, and copper from CCA-treated wood. Several tests were conducted to successfully measure the influence of six operational parameters seeking high yield of metal recovery and to determine the most promising leaching conditions. During each analysis, one parameter was varied while all the other five remained fixed. The variable conditions included the choice of reagent, reagent concentration, total solids content, reaction temperature, leaching time, and size of the wood particles. Several variations of chemical and physical parameters were tested to determine the most adequate leaching conditions aiming to design an efficient process under limited costs. The study of Janin [44] also greatly contributes to the body of literature addressed in the present study, due to the chemical operations conducted aiming the decontamination of waste under a limited-cost perspective, which can be characterized as a CE opportunity when implemented to wood panel industries for separation of synthetic adhesives and other chemicals.

Lastly, but not least, the research conducted by Kim and Song [3] contributes to the present study for addressing the environmental impacts of wood waste recycling, particleboard production e combined generation of heat and energy, using the Life Cycle Assessment (LCA) methodology. The
study of Kim and Song [3] showed that boards produced from wood waste present benefits with regard to GHG emissions; besides, it was noted that the recycling of the referred boards at their end-of-life showed greater reduction of GHG emissions compared to common boards.

From all the aforementioned results, based on a detailed analysis of the approaches of each study, it can be noted that great CE-related opportunities can be identified with regard to wood waste. The most recurrent, dominant, approach seems to be the recycling of wood waste, using it as input to the production of new panels. Nonetheless, there are further opportunities for the sector as a whole and that might not necessarily be at the manufacturing stage. Although further investigations are needed to corroborate their feasibility, a few further practices are identified and presented hereafter.

4.2. Further Practices and Suggestions to Increase Circularity in the Wood Panel Industry

(1) Leaf and Branch Recovery for Use as Fertilizer and Soil Preparation

It is possible to observe that in the raw material extraction stage (e.g., removal of branches, shank and sizing of the logs), so that logs enter the process in uniform size, there is a generation of waste. This stage’s waste can be disposed of in the forest, working as a fertilizer to the next crop. Most of the time (or always) such waste is disregarded. As an organic waste, it can be used as fertilizer and to protect the soil from severe weather. This solution might be used in the very site where trees are grown as well in agricultural lands.

(2) Peel and Wood Chip Recovery for Thermal Energy Generation

At the stage of log peeling and classification of particles and fibers (already in manufacturing), again, there is generation of waste (e.g., peels and wood chips considered unfit to the process), which are destined as biomass to produce thermal energy, used by approximately 50% of the industry.

(4) Reuse and Recovery of End-of-Life Panels as Inputs for New Products

Analyzing the steps of squaring, sanding, and end use of products (manufacturing), there is the generation of waste or “garbage” with toxic additives, such as the formaldehyde present in synthetic resins. Having in mind that these cannot be allocated, disposed of or incinerated, the following question is raised: Where to dispose of such waste so as not to affect society?

Answering this pertinent question, according to MDIC [49] waste that is considered toxic must return to the manufacturer, considering the transport logistics for allocation in a by-product (e.g., decoration objects or production of a new segment of wood panels made of waste of the panels disposed of by consumers). This is one of the most feasible alternatives to minimize the environmental impacts. Another option is to limit the presence of formaldehyde in synthetic resins [49].

Yet, in the context of CE on waste management, the company “Votorantim” can be mentioned as an example. This company is a cement producer that is well-established in the international market that uses in its production waste from its own facilities and “garbage” generated by other industries (e.g., old tires, paper, cardboard, oils, chemical products, other industrial and urban wastes) which replace petroleum coke. The company considers the business advantageous, even though they have to pay to receive the “garbage” of other industries and make it input for their production processes, thus dispensing the purchase of petroleum [50].

Another example of a company that engages in sustainable activities that lie within the scope of CE is the Sonae Arauco, a company with more than 20 industrial and commercial facilities in nine countries and two continents. Sonae Arauco is one of the largest wood panel and wood-based products manufacturers in the world and is committed with the concept of sustainable resource extraction. A few practices adopted by the company include:

- Wood that cannot be recycled is used as energy source;
- After the use phase, products that can be recycled and turned into new products re-enter a continuous recycling;
- Rigorous attendance to the existing environmental regulations with regard to formaldehyde emissions.
Nonetheless, these practices are not yet treated as CE implementation (for further details, see Reference [51]).

Taking CE practices into consideration, the wood panel companies already do consider the examples of waste management applied by Votorantim or by researchers a growing potential to several stages of this process can be seen. These waste management practices incorporate CE principles into the company’s production process, for waste that could be disposed of inadequately and ends up acting as raw material to other production processes and coming back as valuable inputs for the panel manufacturing. Notwithstanding, there is still a gap in the literature concerning the correct disposal of toxic panels. In this study, a few hypotheses were raised to a correct disposal, however, data regarding how many industries carry out such procedure is still incipient.

To affirm that the companies changed completely their current production model towards CE, one must analyze if they met the model premises, in which nothing is wasted but transformed, recycled, or reused. Therefore, the initial product design and its end-of-life, when it loses its use value, must be taken into consideration so that in each step be applied the correct waste management strategy. For if society continues to produce, consume and behave in a linear, devastating model, soon the natural resources will become more expensive and scarcer.

Insights on other practices might be enlightened by investigations on existing research and practices in the wood panel industry (see Reference [40–42]) or seeking circular economy practices on other fields (see for example Reference [52,53]) that could help build and enrich the body of circular economy in the wood panel industry.

5. Final Considerations

While CE is yet a new concept, CE applied to the wood panel industry is even newer. This helps explain the scarcity of CE-related studies in the area. A few practices are already in place in the industry, however, many times not regarded as CE, due to unawareness, as CE is still permeating the industry. The CE model is still incipient and the transition to a more CE model is yet in its initial stage, as well as the scientific investigation on the theme, mainly in the wood panel industry.

The spread of CE will definitely bring positive results both environmentally and economically to the sector, as the correct management of resources will provide a proper balance in the long term. Industries are still learning how to incorporate and deal with CE issues and implications. One of the most challenging issues is the correct identification and establishment of partnerships. Circularity in the wood panel industry may occur in a closed loop, however, open-loop chains involving other companies and industries might be of even greater benefits.

CE practices arise as primordial tools in the search for effective results with regard to waste, by means of prevention, reduction, recycling and reuse. There is no clear explicit evidence of CE in the wood panel industry, however, based on the CE concept and its characteristics, the opportunities present in the wood panel industry vary from the extraction of raw materials to the disposal of wood panel waste at the product end-of-life. Therefore, here lies a gap yet to be explored.

There are several ways to manage waste in the wood panel industry, including from the recycling of wood composites to particle or biofuel production. Moreover, the use and substitution of virgin wood by recycled wood aims to reduce the costs and externalities associated to extraction, transport and disposal. The recycling of wood waste has environmental benefits, as to reduce material inputs such as water and energy used in the manufacturing processes. The recycling of waste in partnership with collection/disposal and recovery centers throughout the supply chain can turn wood waste into potential profit, by turning it into value-added products, with focus on some market niches.

Furthermore, in the role of stewardship, toxic waste must return to the manufacturer, considering the whole logistics, preferably to enter a new product. Options seeking the minimization of environmental impacts (considering the issue of toxics) are limiting the presence of formaldehyde in synthetic resins, and/or the adoption of natural resins. The frequent presence of toxic chemicals is a
critical obstacle to reach CE, as it depends on the capacity to identify the flow of hazardous materials and, in the long term, find ways to detoxify them before recycling.

Therefore, CE is related to the wood panel industry, however, scientific research is not yet well-spread, thus showing a gap to be explored. The literature review allowed identifying the existence of possible applications of CE to the wood panel industry, due to the reuse and recycling of what might be considered waste, by means of returning it to the process or even being raw material for a by-product.

It is suggested that further research be conducted, involving CE applications mainly on the end-of-life phase, for if it is applied to this industry field, it will gouge great advantages to the company, including economic gains on top of the environmental ones. Concerning the population, greater well-being might be expected, due to the reduction of waste, and consequently reduction of pollution, thus improving health.

Author Contributions: C.K.d.C.A wrote Sections 1–4 with the assistance of R.S. and C.C.S., who supported the study’s development. R.S. organized the methods section, did further research on studies supporting the present one, translated and did proofreading on the article. C.C.S. helped structuring the abstract and the conclusions. C.M.P. and A.C.d.F. oriented the authors on the study objectives and relevance. S.K.d.C.A.C. assisted delineating the study and writing the conclusions. All authors analyzed the data, read and approved the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.
### Appendix A. Reading Form for the Analysis of the Final Portfolio

**Table A1.** Reading form for analysis of the final portfolio.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Article Type</th>
<th>Objective of the Study</th>
<th>Topics Addressed</th>
<th>Gap that Motivated the Study</th>
<th>Methods Applied in the Study</th>
<th>Location to Which the Study was Applied</th>
<th>Environmental Practices Addressed in the Study</th>
<th>Circular Economy Practices Addressed by the Study</th>
<th>Sector to Which the Study was Applied</th>
<th>Contribution of the Study to the Present Piece of Research</th>
</tr>
</thead>
<tbody>
<tr>
<td>[32]</td>
<td>Review</td>
<td>To answer by means of a systematic review of the literature the following question: what is the current state of the research in the measurement of the environmental impacts of the wood cascade?</td>
<td><em>Wood cascade</em></td>
<td>&quot;Systematic literature review and categorization and systematization of relevant literature on the environmental impacts of the wood cascade.&quot;</td>
<td>Cascading: is the efficient utilization of resources by using residues and recycled materials for material use to extend total biomass availability within a given system</td>
<td>European Union</td>
<td>Cascading and Life Cycle Assessment</td>
<td>Cascading</td>
<td>Timber industry</td>
<td>Opportunity to use wood residues and wood panels for the production of new panels, using them in the form of a waterfall.</td>
</tr>
<tr>
<td>[27]</td>
<td>Research</td>
<td>The aim of this study was to assess the technical feasibility and environmental aspects of manufacturing to particleboard made with wood waste and epoxy based ink-waste as adhesive.</td>
<td><em>Composite of wood and waste ink</em></td>
<td>Search for materials made from renewable and toxic-free sources (cleaner production).</td>
<td>Laboratory product manufacturing and resistance testing</td>
<td>Brazil</td>
<td>Use of waste</td>
<td>Use of waste for product manufacturing, with joining of different types of materials and companies</td>
<td>Laboratory Scale (wood panel)</td>
<td>Waste sharing between companies, with the objective of developing a sustainable product.</td>
</tr>
<tr>
<td>[34]</td>
<td>Research</td>
<td>This study evaluated the technical feasibility and environmental sustainability of agglomerated cement panels (CBPs) produced with recycled wood aggregates and alternative binders; and compared the performance of their counterparts produced with virgin wood and common binder using experimental analysis and life cycle assessment (LCA).</td>
<td><em>cement-bond particleboards, recycled wood aggregates and alternative binder, waste recycling, Biomass valorization</em></td>
<td>The scarceness of virgin resources and sustainable management of waste materials in high-density city aroused heightened focus on new technology development for waste recycling and local utilization</td>
<td>Production of cement agglomerate with wood residues and alternative binders.</td>
<td>Hong Kong</td>
<td>Use of waste and alternative binder</td>
<td>Use of waste for product manufacturing</td>
<td>Recycling company</td>
<td>Use of wood residues for the production of agglomerate by replacing the thermosetting adhesive with an alternative</td>
</tr>
</tbody>
</table>
### Table A1. Cont.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Article Type</th>
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<th>Sector to Which the Study was Applied</th>
<th>Contribution of the Study to the Present Piece of Research</th>
</tr>
</thead>
<tbody>
<tr>
<td>[35]</td>
<td>Research</td>
<td>The objective of this work was to produce small objects with panels and a mixture of residues of wood panels to compare their qualities.</td>
<td>&quot;Wooden panels, waste and small wooden objects&quot;</td>
<td>The furniture industries are the major generators of these residues. Their use as raw material for the production of handmade small objects emerges as an alternative to use the economic potential of this type of residue.</td>
<td>At first, three workers were selected and supplied with MDF, OSB and plywood boards, as well as graphic projects of 10 small objects. Each worker produced 9 samples of each object. At a second turn, one worker was selected to produce the same 10 objects with three samples, mixing residues from three furniture industries of Ubá, MG.</td>
<td>Brazil</td>
<td>use of wood panel waste for the production of small objects</td>
<td>Reuse of panels after their end of life</td>
<td>Artsisans</td>
<td>Reuse of products, aiming for circularity, since wood panels cannot be disposed of inappropriately due to the materials present in their composition. An alternative post-life</td>
</tr>
<tr>
<td>[36]</td>
<td>Research</td>
<td>This paper presents a life cycle assessment (LCA) study of the production of MUF resin through a case study conducted in Brazil.</td>
<td>&quot;Wood-based panels, Environmental hotspots, Improvement opportunities&quot;</td>
<td>Replacement of urea-formaldehyde (UF) resin by melamine-urea-formaldehyde (MUF) in the production of wood panels, aiming to improve the sheet under wet conditions.</td>
<td>Application of the LCA technique</td>
<td>Brazil</td>
<td>Application of the ACV technique to identify the potential environmental impact caused by melamine-urea resin (MUF).</td>
<td>Substitution of the resin for another that causes less contribution in the impacts of photochemical oxidation and human toxicity</td>
<td>case study</td>
<td>Opportunity to substitute conventional resin (most used) for another that causes less impact in some categories of impact considered important when it comes to the environment.</td>
</tr>
<tr>
<td>[43]</td>
<td>Research</td>
<td>This study aimed to assess the environmental performance of wood waste management systems comparatively, using a case study in Hong Kong.</td>
<td>&quot;Wood waste, Building construction activities, Life cycle assessment, wood panel&quot;</td>
<td>Find alternatives to reduce environmental impacts and resource-efficient solutions for waste management systems that can be used in decision-making processes.</td>
<td>Application of the LCA technique</td>
<td>Hong Kong</td>
<td>Waste Management</td>
<td>Use of wood waste from construction for the manufacture of wood panels and power generation</td>
<td>case study</td>
<td>Use of waste from certain construction procedures for the preparation of new products. It is possible to characterize an opportunity of partnerships between companies to obtain the circularity of the material.</td>
</tr>
<tr>
<td>[2]</td>
<td>Research</td>
<td>I) To systematically assess the GWP of alternative wood waste cascading systems – we do this by considering an emission profile for each scenario and by performing a dynamic accounting where the GWP of biogenic carbon emissions is assessed building on state-of-the-art approaches, II) comparing recycling options for the qualities of mixed wood waste versus the case where the different qualities are treated separately and follow the appropriate management routes.</td>
<td>&quot;Global Warming Potential (GWP), Resource cascading, Dynamic life cycle assessment (LCA)&quot;</td>
<td>Application of the LCA technique on Danish wood waste from recycling centers, for cascade use.</td>
<td>Application of the LCA technique</td>
<td>Danish</td>
<td>LCA on wood waste management</td>
<td>Use cascaded waste</td>
<td>Danish recycling centers</td>
<td>Opportunity to use cascade residuals derived from different timber sectors</td>
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<tr>
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<tr>
<td>[1]</td>
<td>Research</td>
<td>Evaluation of wood waste generation and its true associated cost, which Australian wood furniture manufacturing companies find and are exposed to.</td>
<td><em>Wood waste, Wooden furniture manufacture, Recycling</em></td>
<td>This paper aims to advice the SMEs of the Australian wooden furniture manufacturing sector on how to integrate wood waste reduction and recycling into their current value added production system and to consider surplus wood as a resource rather than a problem.</td>
<td>Researcher-run research was conducted at several representative wood furniture companies from different regions of Australia, analyzing the sites.</td>
<td>Location to Which the Study was Applied</td>
<td>Environmental Practices Addressed in the Study</td>
<td>Circular Economy Practices Addressed by the Study</td>
<td>Sector to Which the Study was Applied</td>
<td>Contribution of the Study to the Present Piece of Research</td>
</tr>
<tr>
<td>[44]</td>
<td>Research</td>
<td>The aim of this study is to design an economic chemical leaching process for the extraction of arsenic, chromium and copper from CCA-treated wood.</td>
<td><em>CCA-treated wood, Chromated copper arsenate, Metal leaching</em></td>
<td>Practical method for decontamination of wood treated with CCA.</td>
<td>Chemical leaching process for decontamination Brand: Canada</td>
<td>Development of options for the management of treated wood</td>
<td>Decontamination of waste wood for reuse</td>
<td>Stella-Jones is a leading North American manufacturer</td>
<td>Opportunity to manage treated wood waste</td>
<td></td>
</tr>
<tr>
<td>[3]</td>
<td>Research</td>
<td>The aim of this study was to evaluate the environmental benefits of particle board production and energy production using wood wastes.</td>
<td><em>Wood wastes, Environmental benefit, Life cycle assessment</em></td>
<td>Issues related to the regulation of carbon emissions associated with climate change are an international concern, motivating the application of this study.</td>
<td>Application of the LCA technique Brand: N/A</td>
<td>Evaluation and comparison of recycling systems for wood waste, material recycling and energy recovery systems.</td>
<td>Waste Management</td>
<td>Waste Management case study</td>
<td>Use of wood residues in products aimed at reducing greenhouse gas emissions.</td>
<td></td>
</tr>
</tbody>
</table>
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