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Assessment of the Possibility of Implementing a Circular Economy by Environmental Evaluating the Life Cycle of Products Derived from Bulky Municipal Waste

Agnieszka Generowicz [1,*], Anna Gronba-Chyła [2], Piotr Godula [2], Joanna Kulczycka [3], Anna Lewandowska [4], Aneta Dorosz [1], Józef Ciuła [5] and Paweł Kwaśnicki [2]

1 Cracow University of Technology, Faculty of Environmental Engineering and Energy, Warszawska 24, 31-155 Cracow, Poland; aneta.dorosz@doktorant.pk.edu.pl
2 Faculty of Natural and Technical Sciences, John Paul II Catholic University of Lublin, Konstantynów 1 H, 20-708 Lublin, Poland; amgronba@kul.pl (A.G.-C.); godula.piotr000@wp.pl (P.G.); pawel.kwasnicki@kul.pl (P.K.)
3 Faculty of Management, AGH University of Krakow, Gramatyka 10, 30-067 Cracow, Poland; kulczycka@agh.edu.pl
4 Institute of Management, Poznań University of Economics and Business, 61-875 Poznań, Poland; anna.lewandowska@ue.poznan.pl
5 Faculty of Engineering Sciences, State University of Applied Sciences in Nowy Sącz, Zamenhofa 1A, 33-300 Nowy Sącz, Poland; jciula@ans-ns.edu.pl
* Correspondence: agnieszka.generowicz@pk.edu.pl; Tel.: +48-12-628-21-83

Abstract: Current wood waste recycling processes need to be improved to prioritize material recovery over energy recovery by cascading the use of wood waste and limiting as much as possible non-recyclable batches that may contain even partially highly contaminated grade C wood and/or Medium Density Fiberboard. In the presented research, a life cycle assessment has been carried out for a new product recovered from bulky waste. The Environmental Footprint 3.1 (adapted) method has been used to assess the potential environmental impact. The results may support a quality assessment of new products undertaken from the perspective of the circular economy and environmental management in the waste sector. The study aimed at the identification of environmental hotspots in the life cycle of the secondary wooden blocks (from cradle to market analysis). Bulky waste was subjected to recovery and recycling processes (a laboratory scale), and by adding starch and water a new product was obtained. The study has demonstrated that the production of blocks has the greatest impact on the life cycle in the following categories: Resource use, fossils (24%), Climate change (23.9%), Eutrophication, freshwater (13.3%), and Resource use, minerals and metals (11.8%). This is due to the high electricity consumption of electricity by equipment and machinery used for the processing of waste and the fabrication of the blocks.

Keywords: environmental impact; life cycle; management; recycling; wood waste

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1. Introduction

A circular economy is a system that aims to eliminate waste and pollution through the efficient use of resources. The reuse and recycling of products slow down the use of natural resources, reduce the destruction of landscapes and habitats, and help to limit the loss of biodiversity. Solutions should be promoted that support the natural landscape and environmental protection in a holistic sense for the entire environmental components: water, air, and soil [1]. Recycling aims at creating new products, which makes the treatment of waste and the substitution of primary resources possible. However, as recycling states a set of technological processes, it is not environmentally neutral. For this reason, new recycling technologies should be evaluated not only from a technological but also from an environmental point of view. Both perspectives will be presented in the paper in relation to the recovery of wood from waste. A rise in wood consumption drives the development of wood recovery technologies. The increased demand can be observed, e.g., for the production of furniture or in new applications such as energy production, building materials, chemicals, etc. In their work, Höglmeier et al. demonstrated that wood production may be insufficient to meet demand in Europe [2]. Worldwide, the furniture manufacturing sector has been experiencing relatively steady growth. Several traditionally important EU producer countries have experienced temporary declines, while Poland, for example, has experienced a sharp rise in domestic production. Altogether, EU countries account for around a quarter of global furniture production [3]. Among the major furniture manufacturing countries in the world, Poland—ahead of Canada and Italy—produces the highest value of sold furniture per million inhabitants [4]. In 2021, Polish furniture manufacturers maintained their leading position in international markets in Europe and second place in the world in terms of the value of exported furniture [5]. Wood is still the most important raw material for the furniture sector and plays a significant role in furniture production. It is estimated that wooden furniture accounts for more than 50% of the total value of furniture production, and wood accounts for approximately 30% of the materials used in furniture production [3]. The rise in wood consumption is accompanied by an increase in the generation of wood waste from used wood-based products. A large amount of wood waste is left unused. Waste wood is considered a valuable material with potential for both recycling and energy recovery; hence, there are two main avenues for waste wood recycling, i.e., for chipboard and thermal use [6].

The paper focuses on the recovery of wood from the specific waste stream—bulky waste. In the waste management sector, household furniture and some household appliances are classified as bulky waste [7]. This type of waste includes, among other things, furniture, mattresses, and carpets. Such wastes constitute a small percentage of the total mass of municipal waste. Although they account for a small percentage of up to 15% of the total mass of municipal waste, due to their dimensions—large mass and volume—they occupy a significant area in the landfills where they are usually deposited, and therefore there is a need to reduce their volume [8]. Furniture is mainly made of various types of wooden boards (predominantly melamine-faced and veneered chipboards) combined with glass and metals. Recent estimates suggest that around 10 million tons of furniture are thrown away in Europe every year. A lot of furniture items have too short a lifespan, and only 10% is recycled. Low-quality materials and poor-quality designs are the main obstacles to applying a circular economy in the furniture industry [9]. Introducing the circular economy concept to the furniture industry could help the industry reduce its waste and environmental impact by recovering the residual value of products at the end of their life cycle. The furniture industry is currently still focused on linear solutions [10,11]. One of the reasons for this is that furniture is generally large and heavy, and hence is difficult to handle; it also has a relatively low remaining value, making the industry difficult to transform. In addition, the nature of the furniture makes it difficult to process and transport [12–15]. Bulky waste management is a serious problem for European countries [7,16,17]. Furniture waste causes significant economic losses, and it is also ecologically harmful due to the chemicals it contains [18,19]. Due to consumer "vanity", furniture in good condition is dumped without taking into account any ecological or economic issues. It is usually deposited in solid waste landfills along with other household waste, and it reduces the capacity of such landfill sites [20–22].

In terms of energy recovery, the use of bulky furniture waste for the production of refuse-derived fuel (RDF) is very problematic. Frequently, cement plants that use RDF do not want to accept aggressive, caustic, or corrosion-triggering chemical elements, e.g., Cl2, S, which are abundant in upholstery. Water-soluble acrylic resin coatings (WSARC) are widely used on wooden furniture surfaces [23–25]. When presenting the findings of preliminary studies obtained from the analysis of ash generated by the combustion of various types of waste used in household furnaces, Poluszyńska indicates that the highest concentrations of zinc were found in samples of bulky waste, rubber ash, and textiles, and the highest concentrations of copper, lead, cobalt, and chromium were found in the samples of rubber and bulky waste containing e.g., lacquered furniture boards [26–28]. With reference to the above issues, bulky furniture waste is highly troublesome and poses difficulties when examining plans to close its circulation. The taxonomy introduced by the EU regulations [29] requires the use of investment principles in a sustainable way, so as to increase the recyclability of products by implementing a closed circle economy, e.g., by replacing or limiting the use of products and materials that are not suitable for recycling, especially in the design and production processes.

Wood waste can be a subject of material recovery. An effective process for homogenizing wood waste includes pulping. The fibers thus obtained are suitable for the development of new avenues for recycling as they are raw materials for the manufacture of many products, such as paper and MDF boards [30,31]. Three-layer MDF panels have been produced from hammer-milled surface-laminated MDF boards. The authors demonstrated that their replacement with >20% content of recycled fibers yielded panels with better properties in terms of formaldehyde emission and increased thickness due to swelling [32]. The study uses value stream mapping as a tool for lean manufacturing analysis in order to identify waste in furniture companies [33]. Valizadeh et al. conducted a study on the air gasification of furniture waste over Ni-loaded ultra-stable Y-type zeolites (Ni-USY) to produce biohydrogen [34]. Maier [35] analyzed the possibility of reusing wood waste in conjunction with magnesium oxychloride cement in order to produce a composite building material. Azambuja et al. [36] suggest the incorporation of construction and demolition wood waste into the inner layer of medium-density fiberboard. Other studies concern the cascade use of wood waste, and they involve the production of wood-plastic composites [37]. The impact of wood waste on the mechanical and biological properties of silicone-based composites was investigated using wood waste from oak, hornbeam, beech, and spruce [38]. Expanded polystyrene, mainly recovered from packaging and wood waste, was used to develop a composite material [39].

Besides technological aspects, the environmental consequences of wood waste treatment are also the subject of discussion in the literature [40–45]. Two research groups—de Souza Pinho and Calmon and den Auwelant et al. [40,41]—made a systematic review of work related to a life cycle assessment and circular practices in the wood sector. They analyzed dozens of studies. Most of the studies related to wood waste generated by the building and construction industry. Another example is a comprehensive assessment made by the Nordic Council of Ministers (NCM) [45] where various applications of wasted wood were environmentally examined and compared. The applications included particle board, wood-plastic composite board, insulation, bioethanol, biochar, and textile fiber. In the NCM report, the environmental impact of wood-waste-based products was calculated and, additionally, compared with the impact of primary substitutes. The results showed that there is no simple answer to what is the environmentally better option [45]. The environmental score differed depending on the impact category and the type of product. For example, for climate change (fossil), most of the waste-based products obtained worse results than their substitutes, while in the case of acidification, they scored better. In all wood-waste-based products, the energy demand was a key driver. Samson-Bręk et al. carried out an environmental analysis of the technology for shredding the non-wood fraction of bulky waste with a stream of water, which is used by the Ecofrag company. The analysis showed that the reuse of foams and mattresses contributes to avoiding their target production, which is associated with a reduction of greenhouse gas emissions and a reduction of fossil resource consumption [7].

Even though many studies have been identified, no environmental assessment for a technology aimed at wood recovery from bulky waste has been found. To fill the gap, the paper presents an environmental assessment of a new recycling technology developed to create a new product—a wooden block. The study is designed to answer the following research questions:

- What are the environmental hotspots in the (from cradle to market) life cycle of the secondary wooden blocks? (Q1);
- Are the results sensitive to a choice of allocation procedure? (Q2);
- Are the secondary wooden blocks an environmentally better or worse option in comparison to similar products? (Q3).

2. Materials and Methods

Answering the research questions required performing relevant analyses. Two methods have been used: the Material Flow Analysis (MFA) and the Life Cycle Assessment (LCA). MFA supported evaluation of the efficiency of the analyzed recycling processes and it provided data on morphological composition and mass balance of waste. With the LCA, a quantitative assessment of potential environmental consequences was performed.

2.1. Material Flow Analysis

Material Flow Analysis (MFA) is a systematic assessment of flows and deliveries of materials in a system that is defined in space and time [46]. MFA is an aid to the assessment of the sustainability of companies, cities, regions, and countries, thus forming the basis for decision-making towards long-term environmental policy, including the realization of environmental goals. Various technologies, e.g., in waste management, can be evaluated and optimized by calculating their balances. MFA can be carried out at two levels: substance level and product level. If it is at the substance level, then it is referred to as substance flow analysis (SFA), and MFA governs the level of products or materials. Over the last decade, MFA has received a lot of attention, and it is a typical analytical tool that is based on the material balance [47]. The results of MFA provide data on morphological composition and mass balance, which are often linked to determine the performance of the systems under study on the basis of quantitative or qualitative indicators [48]. The quantitative indicators refer to the amount of valuable products produced in the sorting installation, or to recycling facilities and to the amount of material recovered [49,50]. The qualitative indicators relate to the composition and to the technical potential for recycling and acting as substitutes for primary materials, which is essential in the transition to a circular economy [50]. In our case study, MFA was used to model the processes and generate data on morphological composition and mass balance. The Sankey diagram has been developed with MFA to reflect the unit processes needed for bulky waste processing. The diagram is presented in Figure 1.

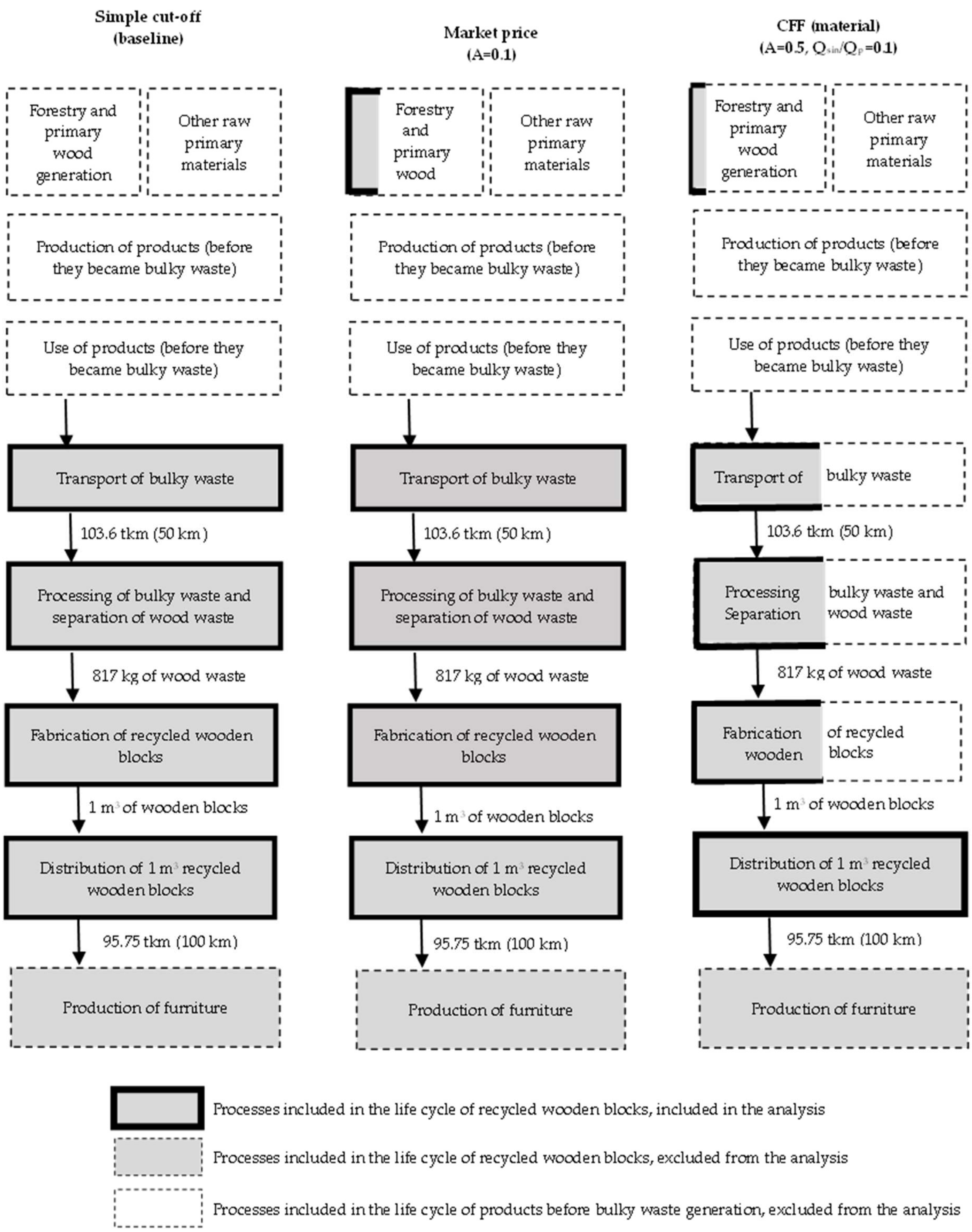

Figure 1. Production and distribution of recycled wooden blocks (from cradle to market)—system boundaries for three used approaches to allocation.

2.2. Life Cycle Assessment (LCA)

Life Cycle Assessment is one of several environmental management techniques that is used e.g., in the study of environmental aspects and potential impacts throughout the life of a product or process, i.e., "from the cradle to the grave". The LCA technique permits the assessment of various stages of the product's life, including: -the extraction and processing of mineral resources, -manufacturing (the production process), -distribution, -transport, -use, -reuse, -recycling, -final disposal of waste. The International Organization for Standardization (ISO) defines LCA as compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle [51,52].

LCA is a technique that illustrates complex interactions that occur between the product and the environment. Owing to the results obtained on the basis of LCA analyses, it is possible to determine the most environmentally friendly system for manufacturing a product [53,54]. The perspective offered by LCA on the environmental performance of products has made it a central concept both in industrial environmental management and in the development of environmental policy in a government or public administration [55,56]. LCA is used in many fields to evaluate technologies, systems, or processes for MSW management [57] as well as to compare waste collection systems, the environmental effects of landfills, incineration, and other waste management scenarios [58–61]. LCA consists of four phases: a goal and scope definition, a life cycle inventory (LCI), a life cycle impact assessment (LCIA), and an interpretation. Assumptions and decisions made in two first phases will be presented in Sections 2.2.1 and 2.2.2 while the LCIA results with interpretation will be provided in Sections 3 and 4.

2.2.1. Goal and Scope Definition

The goal of the study is to assess the potential environmental impact of the production of secondary wooden blocks. The blocks are fabricated from wood waste, previously separated from bulky waste. The recycling process has been developed on a laboratory scale, which states the most important limitation of the LCA study in terms of data quality and comparability. With the developed process wooden blocks are generated with a potential application in the furniture industry as a possible alternative for wood and wood-based products like fiberboards (low, medium, and high density), plywood, particleboards, or sawnwood boards. Ten samples of such blocks have been prepared—varying in starch content, water content, and density. The average recycled content of the blocks is R_1 = 0.85 and the average density is 958 kg/m^3 (Recycled content—the proportion of material in the input to the production that has been recycled from a previous system [62].

The stability and durability of the material depend on the starch and water content. The more starch added to the material, the more water is required to bind the material. Time testing does not affect the durability of the samples. The resulting material had a low mechanical resistance of 4 to 8 MPa and therefore cannot be compared to chipboard. It can be used as a cost-effective filler for other furniture production. Due to the presence of various harmful additives in the received wood blocks, such as adhesives and varnishes derived from furniture boards, which are a barrier to further widespread use, it is a good solution to keep the produced wood blocks in circulation in the furniture industry.

The function of the product system analyzed is to fabricate and distribute secondary wooden blocks with potential applications in the furniture industry. The functional unit has been defined as a production of 1 m^3 of secondary wooden blocks. The following processes have been included in the analysis:

- Transport of bulky waste (transport to the processing site, 50 km),
- Recovery—processing of bulky waste and separation of the wooden fraction with shredding, magnetic separation, ballistic separation, cutting, stirring, pressing,
- Recycling—fabrication of secondary wooden blocks with shredding, homogenization of the structure of the materials, stirring and pressing together with additives,
- Distribution of secondary wooden blocks (transport to the market, 100 km).

The recovery and recycling need to be modeled taking into account the multifunctional character of the processes. As the inherent properties (e.g., a density, a hardness) of the recycled material are not the same as properties of the virgin material, the open-loop recycling has been assumed. Different allocation procedures are usually used in LCA case studies. The following approaches dedicated to the open-loop recycling can be distinguished: a simple cut-off (100:0), a market price-based allocation, and the Circular

Footprint Formula [63–65]. The system boundaries are strongly determined by the approach to allocation selected for the analysis. In our case study, the LCA analysis is made to cover recovery and recycling treated together as a production process, so they appear at the beginning of the life cycle of the wooden blocks. The blocks are manufactured from post-consumer wood scrap which is separated from the bulky waste stream. From the allocation point of view, two stages of the life cycle are common to the previous system (life cycle of products) and the subsequent system (life cycle of secondary wooden blocks): (1) Forestry and primary wood generation and (2) End of life of bulky waste (recovery and recycling)—transport of bulky waste, processing of bulky waste and fabrication of the recycled wooden blocks.

The system boundaries for all three approaches to allocation are presented in Figure 1. The cut-off (100:0) procedure has been assumed as a baseline scenario. Depending on the approach to allocation adopted, both life cycle stages are divided between the previous and subsequent product systems in a different way:

- 100:0 (cut-off), baseline—0% of the burdens for forestry and 100% of the burdens from recovery and recycling are allocated to the secondary wooden blocks;
- The market price-based allocation—the virgin material production (forestry) needs to be partitioned between the product where the virgin material is used and the product where the material is lost [64]. The allocation factor A is defined as the ratio between the market value of scrap or recycled material to the market value of virgin material [64]. In our case study, prices representative of Polish market have been used. Based on yearly reports of the Central Statistical Office [66–70], an average 5-year price for primary wood has been calculated (58 euro/m^3). Because of lack of market data on waste wood, a price of wood waste for 2024 year [71] has been used (6 euro/m^3). The allocation factor A is 0.1 (6/58), which means that 10% of the burdens from forestry and 100% of the burdens from recovery and recycling are allocated to the recycled wooden blocks;
- The Circular Footprint Formula—as our case study has been scoped from the cradle to the market, only a part of the CFF formula (for Material) has been applied. The formula has been sourced from the Commission Recommendation (EU) 2021/2279 [62] and presented in an Equation (1):

$$Material(1 - R_1)E_v + R_1 \times (AE_{recycled} + (1 - A)E_v \times \frac{Q_{sin}}{Q_p}) \tag{1}$$

R_1 means the proportion of material in the input to the production that has been recycled from a previous system. In our case study R_1 = 1, as 100% of secondary wood is used to fabricate the secondary wooden blocks, no primary wood is used. Other ingredients like maize and water have been excluded from calculation of R_1. E_v means specific emissions and resources consumed arising from the acquisition and pre-processing of virgin material. $E_{recycled}$ means specific emissions and resources consumed arising from the recycling process of the recycled (reused) material [62]. Factor A allocates burdens and credits from recycling and virgin material production between two life cycles and it aims to reflect market realities [69]. As a material-specific A value is not available for wooden scrap from bulky waste, an A value of 0.5 has been used. Q_{Sin} means a quality of the ongoing secondary material and Q_p relates to the quality of the primary material [69]. In our case study, the Q_{Sin}/Q_p has been calculated based on the prices and assumed as 0.1 (6/58). Finally, 5% of the burdens from forestry $(1 - A)E_v \times \frac{Q_{sin}}{Q_p}$ = (1 − 0.5) × 0.1 = 0.05) and 50% of the burdens of recovery and recycling (A = 0.5) have been allocated to the recycled blocks.

2.2.2. Life Cycle Inventory (LCI)

The study examines the findings relating to the quality and quantity of the fractions into which bulky waste is sorted. Using a bulky waste processing model verified by the entrepreneur, flows of bulky waste fractions were simulated from the input phase, understood as waste entering the plant, to the output phase, understood as waste leaving the individual processing stages, and also from the amount and composition of waste fractions that are processed. The challenges towards waste recycling and substitutability of primary materials emphasize the importance of improving current processing procedures to improve quality and to enable more market applications of the waste recovered. The purpose of using material flow analysis in the processing of bulky waste was to determine the recycling potential of the waste. The most interesting material fractions in terms of quantity and recyclability include wood, fibers, metals, and plastic fractions. The optimization of sorting processes makes it possible to separate the fraction of wood waste from the stream of bulky waste in order to direct this waste to recycling. The analysis of the flow of materials in the bulky waste sorting installation, based on their morphological composition, is presented in a Sankey Diagram (Figure 2). The potential amounts and types of waste directed to recycling were determined based on the processing of 25,000 Mg [mega grams] of bulky waste using a system of modernized installations. These were selected on the basis of the literature on morphological composition, using transfer coefficients calculated experimentally, and based on a literature review [72]. The efficiency of wood recycling as a result of the processing of a bulky waste stream was calculated to be 39.42% by relating the amount of waste directed to recycling to the stream of waste directed to processing.

On the basis of the Material Flow Analysis and the development of the recycling process, the inventory results have been collected and recalculated per functional unit—the production of 1 m^3 of secondary wooden blocks. In order to receive 1 m^3 of final wooden blocks, 817 kg of wood waste needs to be separated from 2072.3 kg of bulky waste. The final blocks have an average density of 958 kg/m^3. Table 1 presents the names of datasets and activity data used for the baseline scenario where the cut-off (100:0) approach has been applied. This means that 0% of the burdens for forestry and 100% of the burdens from recycling have been allocated to the product system of secondary wooden blocks. The ecoinvent database (3.9.1) has been used to model the background processes.

Table 1. Inventory results per 1 m^3 of secondary wooden blocks—the baseline scenario.

TRANSPORT OF BULKY WASTE		
Transport, freight, lorry 3.5–7.5 metric tons	103.6 (2.07 Mg × 50 km)	tkm
RECOVERY—PROCESSING OF BULKY WASTE AND SEPARATION OF THE WOOD FRACTION (shredding, magnetic separation, ballistic separation, cutting, stirring, pressing)		
Electricity, low voltage (electricity mix for Europe)	2455.5	kWh
RECYCLING—FABRICATION OF SECONDARY WOODEN BLOCKS (shredding, homogenization of the structure of the material, stirring and pressing together with additives)		
Secondary wood, separated from bulky waste (burden free)	817.0	kg
Maize starch	44.9	kg
Tap water	95.6	kg
Electricity, low voltage (electricity mix for Europe)	2663.3	kWh
DISTRIBUTION OF SECONDARY WOODEN BLOCKS		
Transport, freight, lorry 7.5–16 metric tons	95.8 (0.958 Mg × 100 km)	tkm

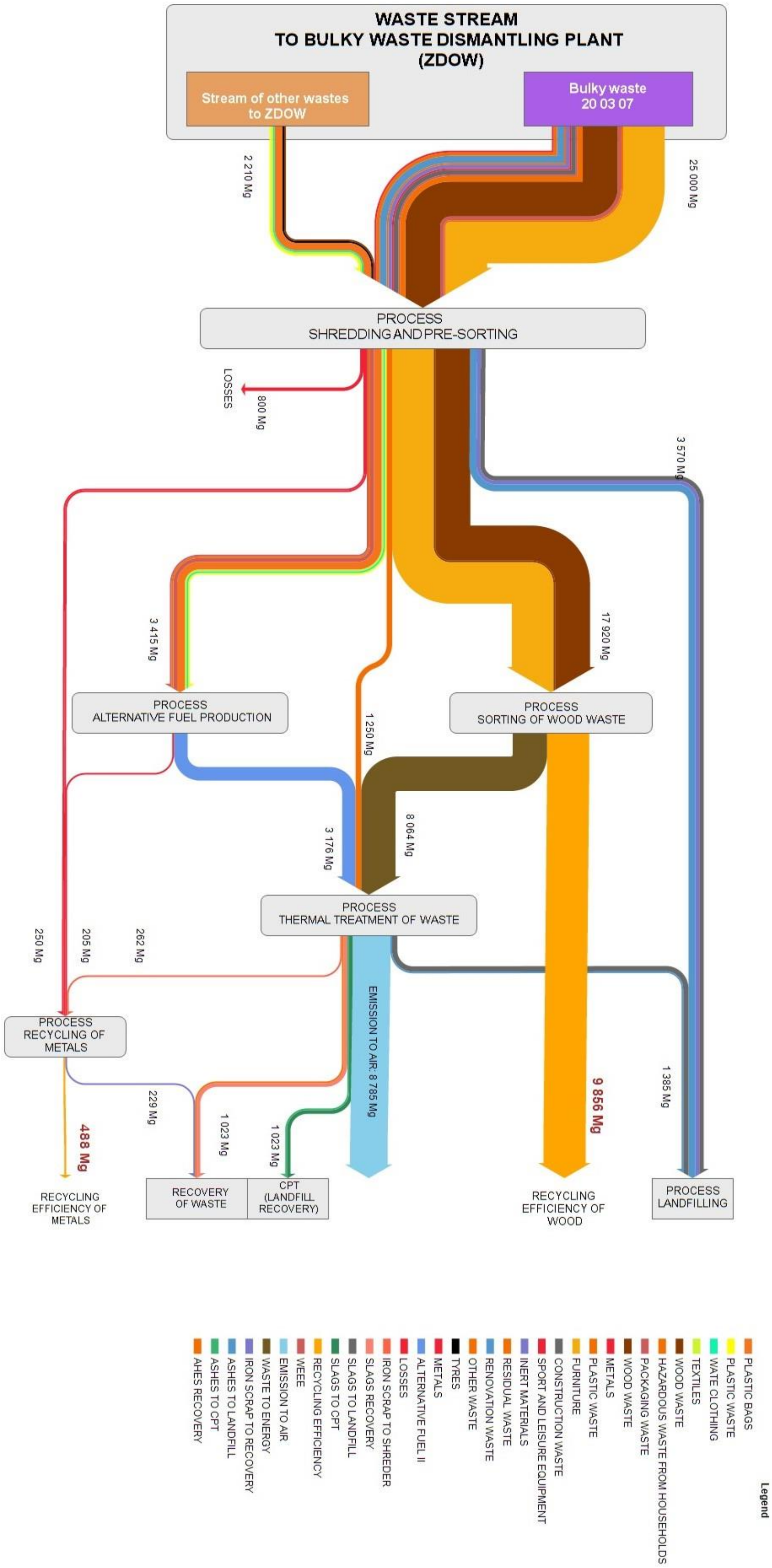

Figure 2. Sankey diagram of bulky waste processing.

3. Results—Life Cycle Impact Assessment (LCIA)

The LCA calculations were made with SimaPro 9.5.0.1 software and the ecoinvent database (3.9.1). The Environmental Footprint 3.1 (adapted) V1.00/EF 3.1 normalization and weighting set method has been used to assess the potential environmental impact. The method includes 16 impact categories. The LCIA results can be obtained on various levels: weighting, normalization, and characterization. Regardless of the level, the higher the score of the indicator, the greater the negative environmental impact. The results will be presented below by reference to the goal of the study.

3.1. What Are the Environmental Hotspots in the Life Cycle of Secondary Wooden Blocks?

For the baseline scenario, the total potential environmental impact (single score) for the life cycle (from cradle to market) of the recycled wooden blocks is 229 mPt (Figure 3). The main drivers of the impact are two processes: recycling (52.2%) and recovery (45%).

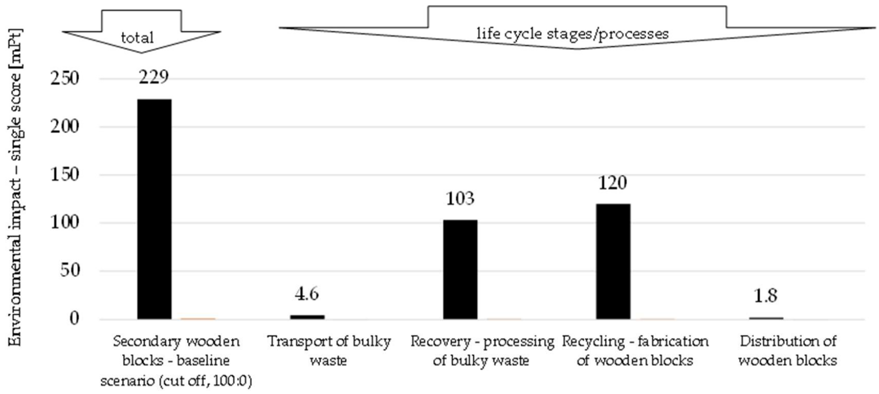

Figure 3. Recycled wooden blocks—cumulative environmental impact from cradle to market and the individual stages for the baseline scenario (cut off) [mPt/m^3 of wooden blocks].

Five of the most relevant impact categories identified: *Resource use, fossils* (24%), *Climate change* (23.9%), *Eutrophication, freshwater* (13.3%), *Resource use, minerals and metals* (11.8%), and *Ionizing radiation* (6.0%). The same relevant impact categories have been identified for the recovery and recycling processes (Table 2). Among the transport-related processes, *Resource use, fossils,* and *Climate change* are also the most important, but *Particulate matter* and *Acidification* are significant as well (Table 2).

Table 2. Secondary wooden blocks (baseline)—a list of the most relevant impact categories.

Life Cycle of the Secondary Wooden Blocks –Baseline Scenario (Cut Off) (% Vertically)	The Most Relevant Impact Categories	Life Cycle Stages (% Horizontally)			
		Transport of Bulky Waste	Recovery—Processing of Bulky Waste	Recycling—Fabrication of Wooden Blocks	Distribution of Wooden Blocks
24.0%	Resource use, fossils	22.6%	24.6%	23.6%	22.6%
23.9%	Climate change	35.1%	23.7%	23.5%	35.0%
13.3%	Eutrophication, freshwater	1.9%	13.9%	13.3%	1.5%
11.8%	Resource use, minerals, and metals	6.5%	12.1%	11.9%	4.7%
6.0%	Ionizing radiation	0.4%	6.4%	6.0%	0.3%
5.4%	Acidification	4.3%	5.4%	5.5%	4.4%
3.1%	Particulate matter	11.0%	2.7%	3.1%	12.9%

Recovery and recycling are the two main drivers of the environmental impact. The main reason for the impact is the high electricity consumption involved in both processes which totaled 5119 kWh per 1 m^3 of wooden block. The share of the particular processes in the results of the most relevant impact categories is presented in Figure 4. It is evident that the impact generated in the supply chain of electricity is the most obvious environmental hot spot. The electricity consumption has been modeled with an electricity mix representative of Europe.

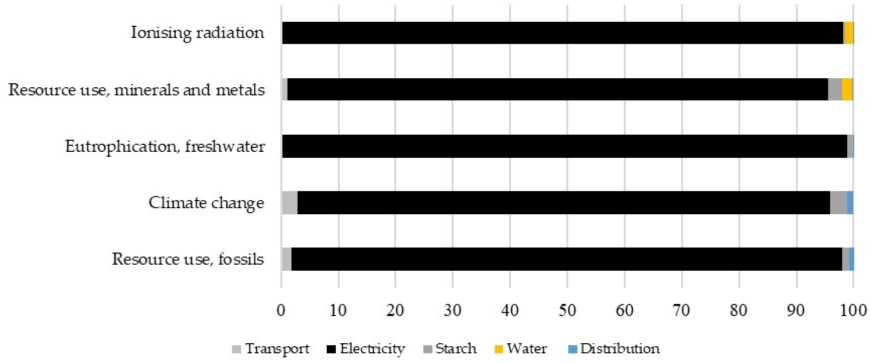

Figure 4. Recycled wooden blocks baseline scenario (cut off)—share of processes in the results identified for the most relevant impact categories.

3.2. Are the Results Sensitive to the Choice of Allocation Procedure?

In the baseline scenario, the cut-off (100:0) approach has been used to model the multi-functionality resulting from the recovery and recycling. However, different approaches to allocation are available in the LCA methodology. The goal of this section is to answer the following question: *are the baseline results sensitive to a choice of allocation procedure?* In order to find the answer, we recalculated the inventory data (to allocate LCI results between the previous and subsequent product systems according to the allocation system) and, as a next step, we made the LCIA calculations. The LCIA results (as a single score) are presented in Figure 5. This shows that the results are sensitive to a change in the allocation procedure. If the CFF approach is applied, the single score is 116 mPt (a reduction of 49%). For the price-based approach, the results have changed negligibly (an increase of 0.5%). This is due to the fact that with the parameters assumed for the market price-based approach (A = 0.1), both approaches (the cut-off and the market price-based) allocate impacts in a very similar way. The inclusion of 10% of burdens from forestry makes a difference only by 1 mPt (from 229 mPt to 230 mPt).

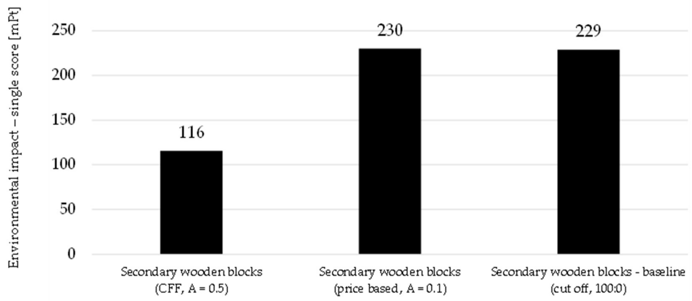

Figure 5. Environmental impact (single score) from cradle to market of secondary wooden blocks modeled with different approaches to allocation [mPt/m^3 of secondary block).

3.3. Are the Secondary Wooden Blocks an Environmentally Better or Worse Option in Comparison to the Market Alternatives?

In order to make a comparison, potential alternative products with recognized applications in the furniture industry were identified. We selected six wood or wood-based boards to be compared with the secondary wooden blocks: Fiberboard, hard (HDF), Fiberboard, medium (MDF), Tabular particleboard/Low-density fiberboard (LDF), Sawn wood board, hardwood, and Sawn wood board, softwood. Additionally, in the case of the secondary wooden blocks, the electricity consumption during recovery and recycling has been modeled as renewable energy generated from wind. The secondary inventory data (from cradle to market) have been taken from the Ecoinvent 3.9.1 database. Figure 6 presents the LCIA results for all alternatives per functional unit (1 m^3 of product).

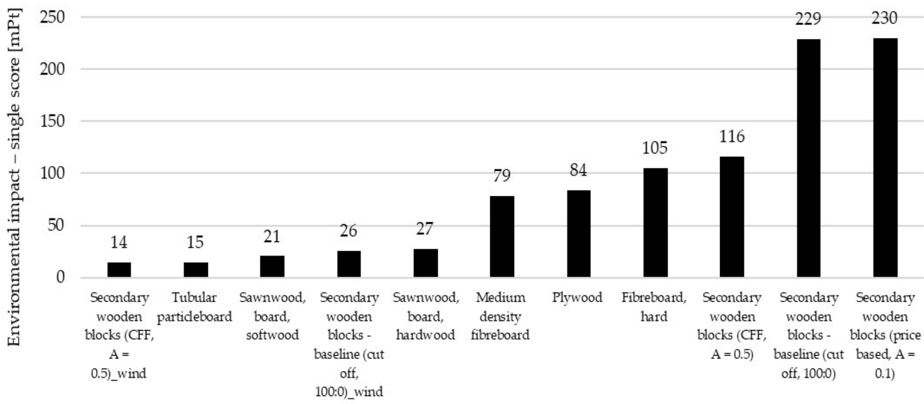

Figure 6. The environmental impact (single score) from cradle to market of secondary wooden blocks and alternative boards [mPt/m^3].

4. Discussion

The taxonomy introduced by the EU regulations [28] requires the introduction of principles of sustainable investment in order to increase the recyclability of products by implementing a closed-circle economy. Therefore, it is important to introduce the recycling of waste, especially recycling involving problematic wastes, on a progressively larger scale. These indisputably include bulky wastes that are difficult to recycle due to their structure and content of harmful substances. Attempts to recycle bulky waste are made by defibering and the fabrication of new boards [30–32]. The production of composites using wood waste is also popular [38,39]. A logical and effective way to achieve a high recycling rate seems to be the cascading use of bulky waste and wood waste [37,73]. Works on the LCA of bulky wastes indicate that their reuse contributes to avoiding a new target production, which is associated with the reduction of greenhouse gas emissions and the consumption of fossil resources [7].

The research carried out in this work shows that the use of the bonding method for processing shredded bulky waste together with the use of a binder (starch combined with water) works well as a method of obtaining a new product. The environmental hot spots in the method have been identified (Q1). In terms of impact categories, the LCA has demonstrated that the production of blocks has the greatest impact in the following categories: Resource use, fossils (24%), Climate change (23.9%), Eutrophication, freshwater (13.3%), Resource use, minerals and metals (11.8%) and Ionizing radiation (6.0%). From the perspective of inventory, electricity consumption has been recognized as the most relevant issue. This is due to the high electricity consumption of electricity by equipment and machinery used for the processing of waste and the fabrication of the blocks. The direct usage is 5119 kWh/m^3 for the baseline (cut off) and for the market price-based scenarios, 2560 kWh/m^3 for the CFF approach with factor A = 0.5. The variation in energy demand is the main driver of differences in LCA results between various approaches to allocation (Figure 6).

The results are sensitive to a change in the allocation procedure (Q2). The potential impact for the baseline scenario is 229 Pt (cut-off). If the CFF approach is applied, the single score is 116 mPt which means a reduction of 49%. For the price-based approach, the results have changed negligibly. This is due to the fact that with the parameters assumed for the market price-based approach (A = 0.1), both approaches (the cut-off and the market price-based) allocate impacts in a very similar way.

The energy demand also impacts the results when compared with alternative products (Q3). Although their production requires a lot of components (resins, organic chemicals, paraffin, aluminum sulfate), the electricity consumption is visibly lower than for wooden blocks. For example, in the case of HDF, the electricity demand is 503 kWh/m^3 and 220 kWh/m^3 for MDF. If no renewable energy is used, the secondary wooden blocks are the worst scenario. The use of renewable (wind, onshore, 1–3 MW, PL) electricity for recovery and recycling makes the results lower and ranks the wooden blocks at the beginning of the ranking (best options). It should be noted that the demand for electricity was calculated on a laboratory scale. Reducing electricity consumption and using renewable electricity are probable to be achieved with an increase in the production scale. After these improvements, this method makes it possible to use furniture waste in its entirety, which is in compliance with the new EU standards. In addition, the use of bulky waste for recycling affects the reduction of waste storage at landfills and the consumption of primary raw materials.

The hot spots identified in our case study are similar to those indicated by Jungmeier et al. [44]. They recognized the quality of recycled material (product), material efficiency, energy consumption (amount and type), water demand, and sludge generation (quality and treatment) as the most relevant issues. As no LCA study has been found for wood recovered from bulky waste, we compared our results with other studies. The comparison with the assessment made by the Nordic Council of Ministers [45] was feasible because similar system boundaries and the same EF method have been used in both cases. We compared the characterized results for our secondary wooden blocks with the results obtained by the Nordic Council of Ministers for wood-waste-based particle boards and composite boards [45]. In both case studies, energy proved to be a main driver of the environmental impact. In all scenarios where the use of electricity mix for Europe was assumed, our secondary wooden blocks were a few times worse than the results obtained for the particle board and the composite. However, the change in the wind electricity in the production of the secondary wooden blocks impacted the ranking substantially. In this situation, the blocks could be recognized as better environmental alternatives in terms of acidification, climate change, freshwater eutrophication (particle board and composite), and fossil abiotic resources and water use (particle board).

5. Conclusions

The taxonomy on the basis of the results obtained, the following conclusions can be formulated:

- The objective of the article was to propose and attempt to evaluate, using LCA, a management system for bulky waste, in particular wood and wood-based wastes coming from the selective collection of municipal waste.
- The largest impact is exerted by the electricity used. Yet, it should be noted that the demand for electricity was calculated on a laboratory scale. Reducing electricity consumption and using renewable electricity are the most evident recommendations for further improving the process.
- A choice of electricity type impacted the results strongly. If the European electricity mix was assumed, the results for secondary blocks were very high. If renewable sources are used (in our calculations wind power has been assumed), the environmental score for secondary wooden blocks decreases to a level similar to or even lower than for other alternatives. Reduction of electricity consumption (as a result of switching from

laboratory to commercial scale) through the use of renewable energy sources will allow the development of a technology for the production of new material with a limited impact on the environment in relation to the current solution. The use of the LCA method ensures that the result of the environmental impact assessment is measurable and objective.

- The results are highly sensitive to the choice of allocation procedure. It should be noted that the secondary blocks have been ranked differently depending on the type of approach used to model multifunctionality. In this context, agreeing on a single common approach to model multifunctionality would be desirable. The Circular Footprint Formula [69] is a good example of looking for this kind of consensus.
- The proposed methodology may serve as an element of quality assessment of new products in the circular economy and in environmental management in the waste management sector.

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Abbreviations

The following abbreviations are used in this manuscript:

CFF	Circular Footprint Formula
EU	European Union
FRO	Furniture Reuse Organizations
FW	Furniture Waste
ISO	International Organization for Standardization
LCA	Multidisciplinary Digital Publishing Institute
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LDF	Low Density Fiberboard
HDF	High Density Fiberboard
MDF	Medium Density Fiberboard
MFA	Material Flow Analysis
RDF	Refuse-Derived Fuel
SFA	Substance Flow Analysis
WPP	Wood Waste Particles
WSARC	Water-Soluble Acrylic Resin Coatings
WWP	Wood Waste Particles

References

1. Gronba-Chyła, A.; Generowicz, A. Municipal waste fraction below 10 mm and possibility of its use in ceramic building materials. *Przem. Chem.* **2020**, *99*, 1318–1321. (In Polish) [CrossRef]
2. Höglmeier, K.; Weber-Blaschke, G.; Richtera, K. Utilization of recovered wood in cascades versus utilization of primary wood—A comparison with life cycle assessment using system expansion. *Int. J. Life Cycle Assess.* **2014**, *19*, 1755–1766. [CrossRef]
3. Vis, M.; Mantau, U.; Allen, B. (Eds.) Cascades. Study on the Optimized Cascading Use of Wood. No 394/PP/ENT/RCH/14/7689. Final Report. Available online: https://op.europa.eu/en/publication-detail/-/publication/04c3a181-4e3d-11e6-89bd-01aa75ed71a1 (accessed on 26 January 2025).
4. Report of Polish Chamber of Commerce of Furniture Manufacturers. Available online: http://www.oigpm.org.pl/865/raport-polskie-meble-outlook-2022 (accessed on 26 January 2025).
5. Polskie Meble Outlook. Sectoral Report Prepared by B+R Studio Tomasz Wiktorski. Available online: www.brstudio.eu (accessed on 26 January 2025).
6. Mantau, U. Wood Flow Analysis: Quantification of Resource Potentials, Cascades and Carbon Effects. *Biomass Bioenergy* **2015**, *79*, 28–38. [CrossRef]
7. Nowaczek, A.; Kowalski, Z.; Kulczycka, J.; Makara, A. Determinants of the Implementation of a Circular Economy Model in the Tire Sector in Poland. *Sustainability* **2024**, *16*, 11167. [CrossRef]
8. Kajda-Szcześniak, M.; Czop, M. Comparison of pyrolysis and combustion processes of vinyl floor panels using thermogravimetric analysis (TG-FTIR) in terms of the circular economy. *Energies* **2022**, *15*, 1516. [CrossRef]
9. Cooper, T.; Kaner, J.; Furmston, K.; Cutts, A. Furniture lifetimes in a circular economy: A state of the art review. In Proceedings of the 4th PLATE 2021 Virtual Conference, Virtual, 26–28 May 2021; pp. 1–8. [CrossRef]
10. Yousef, F.; Truijens, J. Efficient Logistics for Circular Furniture Flows. Master's Thesis, University of Gothenburg, Gothenburg, Sweden, 2016. Available online: https://gupea.ub.gu.se/bitstream/handle/2077/44892/gupea_2077_44892_1.pdf?sequence=1&isAllowed=y (accessed on 26 January 2025).
11. Xiong, N.; Lu, H.; Yang, X.; Wang, J.; Yue, D. Spatial characteristics and multifactorial driving analysis of fly-tipping bulky waste in Beijing based on the random forest model. *J. Clean. Prod.* **2022**, *363*, 132534. [CrossRef]
12. Top, Y. Waste generation and utilization in micro-sized furniture-manufacturing enterprises in Turkey. *Waste Manag.* **2015**, *35*, 3–11. [CrossRef]
13. Report of the European Environmental Bureau on the Circular Economy in the Furniture Sector. Available online: https://eeb.org/wp-content/uploads/2019/05/Report-on-the-Circular-Economy-in-the-Furniture-Sector.pdf (accessed on 26 January 2025).
14. Final Report of MSW Consultants and Center for Ecotechnology on Statewide Bulky Waste Characterization Study. Available online: https://www.mass.gov/doc/statewide-bulky-waste-characterization-study-june-2022/download (accessed on 26 January 2025).
15. Balcerzak, W.; Generowicz, A.; Mucha, Z. Application of multi-criteria analysis for selection of a reclamation method for a hazardous waste landfill. *Pol. J. Environ. Stud.* **2014**, *23*, 983–987.
16. Minelgaitė, A.; Liobikienė, G. Waste problem in European Union and its influence on waste management behaviours. *Sci. Total Environ.* **2019**, *667*, 86–93. [CrossRef]
17. Gotowska, M. New challenges for business of waste management in Poland on the example of REMONDIS Bydgoszcz sp. z o.o. *Manag. Theory Pract.* **2019**, *2*, 29–36. (In Polish)
18. Demirarslan, K.; Demirarslan, D. Furniture Wastes and Their Environmental Impacts as Being a Different Problem of Our Time. *Int. J. Adv. Eng. Pure Sci.* **2021**, *33*, 97–105. [CrossRef]
19. Salthammer, T.; Schwarz, A.; Fuhrmann, F. Emission of reactive compounds and secondary products from wood-based furniture coatings. *Atmos. Environ.* **1998**, *33*, 75–84. [CrossRef]
20. Christensen, T.H.; Fruergaard, T.; Matsufuji, Y. Residential Waste. In *Solid Waste Technology and Management*; Christensen, T.H., Ed.; Wiley: Chichester, UK, 2011; pp. 85–96.
21. Ramusch, R.; Pertl, A.; Scherhaufer, S.; Schmied, E.; Obersteiner, G. Modelling informally collected quantities of bulky waste and reusable items in Austria. *Waste Manag.* **2015**, *44*, 3–14. [CrossRef] [PubMed]
22. Przydatek, G.; Kochanek, A.; Basta, M. Analysis of changes in municipal waste management at the county level. *J. Ecol. Eng.* **2017**, *18*, 72–80. [CrossRef]
23. Chen, Q.; Zhang, J.; Zhang, C.; Dong, Z.; Yue, Y.; Xu, Q. Effects of water-soluble acrylic resin coatings on the pyrolysis behavior of wooden bulky waste. *Fuel Process. Technol.* **2022**, *228*, 107170. [CrossRef]
24. Hanandeh, A.E. Carbon abatement via treating the solid waste from the Australian olive industry in mobile pyrolysis units: LCA with uncertainty analysis. *Waste Manag. Res.* **2013**, *31*, 341–352. [CrossRef]
25. Larsen, A.W.; Petersen, C.; Christensen, T.H. Bulky waste quantities and treatment methods in Denmark. *Waste Manag. Res.* **2012**, *30*, 147–154. [CrossRef]

26. Poluszyńska, J. The content of heavy metal ions in ash from waste incinerated in domestic furnaces. *Arch. Environ. Prot.* **2020**, *46*, 68–73. [CrossRef]
27. Rybiński, P.; Syrek, B.; Szwed, M.; Bradło, D.; Żukowski, W.; Marzec, A.; Śliwka-Kaszyńska, M. Influence of Thermal Decomposition of Wood and Wood-Based Materials on the State of the Atmospheric Air. *Emiss. Toxic. Compd. Greenh. Gases. Energ.* **2021**, *14*, 3247. [CrossRef]
28. Ciuła, J.; Generowicz, A.; Mitryasova, O.; Jasińska, A.; Jurkowski, S.; Kwaśnicki, P. The Analysis of Geospatial Factors Necessary for the Planning, Design, and Construction of Agricultural Biogas Plants in the Context of Sustainable Development. *Energies* **2024**, *17*, 5619. [CrossRef]
29. Regulation of EU Parliment and EU Council 2020/852 of 18 June 2020 Establishing a Framework to Facilitate Sustainable Investments, and Amending EU Regulation 2019/2088. Available online: https://eur-lex.europa.eu/eli/reg/2020/852/oj/eng (accessed on 26 January 2025).
30. Lubis, M.A.R.; Hong, M.-K.; Park, B.-D.; Lee, S.-M. Effects of Recycled Fiber Content on the Properties of Medium Density Fiberboard. *Eur. J. Wood Prod.* **2018**, *76*, 1515–1526. [CrossRef]
31. Ihnát, V.; Lübke, H.; Russ, A.; Borůvka, V. Waste Agglomerated Wood Materials as a Secondary Raw Material for Chipboards and Fibreboards Part I. *Prep. Charact. Wood Chips Terms Their Reuse. Wood Res.* **2017**, *62*, 45–56.
32. Hong, M.-K.; Lubis, M.A.R.; Park, B.-D.; Sohn, C.H.; Roh, J. Effects of Surface Laminate Type and Recycled Fiber Content on Properties of Three-Layer Medium Density Fiberboard. *Wood Mater. Sci. Eng.* **2020**, *15*, 163–171. [CrossRef]
33. Hartini, S.; Wicaksono, P.A.; Rizal, A.M.D.; Hamdi, M. Integration lean manufacturing and 6R to reduce wood waste in furniture company toward circular economy. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1072*, 012067. [CrossRef]
34. Valizadeh, S.; Jang, S.-H.; Rhee, G.H.; Lee, J.; Show, P.L.; Khan, M.A.; Jeon, B.-H.; Lin, K.-Y.A.; Ko, C.H.; Chen, W.-H.; et al. Biohydrogen production from furniture waste via catalytic gasification in air over Ni-loaded Ultra-stable Y-type zeolite. *J. Chem. Eng.* **2022**, *433*, 133793. [CrossRef]
35. Maier, D.A. Review of the Environmental Benefits of Using Wood Waste and Magnesium Oxychloride Cement as a Composite Building Material. *Materials* **2023**, *16*, 1944. [CrossRef]
36. Azambuja, R.d.R.; de Castro, V.G.; Trianoski, R.; Iwakiri, S. Recycling Wood Waste from Construction and Demolition to Produce Particleboards. *Maderas. Cienc. Tecnol.* **2018**, *20*, 681–690. [CrossRef]
37. Akinyemi, B.A.; Okonkwo, C.E.; Alhassan, E.A.; Ajiboye, M. Durability and Strength Properties of Particle Boards from Polystyrene–Wood Wastes. *J. Mater. Cycles Waste Manag.* **2019**, *21*, 1541–1549. [CrossRef]
38. Mrówka, M.; Szymiczek, M.; Skonieczna, M. The Impact of Wood Waste on the Properties of Silicone-Based Composites. *Polymers* **2020**, *13*, 7. [CrossRef]
39. Kaho, S.P.; Kouadio, K.C.; Kouakou, C.H.; Eméruwa, E. Development of a Composite Material Based on Wood Waste Stabilized with Recycled Expanded Polystyrene. *Open J. Compos. Mater.* **2020**, *10*, 66–76. [CrossRef]
40. De Souza Pinho, G.C.; Calmon, J.L. LCA of Wood Waste Management Systems: Guiding Proposal for the Standardization of Studies Based on a Critical Review. *Sustainability* **2023**, *15*, 1854. [CrossRef]
41. Van den Auwelant, E.; Nimmegeers, P.; Van Passel, S. Life cycle assessment and circular practices in the woodworking sector: A systematic review. *Clean. Technol. Environ. Policy.* **2024**, 1–20. [CrossRef]
42. Sari, D.P.; Mahdiyah, A.S.; Purwaningsih, R. Assessing environmental impact and eco-efficiency of wood waste gallon holders using life cycle assessment. *J. Ecol. Eng.* **2025**, *26*, 336–349. [CrossRef] [PubMed]
43. Rivela, B.; Moreira, M.T.; Munoz, I.; Rieradevall, J.; Feijoo, G. Life cycle assessment of wood wastes: A case study of ephemeral architecture. *Sci. Total Environ.* **2005**, *357*, 1–11. [CrossRef]
44. Jungmeier, G.; Merl, A.; Mcdarby, F.; Gallis, C.; Hohenthal, C.; Petersen, A.K.; Spanos, S. End of Use and End of Life Aspects in LCA of Wood Products—Selection of Waste Management Options and LCA Integration. Available online: https://www.researchgate.net/publication/237678691_End_of_Use_and_End_of_Life_Aspects_in_LCA_of_Wood_Products_-_Selection_of_Waste_Management_Options_and_LCA_Integration/link/53d37c5e0cf220632f3cd045/download?_tp=eyJjb250ZXh0Ijp7InBhZ2UiOiJwdWJsaWNhdGlvbiIsInByZXZpb3VzUGFnZSI6Il9kaXJlY3QiLCJzdWJQYWdlIjpudWxsfX0 (accessed on 26 March 2025).
45. Nordic Council of Ministers. LCA for Treatment of Wood Waste in the Nordics. Available online: https://www.norden.org/en/publication/lca-treatment-wood-waste-nordics (accessed on 26 March 2025).
46. Gronba-Chyła, A.; Generowicz, A.; Alwaeli, M.; Mannheim, V.; Grąz, K.; Kwaśnicki, P.; Kramek, A. Municipal waste utilization as a substitute for natural aggregate in the light of the circular economy. *J. Clean. Prod.* **2024**, *440*, 140907. [CrossRef]
47. Markic, D.N.; Carapina, H.S.; Bjelic, D.; Bjelic, L.S.; Ilic, P.; Pesic, Z.S.; Kikanovicz, O. Using Material Flow Analysis for Waste Management Planning. *Pol. J. Environ. Stud.* **2019**, *28*, 255–265. [CrossRef]
48. Kleinhans, K.; Hallemans, M.; Huysveld, S.; Thomassen, G.; Ragaert, K.; Van Geem, K.M.; Roosen, M.; Mys, N.; Dewulf, J.; De Meester, S. Development and application of a predictive modelling approach for household packaging waste flows in sorting facilities. *Waste Manag.* **2021**, *120*, 290–302. [CrossRef]

49. Roosen, M.; Mys, N.; Kleinhans, K.; Lase, I.S.; Huysveld, S.; Brouwer, M.; Thoden van Velzen, E.U.; Van Geem, K.M.; Dewulf, J.; Ragaert, K.; et al. Expanding the collection portfolio of plastic packaging: Impact on quantity and quality of sorted plastic waste fractions. *Resour. Conserv. Recycl.* **2022**, *178*, 106025. [CrossRef]
50. Demets, R.; Van Kets, K.; Huysveld, S.; Dewulf, J.; De Meester, S.; Ragaert, K. Addressing the complex challenge of understanding and quantifying substitutability for recycled plastics. *Resour. Conserv. Recycl.* **2021**, *174*, 105826. [CrossRef]
51. *ISO 14040*; Environmental Management—Life Cycle Assessment—Principles and Framework. The International Organization for Standardization: Brussels, Belgium, 2006.
52. *ISO 14044*; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. The International Organization for Standardization: Brussels, Belgium, 2006.
53. De la Rúa Lope, C.; Lechón, Y. Life Cycle Assessment of Biofuel Production. In *Biofuels Production and Processing Technology*, 1st ed.; Riazi, M.R., Chiaramonti, D., Eds.; Taylor & Francis Group CRC Press: Boca Raton, FL, USA, 2017; Chapter 21; pp. 587–605. [CrossRef]
54. Mandegari, M.A.; Farzad, S.; Görgens, J.F. Economic and environmental assessment of cellulosic ethanol production scenarios annexed to a typical sugar mill. *Bioresour. Technol.* **2017**, *224*, 314–326. [CrossRef]
55. Meyer, D.E.; Upadhyayula, V.K. The use of life cycle tools to support decision making for sustainable nanotechnologies. *Clean. Technol. Environ. Policy* **2014**, *16*, 757–772. [CrossRef]
56. Yay, A.S.E. Application of life cycle assessment (LCA) for municipal solid waste management: A case study of Sakarya. *J. Clean. Prod.* **2015**, *94*, 284–293. [CrossRef]
57. Farzad, S.; Mandegari, M.A.; Görgens, J.F. Integrated techno-economic and environmental analysis of butadiene production from biomass. *Bioresour. Technol.* **2017**, *239*, 37–48. [CrossRef]
58. Beylot, A.; Muller, S.; Descat, M.; Ménard, Y.; Villeneuve, J. Life cycle assessment of the French municipal solid waste incineration sector. *Waste Manag.* **2018**, *80*, 144–153. [CrossRef]
59. Mayer, F.; Bhandari, R.; Gäth, S.A. Life cycle assessment on the treatment of organic waste streams by anaerobic digestion, hydrothermal carbonization and incineration. *Waste Manag.* **2021**, *130*, 93–106. [CrossRef]
60. Pérez, L.; Ziegler-Rodríguez, K.; Pérez, A.; Vásquez, Ó.; Vázquez-Rowe, I. Closing the gap in the municipal solid waste management between metropolitan and regional cities from developing countries: A life cycle assessment approach. *Waste Manag.* **2021**, *124*, 314–324. [CrossRef]
61. Generowicz, A.; Gronba-Chyła, A.; Kulczycka, J.; Harazin, P.; Gaska, K.; Ciuła, J.; Ocłoń, P. Life Cycle Assessment for the environmental impact assessment of a city' cleaning system. The case of Cracow (Poland). *J. Clean. Prod.* **2023**, *382*, 135184. [CrossRef]
62. Recommendation 2021/2279 of 15 December 2021 on the Use of the Environmental Footprint Methods to Measure and Communicate the Life Cycle Environmental Performance of Products and Organisations. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32021H2279 (accessed on 26 January 2025).
63. Corona, B.; Shen, L.; Reike, D.; Carreón, J.R.; Worrell, E. Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics. *Resour. Conserv. Recycl.* **2019**, *151*, 104498. [CrossRef]
64. Ekvall, T.; Björklund, A.; Sandin, G.; Jelse, K. Modeling Recycling in Life Cycle Assessment. Swedish Life Cycle Centre. Report number: 2020:05. Available online: https://www.lifecyclecenter.se/wp-content/uploads/2020_05_Modeling-recyling-in-life-cycle-assessment-1.pdf (accessed on 26 January 2025).
65. *ISO 14067*; Greenhouse Gases—Carbon Footprint of Products—Requirements and Guidelines for Quantification. The International Organization for Standardization: Brussels, Belgium, 2018.
66. Announcement of the Central Statistical Office on the Average Price of Wood in 2021 Year. Available online: https://stat.gov.pl/sygnalne/komunikaty-i-obwieszczenia/lista-komunikatow-i-obwieszczen/komunikat-w-sprawie-sredniej-ceny-sprzedazy-drewna-obliczonej-wedlug-sredniej-ceny-drewna-uzyskanej-przez-nadlesnictwa-za-pierwsze-trzy-kwartaly-2021-roku,268,8.html (accessed on 26 January 2025).
67. Announcement of the Central Statistical Office on the Average Price of Wood in 2019 Year. Available online: https://stat.gov.pl/sygnalne/komunikaty-i-obwieszczenia/lista-komunikatow-i-obwieszczen/komunikat-w-sprawie-sredniej-ceny-sprzedazy-drewna-obliczonej-wedlug-sredniej-ceny-drewna-uzyskanej-przez-nadlesnictwa-za-pierwsze-trzy-kwartaly-2019-roku,268,6.html (accessed on 26 January 2025).
68. Announcement of the Central Statistical Office on the Average Price of Wood in 2020 Year. Available online: https://stat.gov.pl/sygnalne/komunikaty-i-obwieszczenia/lista-komunikatow-i-obwieszczen/komunikat-w-sprawie-sredniej-ceny-sprzedazy-drewna-obliczonej-wedlug-sredniej-ceny-drewna-uzyskanej-przez-nadlesnictwa-za-pierwsze-trzy-kwartaly-2020-roku,268,7.html (accessed on 26 January 2025).

69. Announcement of the Central Statistical Office on the Average Price of Wood in 2022 Year. Available online: https://stat.gov.pl/sygnalne/komunikaty-i-obwieszczenia/lista-komunikatow-i-obwieszczen/komunikat-w-sprawie-sredniej-ceny-sprzedazy-drewna-obliczonej-wedlug-sredniej-ceny-drewna-uzyskanej-przez-nadlesnictwa-za-pierwsze-trzy-kwartaly-2022-roku,268,9.html (accessed on 26 January 2025).
70. Announcement of the Central Statistical Office on the Average Price of Wood in 2023 Year. Available online: https://stat.gov.pl/sygnalne/komunikaty-i-obwieszczenia/lista-komunikatow-i-obwieszczen/komunikat-w-sprawie-sredniej-ceny-sprzedazy-drewna-obliczonej-wedlug-sredniej-ceny-drewna-uzyskanej-przez-nadlesnictwa-za-pierwsze-trzy-kwartaly-2023-roku,268,10.html (accessed on 26 January 2025).
71. WasteMaster. Price List of Waste Wood. Available online: https://mamodpad.wastemaster.pl/cennik/odpady-drewniane (accessed on 26 January 2025).
72. Allesch, A.; Brunner, P.H. Material Flow Analysis as a Tool to improve Waste Management Systems: The Case of Austria. *Environ. Sci. Technol.* **2017**, *51*, 540–551. [CrossRef]
73. Besserer, A.; Troilo, S.; Girods, P.; Rogaume, Y.; Brosse, N. Cascading Recycling of Wood Waste: A Review. *Polymers* **2021**, *13*, 1752. [CrossRef]