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Circular Economy-based Product Substitution Design Rationale

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Abstract:

Purpose: This study describes an empirical study demonstrating the application of circular economy (CE) to respond to an urgent call to reduce plastic waste by utilizing waste from the furniture industry.

Design/methodology/approach: this study employed the measurements of environmental impacts of plastic and wood-based toothbrushes using a life cycle assessment, complemented by an analysis of the wood substitution design process from a CE perspective.

Findings: The findings from this study not only shed light on quantifying the benefits of product valorization improvement and retention but also provide a means of weighing the value against raw materials and production costs.

Research limitations/implications: The developed model is still limited to the use of waste to replace existing product materials. This study also did not include other industrial waste such as agro-industrial waste or other degradable materials which may open up many chances for further studies.

Practical implications: The study's primary contribution is a design rationale that assists the substitution of plastic material with wood waste, using toothbrushes as a case example of the substituted products.

Social implications: This newly developed material can give potential income sources for the communities.

Originality/value: The novelty of this study lies to the substitution model of non-degradable materials to a more environmentally friendly material which is studied thoroughly from functional analysis, design alternatives, and evaluation based on environmental, economic, and social aspects especially in case of personal care products (toothbrush).

Keywords: circular economy, life cycle assessment, material substitution, personal care product, sustainable design, wood waste

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1. Introduction

Plastic is not degraded in the soil and contains materials harmful to humans (Alam, Billah & Yajie, 2018; Olofinnade, Chandra & Chakraborty, 2020). Plastics originating from personal care products (PCP) are mainly released into the marine environment for several hundred years before being degraded (Cheung & Fok, 2016). Theoretically, plastic on the surface can be processed, but it can sink due to biofouling (Fazey & Ryan, 2016). Plastic pollution has been found in many coastal areas and seawater. The most abundant contaminants that can be found is plastic additives and PCP (León, García-Agüera, Moltó, Fernández-González, Llorca-Pérez, Andrade, J.M. et al., 2019), calling for an urgent response to tackle plastic pollution at the source (Cheung & Fok, 2016).

Microplastics have been commonly used in PCP until later documented as pollutants. The microplastic contamination of PCP was around 1500 tonnes/year and entered the global aquatic environment. PCP contributes emissions of about 1.2×10^4 tonnes/year. The primary plastic in PCP is polyethylene, which is known to be a highly degradation-resistant polymer. Even if microbeads are completely banned globally by 2020, the microplastics dumped into the environment will last for a long time (Sun, Ren & Ni, 2020). As the main source of primary microplastics, adding plastics to PCP should be stopped, and more environmentally friendly additives should be used.

One such product that is commonly made using polystyrene is a toothbrush. The toothbrush is disposable and has a short life, and as a result, toothbrush waste is considered high. In the US alone, considering the ideal age of toothbrushes is 3 months at most, more than 1 billion toothbrushes are disposed of yearly. A recent survey conducted in Malaysia has identified the potential of substituting PCP with environmentally friendly materials (Praveena, Shaifuddin & Akizuki, 2018). Furthermore, they recognized that toothbrush handles using plastic materials have the potential to be substituted by other renewable sources, e.g., wood waste, without degrading their primary functions, performance, and durability. These wooden pieces from the furniture industry can be used as a replacement material for toothbrush handles made of polystyrene. Refusing wood waste brings essential benefits in terms of material and energy savings and avoidance of GHG emissions in the forest and landfill (Bais-Moleman, Sikkema, Vis, Reumerman, Theurl & Erb, 2017).

Wood waste is inevitable during production, especially in the furniture industry. It poses unique challenges calling for an integrated approach to tackle it by better, more efficient design, better use of technology, and better manufacturing process to reduce its concomitant environmental impacts (Eshun, Potting & Leemans, 2012). There are several alternative solutions to environmental problems, including developing products by utilizing industrial waste (Changwichan & Gheewala, 2020; Ragaert, Huysveld, Vyncke, Hubo, Veelaert, Dewulf, J. et al., 2020; Jung, Pacheco, Sporket, Nascimento & Caten, 2021), and perhaps the most prevalent in the last 5 years is the adoption of the circular economy (CE) principles.

With the principles of "cascading, minimizing leakage, maximizing retained value" (Ripanti & Tjahjono, 2019), the growing population pressures natural resources, and this unfettered growth makes it imperative to shift from the traditional linear model (take-make-dispose) to a CE model (Govindan & Hasanagic, 2018; Kurdve & Bellgran, 2021). Companies must keep materials in proper status toward the CE by avoiding dissipation and hibernation of materials into the environment. Key strategies to prevent dissipation are increasing material efficiency and maintaining the material in the in-use state (Moraga, Huysveld, Meester & Dewulf, 2021). Traditionally, CE is closely associated with resource efficiency, leading to the introduction of 6R: reuse, reduce, recycle, recovery, redesign, and remanufacturing (Jawahir & Bradley, 2016). Nonetheless, CE should cover technical and biological materials, the latter focusing on cascading biological and chemical processes that prevent waste and pollution rather than a closed loop recirculation.

This paper describes an integrated study to substitute non-degradable products with degradable materials from other products' waste. Along with the advancement in eco-design, sustainable product substitution has gained popularity in recent years. The urgency for this study was triggered by the amount of non-degradable materials entering the waste stream and causing environmental concerns. The subsequent sections are organized as follows. Section 2 provides a literature review on CE and previous studies on product substitution. Section 3 describes the development of the framework for a product substitution. Section 4 presents a case study to substitute polystyrene material on a plastic toothbrush using wood waste and discusses its findings. The paper concludes with the lessons learned, followed by a summary of the contributions to knowledge and future research direction.

2. Literature Review

2.1. Circular Economy (CE)

The circular economy (CE) is an economic model that efficiently uses resources through waste minimization, long-term value retention, reduction of crucial resources, and closed-loop products. In CE, the part of products and materials is within the boundaries of environmental protection and social-economic benefits. CE can lead to sustainable development, where economic growth is voided by the negative consequences of resource depletion and environmental degradation (Hofmann, 2019; Morseletto, 2020). CE is a matter of maintaining added value to products for as long as possible and waste eliminated (Mair & Stern, 2017). The Ellen MacArthur Foundation defines a CE as an industrial system that is restorative and regenerative by intention and design (Lieder & Rashid, 2016). CE is based on three principles: reduce, reuse, and recycle (Yong, 2007). In CE theory, the cascade term is also used. Although some literature states the concepts of CE and cascading use (CU) have differences, CE and CU use materials and products several times to improve resource utilization and efficiency (Mair & Stern, 2017). The CU is only in the scope of biomass and biobased waste streams (Bezama, 2016).

The principle of CU is an approach to retaining the value of the material as long as possible (Bezama, 2016; Mair & Stern, 2017). Cascading is the sequential use of a resource for different purposes, ideally going through several phases of material reuse before being recycled or incinerated for energy recovery. Cascading is concerned with resource efficiency sequences often combined with recycling (Blomsma & Brennan, 2017). Study on cascading of CE has focused on the possibility of using waste by-products (Zabaniotou & Kamaterou, 2019). The cascading process includes several use phases to maximize the material's highest value and must be understood from multiple perspectives. Timber receives the most significant conceptual and empirical attention on CE integration and cascading (Mair & Stern, 2017).

Several studies related to CE in the furniture industry have been conducted. Those studies include barriers and drivers (Barbaritano, Bravi & Savelli, 2019); challenges and opportunities (Oliveira, França & Rangel, 2018); business model (Wicaksono, Hartini, Sutrisno & Nabila, 2020); the relationship between environmental-oriented supply chain cooperation on the CE-targeted performances (Susanty, Tjahjono, and Sulistyani, 2020); and strategy to reduce wood waste (Hartini, Wicaksono, Rizal & Hamidi, 2021). Empirical studies of the potential waste from the furniture production process and the challenges of utilizing the waste in a circular economy are still rarely conducted. When CE is combined with 6R, a closed-loop material flow can be realized, thus relieving inherent challenges in sustainable manufacturing systems (Bradley, Jawahir, Badurdeen & Rouch, 2018). The global Medium Density Fibreboard (MDF) production has reached more than 99 million m^3 in 50 countries (Selvatti, Borges, Soares, Souza & Junior, 2018), but only 40 to 60% is used effectively, and the rest becomes waste (Feil, Quevedo & Schreiber, 2015; Hartini, Puspitasari, Aisy & Widharto, 2020). Toxic substances further complicate the furniture industry as finishing materials (Zeng, Lu, Zhou, Chen, Rao, J. & Fan, 2018; Rinawati, Sriyanto, Sari & Prayodha, 2018; Hartini, Wicaksono, Prastawa, Hadyan & Sriyanto, 2019).

2.2. The Impacts of Plastic Waste

The most critical environmental issue today is the increase in plastic waste (Wu & Montalvo, 2020). A survey in Australia revealed that the ability to recycle plastics in 2016-2017 was only 415,200 tonnes of the 3,513,100 tonnes of plastic waste. The use of plastics in China generates more than 30 million tonnes of plastic waste per year (Wang, Zhao, Lim, Chen & Sutherland, 2020; Chen, Li, Xu & Zhang, 2019). Unfortunately, 4.8 to 12.7 million metric tons of plastic waste in coastal countries entered the sea (Jambeck, Geyer, Wilcox, Segler, Perryman, Andrady et al., 2015). With good plastic waste management in European countries, still, 41% is sent to incineration, and only 30% is recycled (Filho, Saari, Fedoruk, Iital, Moora, Kloga et al., 2019). Microplastics were found in leachate samples from landfills (Kazour, Jemaa, Issa, Khalaf & Amara, 2019), threatening the quality of drinking water and other water sources. Apart from plastic waste, many other wastes are generated by industry. Furniture industry waste also poses a serious problem (Kouchaki-Penchah, Sharifi, Mosazadeh & Hosseinabadi, 2016; Zeng et al., 2018; González-García, Feijoo, Heathcote, Kandelbauer & Moreira, 2011).

2.3. Previous Studies Related to Product Substitution

Several studies comparing the environmental impacts of products made from Plastic and alternative products have been carried out (see Table 1) (Woods & Bakshi, 2014; Foteinis, 2020; Barros, Puglieri, Tesser, Kuczynski & Piekarski, 2020). This situation is essential to determine the impacts of each product on the environment so that it can provide recommendations for users to choose more environmentally friendly products. However, studies providing alternative designs or more environmentally friendly materials seems to be lacking.

Mendoza, D'Aponte, Gualtieri and Azapagic (2019) conducted a study to reduce environmental impact by redesigning diapers using innovations "glue less." The glue-less diapers have a higher eco-efficiency. However, this research still uses non-degradable material, which negatively impacts the environment. Some are trying to conduct studies using degradable materials to substitute products with non-degradable materials. This material is more environmentally friendly and can function the same as non-degradable products, for example, the leaves used to make plates, Areca palm sheaths to make containers, and MDF waste to produce automotive components. Some of these studies can be seen in Table 2.

Author	Country	Object Research	Environmental Analysis	Result
Woods & Bakshi, 2014	US	Disposable cups versus Reusable cups	LCA using cumulative energy demand (CED), CML 2, TRACI2, and ReCiPe midpoint methods	Reusable cups are a better choice than polystyrene cups. Cups are washed in a standard dishwasher every use.
Foteinis, 2020	Greece	Paper cup versus reusable cup	ReCiPe LCIA method at the endpoint level.	Reusable cups are more environmentally sustainable than disposable ones for the landfilling and recycling scenario.
Barros et al., 2020	Brazil	Disposable plastic cups versus reusable plastic cups made of polypropylene	Intergovernmental Panel on Climate Change (IPCC), Institute of Environmental Science of Leiden University (CML), and International Life Cycle Data System (ILCD)	Replacing disposable plastic cups with reusable ones reduces waste and increases water consumption.

Table 1. Studies about conventional product and its alternative product

Author	Object Research	Substitution Material	Env. Analysis	Eco Analysis	Design Product	Circularity Strategy	Result
Papong, Malakul, Trungkavashirakun, Wenunun, Chom-in, Nithitanakul et al., 2014 Thailand	Comparing PET Bottles with PLA Bottles from cassava	Bioplastic polymer that is produced from cassava	LCA	N/A	N/A	Bioplastic waste: composting, incineration, and recycling.	PLA bottles are more environmentally friendly than PET bottles in terms of GHG emissions.
Jung et al., 2021 Brazil	A pyramidal absorber of electromagnetic radiation	The agriculture and furniture waste: rice husks and MDF waste	N/A	N/A	A pyramidal absorber of electromagnetic radiation	Product development from MDF and rice husk waste.	The pyramidal absorbers performed technically better in the frequency
van der Harst, Potting & Kroeze (2014) Netherlands	Comparing disposable cups from PS, PLA, and bio paper	Bio paper	LCA	N/A	N/A	Incineration Recycling Composting Anaerobic digestion	Bio compost cups (PLA or bio paper cups) are not necessarily more environmentally friendly.

Author	Object Research	Substitution Material	Env. Analysis	Eco Analysis	Design Product	Circularity Strategy	Result
Potting & van der Harst, 2015 Netherlands	Fossil-based PS cup versus bioplastic, bio paper, and reusable cups	Biobased and compostable plastic (polylactic acid; PLA), bio paper,	LCA	N/A	N/A	N/A	Reusable cups are not better or worse than disposable PS.
Schöggl, Baumgartner & Hofer, 2017 Germany	Automotive component	Bio-plastic automotive	N/A	N/A	Bio-plastic automotive	N/A	The development of a Checklist for Sustainable Product Development (CSPD)
Venkatachalam, Spierling, Endres & Siebert-Raths, 2018 Austria	Bio-based Plastic computer mouse body	Bio-based Plastic made of Poly Lactic Acid	ILCD/PEF, GaBi software.	N/A	Eco-design using bioplastics	N/A	Environmentally friendly design strategy in bio-based computer mouse
Gautam, Mata, Martins & Caetano Portugal	Plastic container versus areca palm sheath	Areca palm sheath	CML 2000, Simapro 7.3	N/A	N/A	N/A	Plates made from Areca palm sheath have lower environmental impacts than plastic plates.
Changwichan & Gheewala, 2020 UK	Single-use plastics cup versus multiple-use stainless steel	Single-use bio-based beverage cup from sugarcane feedstock	The ReCiPe life cycle impact assessment method	-	-	Reusing and recycling	Multiple-use stainless steel cups show better environmental performance than PP, PET, and PLA single-use cups.
Korbelyiova, Malefors, Lalander, Wikstrom & Eriksson, 2021 Sweden	Paper plate and leaf plate	Leaf waste	Carbon footprint paper and leaf plate	N/A	N/A	N/A	Paper plates have a lower climate change impact than leaf plates due to imports (energy for transportation)

Table 2. Research about comparing plastic products and alternative material

Reducing plastic waste can be done by reusing and repurposing (Changwichan & Gheewala, 2020; Barros et al., 2020), recycling, and composting (Jang, Lee, Kwon, Lim & Jeong, 2020; Changwichan & Gheewala, 2020; Wu & Montalvo, 2020). Reducing plastic waste can also be done by replacing plastics with degradable materials (Papong et al., 2014; Potting & van der Harst, 2015; Venkatachalam et al, 2018; Gautam et al., 2020; Changwichan & Gheewala, 2020; Korbelyiova et al., 2021). Previous studies that have been carried out to reduce environmental impacts have made significant contributions. The contribution is dominated by the effects of alternative materials on the environment. Economic analysis and the model for research design in providing direction so that material substitution efforts can have optimal performance have not been widely carried out and are fascinating to develop in producing environmentally friendly and circular products. According to Bocken, Pauw, Bakker and Grinten (2016), circular effects must be assessed on environmental, social, and economic sustainability performance.

3. Methodological Framework

3.1. Development of Framework

A circular economy describes an economic system based on business models that replace the "end-of-life" concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes (Kirchherr, Reike & Hekkert, 2017). Thus, operating at the micro, meso, and macro levels to accomplish sustainable development will create environmental quality, economic prosperity, and social equity for current and future generations. Based on the spirit of the CE, product design will use degradable production waste as a substitute for non-degradable products. This idea aims to reduce waste and, at the same time, reduce non-degradable product waste using Design Research Science (DSR). DSR is a domain-independent research strategy that develops knowledge of actions, processes, and systems to tackle field problems and take advantage of promising opportunities. It is not a specific method with fixed rules; instead, it is a strategy that can be operationalized in various ways (van Aken, Chandrasekaran & Halman, 2016). The research begins with developing a framework for using biomass waste to substitute non-degradable materials. This study starts with creating a framework for using biomass waste to replace non-degradable materials. The framework can be seen in Figure 1.

Economic circulation can be done by reusing, repurposing, and recycling existing waste. The first stage is to identify the waste based on its type, shape, and availability of the waste. Types of waste, for example, include solid or liquid objects and chemical substances contained therein. The shape consists of dimensions and levels of hardness. Apart from the type and form, the level of availability must also be a basis for consideration. Based on the waste identification, it is necessary to have information on non-degradable products that will be substituted. In this case, daily consumption of products with a short life was a priority. This situation considers that products routinely consumed with a short life potentially become a source of waste. The next stage is the product design stage, after it has been decided on the product to be substituted.

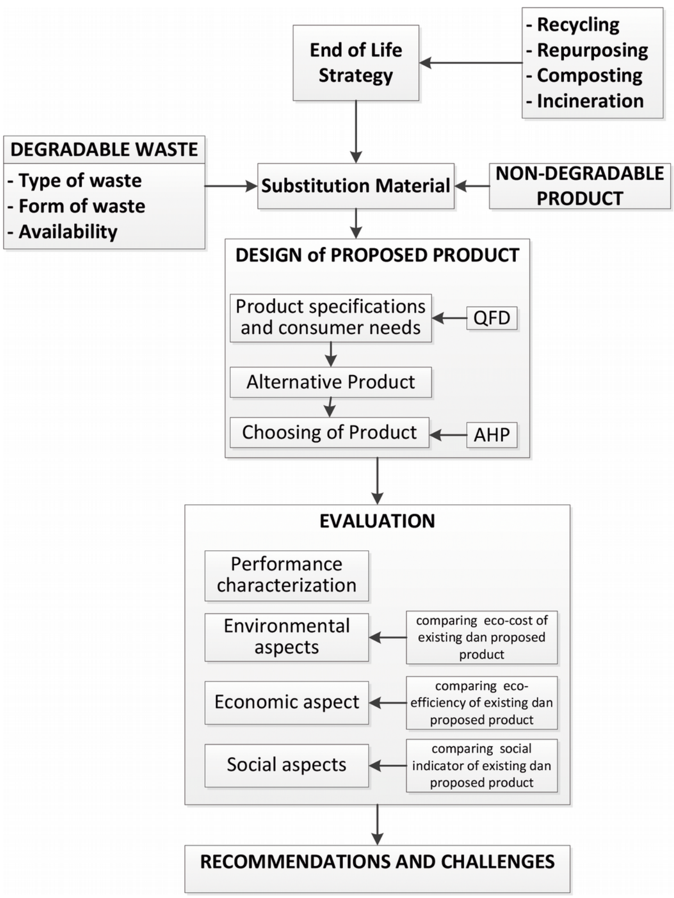

Figure 1. The framework for material substitution

3.2. Design of Proposed Product

Focusing on function and what matters about a product or process will lead to a better product or solution (Borza, 2011). Functional analysis is performed using the diagram Function Analysis System Technique (FAST), which can analyze product functions and describe the relationship between processes to increase the value of a product. The design stage begins with a functional analysis by considering the main, secondary, safety, ergonomic, and aesthetic functions. At this stage, several design alternatives were generated. Furthermore, the selected design was decided based on several criteria that have been developed using Analytic Hierarchy Process (AHP). The chosen product was made, and its performance was measured based on environmental, economic, and social aspects. The performance of the alternative product was compared with existing products.

3.3. Product Evaluation

3.3.1. Environmental Aspect

Evaluation is carried out by considering environmental, economic, and social aspects. Environmental aspects are evaluated by analyzing the environmental impact of the proposed product. LCA is a technique for assessing environmental impacts using quantitative analysis of the environmental impact of a product (Li, Xiao, Zhang & Amirkhanian, 2019). The performance of environmental aspects is measured by a life cycle assessment using the eco-cost method with the help of Simapro software. LCA has four stages of the process, consisting of 1) goal and scope definition,2) Life Cycle Inventory (LCI) analysis, 3) Life Cycle Impact Assessment (LCIA), and 4) interpretation (Corona, Shen, Sommersacher & Junginger, 2020; Dara, Hachem-Vermette & Assefa, 2019; Li et al., 2019; Ramos & Rouboa, 2020). The Life Cycle Impact Assessment (LCIA) analyzed the environmental impact where the value of each category is generated using the 2012 v1.00 eco-costs method with the help of SimaPro v 7.18 software. The category measured in the Eco Cost method is climate change, acidification, eutrophication, photochemical oxidant formation, fine dust, human toxicity, ecotoxicity, metals depletion, and oil and gas depletion, waste, and depletion of natural (Vogtlander, 2014; Vogtlander, Scheepens, Bocken & Peck, 2017). The stages of the LCIA calculation are divided into four stages: characteristics, normalization, weighting, and a single score of the resulting environmental impact (Suhariyanto, Wahab & Rahman, 2017; Corona et al., 2020)

3.3.2. Economic Aspect

A cost-benefit analysis was conducted to determine the net value of the product. Net value is obtained by reducing the benefits the company acquires in the product selling price with production cost represented by the cost of goods manufactured, including material costs, labor costs either directly or indirectly, the cost of electrical energy, and the cost of overhead companies.

A product feasibility measure has been developed by Vogtlander (2014) known as the eco-efficiency index (EEI). Eco-efficiency is a strategy combining economic and ecological efficiency concepts in using natural resources (Kharel & Charmondusit, 2008; Vogtlander et al., 2017; Hartini, Puspitasari et al., 2020; Purwaningsih, Simanjuntak & Rosyada, 2020). The formula for measuring EEI is net value divided by eco-cost.

$$\text{Net Value} = \text{Selling Price} - \text{Cost} \tag{1}$$

$$\text{EEI} = \text{Net Value} / \text{Eco-cost} \tag{2}$$

Eco-cost is a measure to express the amount of environmental burden of a product, based on the costs which should be made to reduce the environmental pollution and materials depletion to the environment's carrying capacity. The eco-costs should be regarded as hidden obligations, also called "external costs" in environmental economics (Vogtlander et al., 2017). The eco-cost measurement is calculated using the LCA approach with the help of Simapro software. Eco-cost is determined based on the use of the material and the energy and waste used (Susanty, Hartini, Puspitasari, Budiawan & Hidayatullah, 2015; Prastawa, Hartini, Anshori, Hans & Wimba, 2018; Hartini et al., 2019). If the EEI is more than 1, it is profitable and sustainable. If the EEI is in the range 0-1, it is said to be advantageous but not sustainable. Meanwhile, if the EEI is less than 0, it is not beneficial and unsustainable (Hur, Lim & Lee, 2003; Vogtlander, 2014).

Eco-Value Ratio (EVR) is an indicator of Eco-Efficiency (E/E) to describe the eco-efficiency of a product in terms of its economic contribution (value) to the environment. EVR is a dimensionless number that shows the relationship between the 2 P (profit and planet) of the Triple P (profit, planet, and people) model (Vogtlander et al., 2017; Klassen, Scheepens, Flipsen & Vogtlander, 2020; Hartini, Widharto, Indarto, & Murdikaningrum, 2021.

$$EVR = Eco{=}cost/value \quad (3)$$

EER Rate is the final calculation of the eco-efficiency measurement of the production process of products. The EER Rate calculation is obtained by reducing the product's net value with the eco-cost of the production process. Then the reduction result is subdivided by the net value of the product. Formula EER can be seen in Equation 3 (Purwaningsih et al., 2020).

$$EER = (1 - EVR)100\% \quad (4)$$

3.3.3. Social Aspect

Sustainable products also consider social aspects related to consumers' perception of the product (Cimatti, Campana & Carluccio, 2017). Social aspects can also be viewed regarding health and safety for stakeholders and the surrounding community (Hartini, Ciptomulyono, Anityasari & Sriyanto, 2020).

3.4. Final Recommendations

Recommendations was given based on the evaluation results at the previous stage. Recommendations suggest whether the waste used to substitute non-degradable materials is feasible to be developed or not.

4. Results and Discussion

4.1. CE Strategy of Polystyrene Toothbrushes

According to (Geissdoerfer, Pieroni, Pigosso & Soufani, 2020), there are 4 generic strategies for circular business models identified in the literature: (1) cycling; (2) extending; (3) intensifying; and (4) dematerializing. Toothbrush products have the potential to be cycled and extended. Cycling means that materials and energy are recycled within the system through reuse, remanufacturing, refurbishing, and recycling. Extending resource loops implies that the use phase of the products is extended through durable and timeless design and marketing that encourages long use phases, maintenance, and repair.

Plastic toothbrushes can be recycled into plastic pellets as raw material for other products. This recycling process requires a lot of energy. Communities that carry out recycling are still minimal and dominated by people who prefer to throw away. However, the toothbrush is challenging to degrade because toothbrushes are usually made of many components, including crude oil, rubber, and other plastic mixtures. This condition causes a toothbrush can decompose for more than hundreds of years. The cycling strategy on polystyrene toothbrushes can be seen in Figure 2.

When the toothbrush's bristles are not optimal, the head of the toothbrush can be removed from the handle. The brush head can be used as another cleaning tool until the bristles completely malfunction. When the bristles are damaged, the wood can be recycled into sawdust to become the raw material for MDF or composting. When the toothbrush handle is still in good condition, the handle can still be used again, where the user can simply buy a toothbrush head to be linked with the toothbrush handle. Extending the lifetime of a toothbrush handle is an example of a growth strategy in a circular economy. If the toothbrush handle's protective layer has faded, it can be remanufactured to be coated with a water-based coating. If the toothbrush handle is brittle, it can be recycled into sawdust. Even though wood is a degradable material, it is best not to throw away post-used toothbrushes.

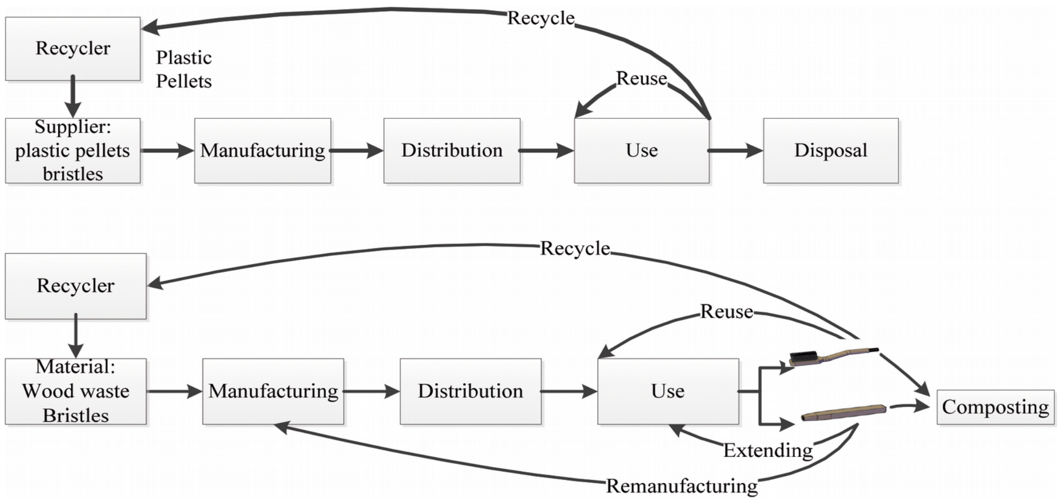

Figure 2. Cycling and extending strategy on waste wood toothbrushes

4.2. Furniture Waste Potential in Indonesia

Indonesia is Asia's largest wood furniture exporting country, along with China, Malaysia, Thailand, and India. The company numbers nearly 140,000 businesses and empowers more than 437,000 workers, and the investment value is US$ 333 million (Susanty et al., 2020). According to the Indonesian Furniture and Handicraft Industry Association, the export value of Indonesian furniture reached the US$ 1,627 billion in 2017, an increase of 1% compared to 2016.

The Indonesian wood furniture industry has large amounts of wood waste in various forms, for example, sawdust, slabs, barks, wooden boards, and pieces of wood (Hartini, Ciptomulyono et al., 2020). The joint finger technique can join large wood waste to become a blockboard. Then, wood sawdust is used as a mixture of bricks or composting. Meanwhile, wood with small pieces is only used as firewood, and the economic value is low. On the other hand, the need for toothbrushes in Indonesia is enormous. Currently, post-use toothbrushes are disposed of with household waste. Even though the existing tooth skates are made of polystyrene, which is difficult to degrade, it is interesting to conduct a study using wood waste as a toothbrush to replace polystyrene.

4.3. Design of Wooden Toothbrush

In addition to the main functions, toothbrushes must possess ergonomic functions that emphasize a comfortable and non-slip brush handle and aesthetic functions that expose the attractiveness and elegance of the design. Modern toothbrushes are often designed modularly with a knockdown between the handle and the brush head to reduce the natural resources. The concept of modularity has two alternative connection techniques, namely knockdown or connecting bolts. Knock-down is a pull-down system with a lock system without using nails but using wood as a lock construction. At the same time, the connecting bolt is a loading and unloading system where the connections are like bolts and nuts.

Regarding raw materials, wood furniture waste is pine, meranti or sengon wood. Each wood has a different level of strength, durability, and texture. The classification of strength and durability between pine, sengon, and meranti wood is not much different. Pinewood has power at class 4, which is lower than meranti. But in terms of durability, both are classified as class 3. Although the price of pinewood is higher, when it becomes waste, all three have the same price. Pinewood is lighter and easier to shape without heavy mechanical tools. Another advantage of pine wood lies in its smooth texture and straight or blended fibers.

The ergonomic function is achieved by designing toothbrush handles. The toothbrush handles are contoured to fit the hand grip and an oval-shaped head for easy access to the inside. For that, we need wood that is easily formed. The safety function is developed using water-based finishing. Meanwhile, the aesthetic function is developed by choosing a transparent layer so that the aesthetic beauty of the wood fibers can be seen. Based on the analysis of these functions, this study succeeded in developing 4 designs.

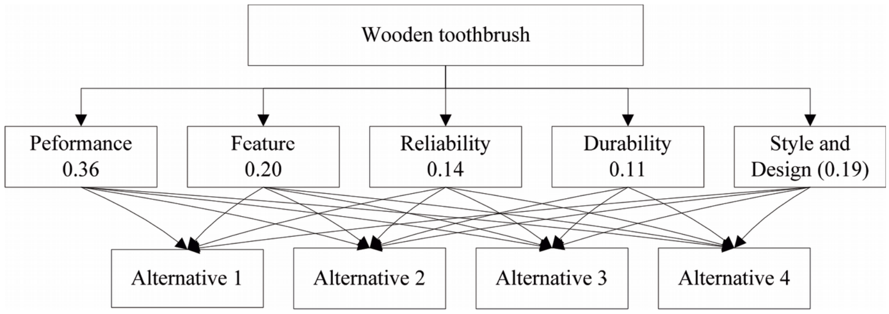

Figure 3. The decision-making hierarchy of wooden toothbrushes

	Performance	Feature	Reliability	Durability	Style and Design	Total
Alternative 1	0.11	0.24	0.21	0.21	0.22	0.18
Alternative 2	0.15	0.20	0.21	0.21	0.23	0.19
Alternative 3	0.34	0.19	0.16	0.16	0.16	0.23
Alternative 4	0.15	0.15	0.26	0.26	0.19	0.18

Table 3. The calculation of the assessment of each alternative is based on the criteria

The Analytical Hierarchy Process (AHP) selects the best design based on performance, features, reliability, durability, style, and design criteria. The respondents involved were three dentists, three wood manufacturers, and three toothbrush users. The chosen design is alternative 3, where the brush head is oval, has a round neck, has an indentation on the neck, knockdown without bolts, and has a straight handle. The material used is pine wood (*Merkusii pine*). The decision-making hierarchy can be seen in Figure 3, while the results of weight and scoring calculations are described in Table 3. Wooden toothbrush design with the concept of modularity can be seen in Figure 4.

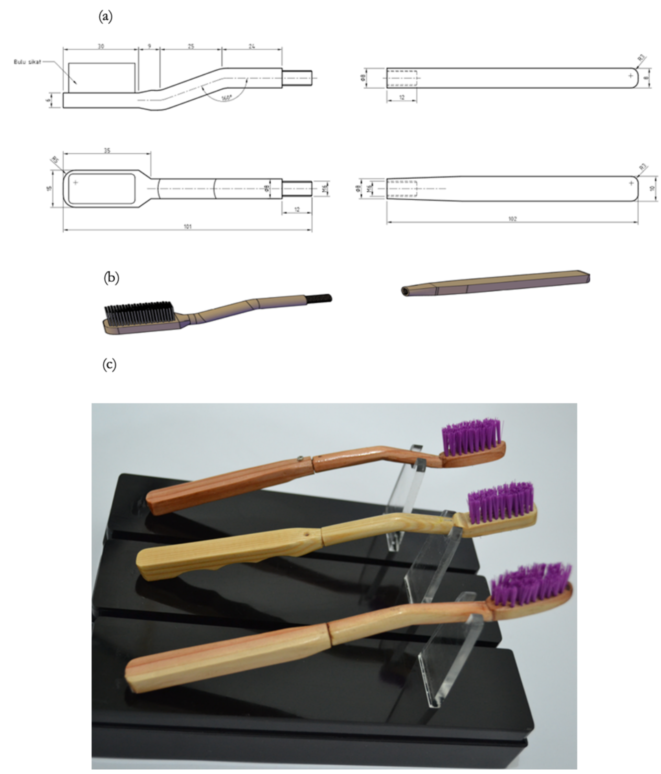

Figure 4. Wood waste toothbrush (a) Toothbrush design made from wood waste;
(b) 3D wood waste toothbrush; (c) Prototype of wood waste toothbrush

4.4. Product Evaluation

4.4.1. Environmental Aspect

The scope evaluated by LCA includes making polystyrene toothbrushes and the production process of toothbrushes using wood waste, Figure 5. The life Cycle Inventory (LCI) of polystyrene toothbrushes is calculated based on the production of 1 day. The production process for a toothbrush made from polystyrene can be seen in Figure 6.

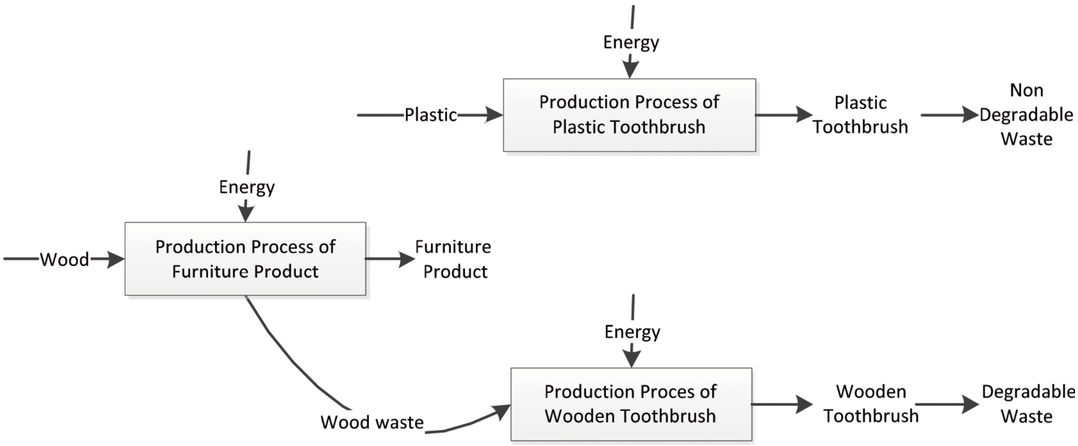

Figure 5. Evaluation boundary

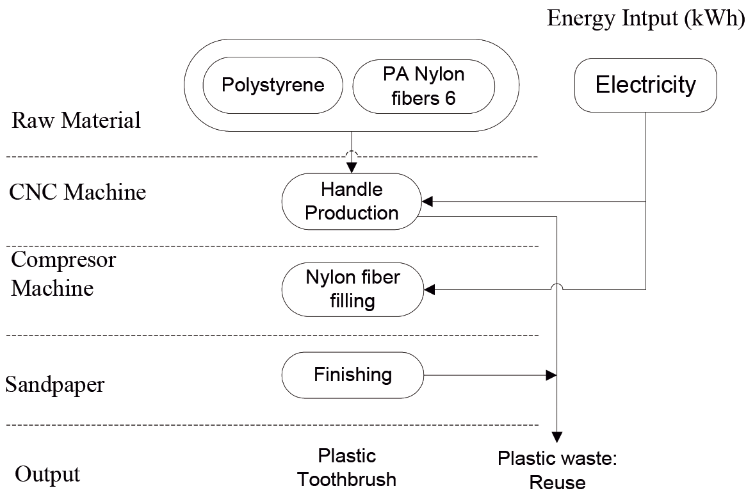

Figure 6. Process production of polystyrene toothbrush

The Life Cycle Inventory (LCI) of the wooden toothbrush is calculated based on the process in 1 day. The production process can be seen in Figure 7.

As it can be seen in Table 4, plastic, nylon, and electricity have resulted in the highest impact on the climate change category, namely 1,230.982 kg CO_2 eq which results in environmental costs of 107.912/unit. Wood waste toothbrushes also have the highest impact on climate change, namely 0.727 kg CO_2 eq, equivalent to an environmental cost of IDR 78.571. The substitution of plastic toothbrushes for wood waste has reduced the eco cost from 154.417 to 127.272. This result means there has been a decrease in environmental impact costs of around IDR 27.145. In the application of the modular concept, if the toothbrush bristles are damaged, only the head of the toothbrush was removed. There are savings on toothbrush handles that are not thrown away if they are still in good condition. The eco-cost of wood waste toothbrush heads is about IDR 44.676. The Central Bureau of Statistics prediction for Indonesia's population by 2020 is around 270 million. If there are 75% who use toothbrushes and toothbrushes changes are done 3 times each year, then there will be a need for toothbrushes of around 600 million. If everyone switches from plastic toothbrushes to wood waste toothbrushes, then this substitution will lower the environmental impact costs by around IDR 16 billion per year.

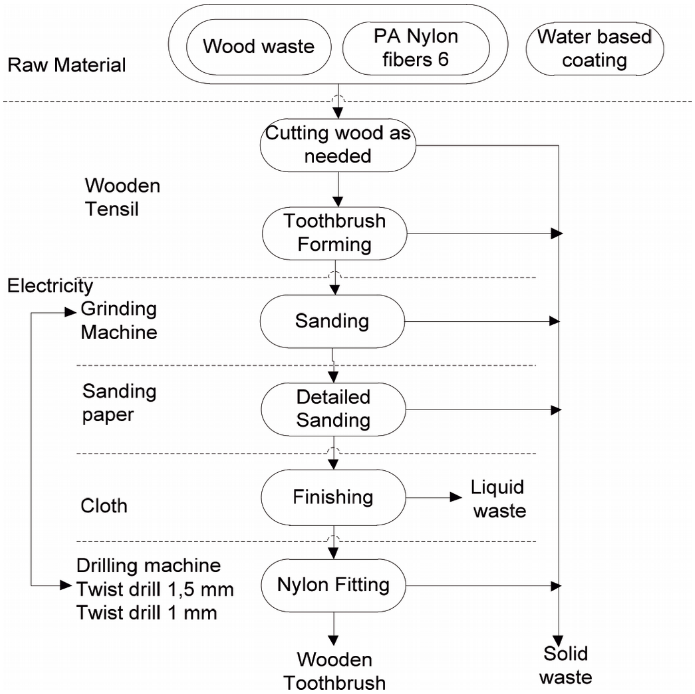

Figure 7. The production process flow of a wood waste toothbrush

Impact category	Life Cycle Impact Assessment			Eco-cost (IDR)	
	Unit	Polystyrene	Wood waste	Polystyrene	Wood waste
Total				154.417	127.272
Climate change	kg CO_2 eq	1,230.982	0.727	107.912	78.571
Acidification	kg SO_2 eq	3.671	0.005	19.665	29.22
Eutrophication	kg P eq	0.04	0	19.301	0.081
Photochemical oxidant formation	kg NMVOC	1.137	0	4.236	2.516
Fine dust	kg PM2.5 eq	0.087	0	1.67	1.461
Human toxicity, cancer	CTUh	0	0	1.103	7.549
Ecotoxicity	CTUe	1,192.546	0.354	0.31	0
Metals depletion	euro	0.284	0	0.184	0
Oil & gas depletion excluding energy	kg oil eq	0	0	0.035	0
Waste	MJ	4.588	0.59	0	5.357
Depletion of natural forests	euro	0	0	0	0

Table 4. The comparison of environmental aspect

4.4.2. Economic Aspect

Cost benefit analysis is calculated based on the production process of 20,000 polystyrene toothbrush products in 1 day. Material costs are calculated based on the type of material used, material consumption, and cost per unit of material. Labor costs use regional minimum wages and labor requirements. Meanwhile, the basic electricity tariff uses the rules of the state electricity company. The manufacture of polystyrene toothbrushes uses a compressor and CNC machines with electric power. In contrast, the wooden toothbrush is made manually. Wooden toothbrushes are done manually so it takes a long time. This requires more labor time, so it requires high labor costs. However, although only slightly, grinding machines and drilling machines are still used in the manufacture of wooden toothbrushes to smooth the surface and make holes for brush bristles. The need for grinding machines is 0.18 kwh per product (equivalent to IDR 4.7/unit) while drilling machines are 0.12 kwh (equivalent to IDR 21.2/unit). The comparison of the cost of the production process can be seen in Table 5.

Meanwhile, the entrepreneur determines to take a profit of IDR 1,000.00/unit so that the product price is around IDR 2,000.00/unit. Based on formula 1, the EEI of the polystyrene toothbrush is obtained as 6.48. The EEI value of toothbrushes made from polystyrene is more than 1, so it can be said that toothbrush products made from polystyrene are affordable and sustainable. Meanwhile, the EVR rate is around 0.154 (154/1000) and EER rate is around 84.6 %.

The total cost of a wooden toothbrush is IDR 9,556/unit. The EEI of the wood waste toothbrush is 19.20. The wooden toothbrush price is assumed to be equivalent to bamboo toothbrushes already on the market. The EEI value of wood waste toothbrushes are more than 1, so it can be said that toothbrush products made from wooden toothbrush are affordable and sustainable. The EER rate of wood waste toothbrushes are around 94.79%.

Although the price of wood waste is assumed to be non-existent, the cost of producing wood waste toothbrushes is still higher than that of polystyrene toothbrushes. Production costs impact the product's eco-efficiency index (EEI). In this case, EEI wood waste toothbrushes are more petite than polystyrene. However, both have a value of more than 1, so they are included in the affordable category and sustainable. This result means that economically it is still feasible because it still benefits. And the profit is greater than the eco cost. It means that the gain can cover the eco cost. The comparison between polystyrene and wood waste toothbrush from the economic aspect can be seen in Table 6.

No	Cost Component	Total cost Cor Polystyrene (IDR)	Total Cost for Wooden toothbrushes (IDR)
A	Material	4,905,000	331,360
B	Labour	16,350,000	2,708,303
C	Energy: machine	26,237	8,288
	Basic Electricity Tariff	10,421	10,200
Total cost /day		21,291,658	3,058,151
Total cost per unit (capacity 20,000 unit/day for polystyrene and 320 unit/day for wooden toothbrushes)		1,064	9,556

Table 5. The comparison of the cost of the production process

Toothbrush	Net Value (IDR)	Eco-cost	EEI	EVR	EER Rate	State
Polystyrene	1,000	154.42	6.48	0.154	84.60%	Affordable, sustainable
Wood waste	2,443	127.27	19.20	0.052	94.79%	Affordable, sustainable

Table 5 The comparison between polystyrene and wood waste toothbrushes

4.4.3. Social Aspect

Using wood waste to become toothbrush products can potentially emerge new business fields. Of course, this situation will add new income sources for the community. The high price of toothbrushes made from wood waste challenged researchers to design a simpler toothbrush that could be produced using a machine. The hope is that if the toothbrush design is more straightforward and can be produced by machine, the production costs will be lower. The government's role in encouraging efforts to reduce waste and environmentally friendly products need to be increased.

5. Recommendations and Challenges

Case studies that have been carried out on toothbrushes state that material substitution from plastic to pine wood waste has been able to reduce environmental impacts. However, because the cost of manufacturing the proposed product is done manually, the production costs are higher. Although the same is classified as affordable and sustainable, EEI toothbrushes for wood waste are better than polystyrene. However, the proposed product provides potential employment opportunities for the surrounding community. It is necessary to develop a wood waste toothbrush design that can be produced using a machining process to reduce processing time and production costs.

The product function has considered the suitability of both the characteristics and production of waste. However, indicators relevant to the product do not assume consumer voices. Design alternatives are still being generated from the perspective of researchers. Future research could use a product design that considers consumer voices, such as Green Quality Function Deployment (Green-QFD) (Prastawa et al., 2018). In addition, this research only focuses on degradable waste to replace products made from non-degradable materials. Meanwhile, non-degradable industrial waste is also abundant and can be used as raw material for other products. The model developed is not limited to toothbrushes. This model can be applied to the same waste for different products, or it can also be applied to substitute another waste into another product. The developed model is still limited to using waste to replace existing product materials. Future studies can be applied to other types of furniture waste for different products. Or case studies also do not rule out other industrial sector waste such as agro-industrial waste or other degradable materials.

From a theoretical perspective, the paper addresses specific gaps identified during a literature review, specifically, the need for a substitution model for product design. This research adds to the study of the value capture of residual material that has the potential to generate new business that has been previously done (Papong et al., 2014; Changwichan & Gheewala, 2020; Korbelyiova et al., 2021). Previous research has used waste in materials that can be used to make new products, but the evaluation is only based on environmental aspects. The novelty of this research lies in the waste substitution model to replace non-degradable materials, which is carried out thoroughly, from functional analysis, design alternatives, selection of the best design, and evaluation based on environmental, economic, and social aspects. The case study in this research was only conducted on wood waste to substitute for plastic toothbrushes, but the proposed substitution model could be duplicated for other waste and products. This research provides practical recommendations for the industrial sector to utilize wood waste in more valuable and environmentally friendly products.

6. Conclusions

This research has produced several findings. Toothbrush design made from wood waste replaces the polystyrene toothbrush. The wood waste toothbrush can reduce waste while reducing environmental impact. The production process of wood waste toothbrushes is more complicated, and the production cost is more expensive. The eco-cost is smaller, and the eco-efficiency index of wood waste toothbrushes is greater. Both are included in the affordable and sustainable category. Substitution efforts also can create new businesses that will benefit the surrounding community. The study of material substitution to reduce waste towards a circular economy is very potential. With so many types of waste, applying a substitution model for other kinds of waste is very interesting. Technical efforts to produce products made from waste that are environmentally friendly as well as inexpensive are still a challenge. In this study, the effort is needed to create a simpler wood waste toothbrush design that can be mass-produced using machinery. A study about triple helix cooperation between universities - industry, and government in utilizing waste into products that are more valuable both economically, environmentally, and socially is needed. From the consumer perspective, the level of public acceptance of products from waste by assessing the willingness to pay and ability to pay is needed to study.

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