Upcycle strategy on tree branches to improve ecoefficiency towards a circular economy using life cycle assessment

by Sri Hartini

Upcycle strategy on tree branches to improve eco-efficiency towards a circular economy using life cycle assessment

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Abstract. A circular economy (CE) is considered capable of being a solution to reduce the use of natural resources and reduce waste without harm. A circular economy system uses products and materials at maximum value and function. Various strategies were developed for this purpose. However, these efforts often require additional energy and materials to create more valuable products. Does the increase in value-creation mean more than the energy consumption and materials to make it happen? This study conducted a study of efforts to increase wood branch waste, which is usually only used for firewood, which is processed into hanger products with an upcycle strategy. This study uses the eco-efficiency method to determine the increase in value in the economic aspect compared to the environmental impact it causes. The cost of environmental impact is calculated using a life cycle assessment with Simapro software. The findings from this study are that upcycle efforts can increase product eco-efficiency. The eco-efficiency index (EEI) of hanger products is 4.512 and the EEI of firewood is 3.816..

1. Introduction

A circular economy (CE) differs from a linear economy (LE). The linear economy applies the economic model using "take, make, use and throw away". Post-use products are underutilized and pollute the environment [1]. LE utilizes extracted product resources as much as possible with efficiency and product life is not maximized [2]. Some argue that the circular economy (CE) can be a solution to reduce the use of natural resources and reduce waste without harm [3]; [4]. CE is a regenerative system that minimizes resources, inputs, waste emissions, and energy leakage by slowing, closing, and narrowing material and energy loops [5]. CE can be achieved through durable design, maintenance, repair, reconditioning, refurbishing and recycling. The CE system uses products and materials at their maximum value and functionality.

Much of the decline in environmental conditions from industrial activities spread globally. Global furniture production in 2016 reached more than 99 million m^3 from 50 countries [6]), but only 40 to 60% of the total volume of raw wood is effectively used, and the rest becomes waste [7]. The burden faced by the traditional wood furniture industry is exacerbated by its inefficient production process resulting in a lot of wood waste [8]. On the other hand, the furniture industry that uses tree branches is starting to develop. So far, efforts to use tree branches have only been used as fuel. This effort is known as an upcycle. Upcycle is a recycling concept to reuse discarded objects or materials without deterioration, resulting in a product that has a higher quality or value than the original [9].

Hanger is one of the products that are upcycled. The reuse of waste from wood tree branches supports the implementation of a circular economy. However, upcycle requires additional energy and materials to create more valuable products. Thus, on the one hand, upcycle efforts will increase added value and reduce waste, but on the other hand, it still requires materials and energy that impact the environment. It is interesting to study whether upcycle efforts in the case of utilizing teak waste will increase the value of eco-efficiency. This study intends to study wood waste's environmental impact and eco-efficiency if it is upcycled into a more valuable product and compare products when tree branch waste is burned.

2. Methodology

2.1. Case Study

PT X is a medium-scale furniture company in Central Java that produces various furniture products from waste teak tree branches. The reason for choosing teak branches as the primary raw material is the low price factor and the ease of availability and processing techniques. Hanger is a product most in demand by consumers whom Europe and America dominate. Product hangers function to hang hats and coats without painting. Finishing is done by leaching to produce a brighter and more natural wood color using white agent 250.

2.2. Circular Economy

Several studies on circular economy in the furniture industry have been carried out previously. There are investigations about Circular Economy practices, barriers, and drivers of CE [10]), the challenges and opportunities [11], the design of a business model [12], the relationship between varying ESCC practices on the CE-targeted performances [13], and the strategy to reduce wood waste [8]. Empirical studies of using tree waste as raw material for furniture products in a circular economy perspective are still rarely carried out. When CE is combined with 6R, a closed-loop material flow can be realized, thus relieving inherent challenges in sustainable manufacturing systems [14].

2.3. Life cycle Assessment

Several stages of LCA will be discussed in this subchapter, namely Goal and scope, Life Cycle Inventory, and Life Cycle Impact Assessment.

2.3.1. Goals and Scopes. This study aims to compare, identify the impact, and determine the environmental costs arising from the upcycle strategy of teak wood waste into a more valuable product, in this case, the hanger product. An analysis of the effect of upcycling on the value of eco-efficiency was also carried out. The scope of the study is Life Cycle Assessment, a hanger production system that includes stripping, material, sanding, assembly, treatment, and finishing. The production process flow chart of the hanger is shown in Fig 1.

2.3.2. Life Cycle Inventory (LCI). Life Cycle Inventory (LCI) shows the inputs (material, energy, and waste) and outputs (product output and non-product output) related to the product throughout the specified life cycle. The inputs include material requirements (kg) and electrical energy (kWh). While the output is in the form of product and non-product output in the form of waste generated, for example, scrap and pulp (kg). Energy and material consumption are needed to measure the environmental impact of a production process. Energy and material consumption can be seen in the following Table 1 and Table 2. The output of the hanger production process in the upcycle process can be seen in Table 3. Electrical energy consumption data is calculated based on the power of the production machine and the time of using the machine as measured by a stopwatch time study.

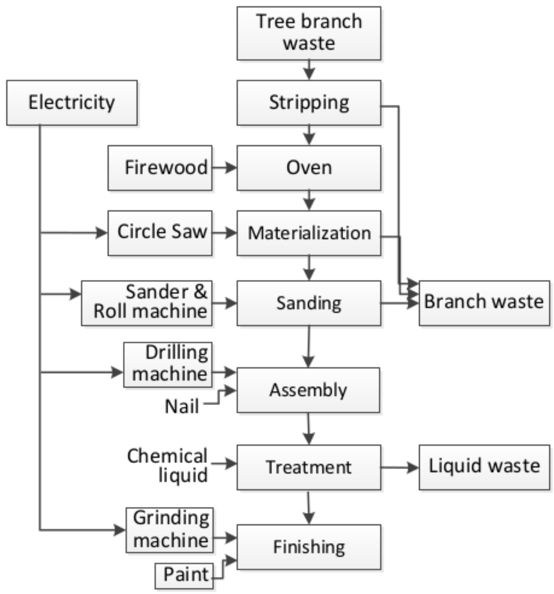

Figure 1. Hanger Production Process Flow Chart (Upcycle)

Table 1. Energy consumption

No	Machine	*Power (watt)*	*Duration (Hour)*	Consumption of energy (kWh)
1	Circular Saw	2200	36,281	79,818
2	Sander	520	21,78	11,326
3	Roll	1200	37,69	45,228
4	Boring	250	0,97	0,243
5	Grinding	450	16,77	7,547

Table 2. Material consumption

No	Material	Unit	Consumption	Function
1	Branches	Kg	666,25	Material
2	Firewood	Kg	450	Burning/oven
3	M8 x 1.5. Screws	Pcs	1400	Assembly
4	Kerosene	L	10	Treatment
5	Chemical material (DTM)	ml	50	Treatment
6	White Agent 250	L	2,5	Finishing

Table 3. The output of the production process

Category	Output		Total
Products Output (PO)	Hanger	Kg	387,5
Non Product Output (NPO)	Wood Waste	Output LCIA Indicator Simapro v 9.1.1.7	
	Electricity	kWh	144,161
	Liquid waste	Liter	0,635

2.3.3. Life Cycle Impact Assessment (LCIA) phase. This phase aims to evaluate how much environmental impact the system has on the product under study. The LCIA phase uses the Eco-cost 2017 version 1.5 method on the Simapro v.1.1.7 software. The advantage of eco-cost is that the output of this calculation is expressed in monetary value (€ or US$), which seems easy to understand directly. The LCIA phase is divided into several stages, namely characterization, normalization, weighting, and a single score. The indicators analyzed are climate change, human health, ecosystem quality, and resources. The units of analysis are 50 hanger units.

2.3.4 Interpretation. Researchers will discuss the results of the analysis at the interpretation stage and summarize them into a conclusion. At this stage, the researcher will usually provide recommendations on the objectives and scope of the research.

2.4. Eco-Efficiency

The results of the LCA measurement are information to measure the Eco-efficiency index as one of the parameters in a clean production strategy. Eco-efficiency index is the environmental cost effectiveness which is determined from the comparison of net value, production costs, and Eco-costs [17], [[18], [19]. Eco-efficiency is an indicator of the sustainability of a system in several studies. If the eco-efficiency value is negative, the production system is included in the non-affordable category. It is not affordable because, economically, it still suffers losses because production costs are still greater than profits. If the eco-efficiency value is between 0-1, then the system is in the affordable but not sustainable category. The system is included in the affordable category because it has already made a profit and is economically feasible. However, because the environmental costs are still greater than the profit earned, the system is in the unsustainable category. If the eco-efficiency value is more than one, it means that the system is included in the affordable and sustainable category. If the cost of environmental impact is low, the system can have a higher level of eco-efficiency if the net value of the system does not change [20]. The higher the ratio, the better the eco-efficiency and vice versa. If the cost of environmental impact is low, the system can have a higher level of eco-efficiency if the net value of the system does not change.

$$Net\ Value = \text{Harga Jual} - \text{Biaya Produksi} \quad (2.1)$$

$$EEI = \frac{Net\ Value}{EcoCost} \quad (2.2)$$

$$EVR = \frac{Eco\ cost}{Net\ value} \quad (2.3)$$

$$ERR\ Rate = (1 - EVR)100\% \quad (2.4)$$

3. Result and Discussion

3.1. Impact of the tree branches as firewood

Impact Category of tree branches as firewood is climate change 8.28 (kg CO2 eq), acidification 0.154(kg SO2 eq), Photochemical Oxidant Formation 0.033 (Kg C2H2 eq), eutrophication 0.019 (kg PO4 eq), fine dust 0,28 (kg PM 2.5 eq), human toxicity 1.78E-7 (Cases), ecotoxicity 26600 (PAF.m3.day), metals scarcity 0.144 (Euro), water stress indicator 0.019 (WSI Factor), oil & gas depletion excl energy 0,19 (kg oil equ), land use 0 (Bio Factor), and waste 0 (MJ).

3.2. Life Cycle Assessment of the tree branches production process

Table 4 shows the impact characterization values of the hanger production process with a strategic upcycle. The environmental impact value is obtained from Simapro software calculation based on life cycle inventory. The characterization stage identifies the factors of production and groups them into several categories of environmental impacts.

Table 4. *The result of the characterization stage*

Impact Category	Firewood	Upcycle
Climate Change (kg CO2 eq)	8,28	127
Acidification (kg SO2 eq)	0,154	0,595
Eutrophication (kg PO4 eq)	0,0189	0,0365
Photochemical Oxidant Formation (kg C2H2 eq)	0,0327	0,021
Fine Dust (kg PM 2,5 eq)	0,276	0,149
Human Toxicity (Cases)	1,78E-7	0,000003
Ecotoxicity (PAF.m3.day)	26600	47600
Metals Scarcity (Euro)	0,144	6,28
Oil & Gas Depletion excl Energy (kg oil equ)	0,197	1,86
Waste (MJ)	0	0
Land Use (Bio Factor)	0	0
Water Stress Indicator (WSI Factor)	0,0185	0,289

To assess the contribution of an activity to the environmental impact, normalization is carried out. The normalization is done by multiplying the characterization and normalization values to have the same units. The method used to determine the normalization factor is Eco-Cost 2017 v1.5.

Furthermore, weighting is carried out on each category of environmental impact. The weighting factor has different values depending on the method used and the level of importance of the impact category. In this study, all impact categories have a weight value of 1. Thus, the normalization and weighting stages have the same impact category value. The single score stage aims to classify the impact category values of each process or activity. Processes that have contributed to environmental damage can be identified from the results of a single score. Table 5 shows the results of a single score for the production process of upcycling tree branches into hangers. Activity assessed include stripping & oven, materialization, sanding, assembly, treatment, and finishing in 10 impact categories. Table 5 shows the single score after the euros' normalization and weighting stages. While Table 6 shows the result of a single score in rupiah. Figure 2 is the result of a single score in a bar chart.

Table 5. *Single Score of Upcycle process (Euro)*

Impact Category	Stripping &	Materializa	Sanding	Assembly	*Treatment*	*Finishin*
Climate Change	0,387	6,930	4,910	0,946	0,436	1,097
Acidification	0,543	2,080	1,480	0,266	0,300	0,534
Eutrophication	0,031	0,050	0,036	0,009	0,009	0,015
Photochemical	0,137	0,020	0,014	0,028	0,005	0,013
Fine Dust	3,780	0,613	0,435	0,136	0,025	0,086
Human Toxicity	0,066	0,493	0,349	1,732	0,022	0,097
Ecotoxicity	0,059	0,087	0,061	0,021	0,006	0,029
Metals Scarcity	0,058	0,238	0,168	1,071	0,033	4,723
Oil&Gas Depletion	0,063	0,741	0,525	0,033	0,009	0,117
Water Stress Indicator	0,007	0,108	0,076	0,061	0,008	0,029
TOTAL	5,133	11,361	8,055	4,303	0,853	6,741

The hanger from the upcycle process has an eco-cost of IDR. 12,559.06. This value states that the company must incur environmental impact mitigation costs for hanger (upcycle) product. 12,559.06 for one product. Firewood has a total eco-cost value of IDR 4.388,02. This value states the cost of mitigating the environmental impact of firewood for 1116.25 kg or equivalent to the number of wood branches used to make upcycle hanger products.

The value of the environmental impact on the hanger production process was greatest in the climate change category of 127 Kg CO2 equivalent. Meanwhile, the impact of climate change on firewood is 8.28 Kg CO2 equivalent. Climate change is a change in geothermal conditions caused by the increase in greenhouse gases, one of which is CO2 in the troposphere. Greenhouse gases are like the greenhouse effect, which reflects radiation from the earth back to the earth [21]. This is due to the continuous use of fossil fuels and land. In the hanger production process with an upcycle, this CO2 gas is produced from the oven process and is caused mainly by the use of electrical energy caused by the use of coal to produce electrical energy.

Table 6. *Single Score of Upcycle process*

Impact Category	Upcycle		Woodfire	
Climate Change	IDR	253.366,701	IDR	16.546,397
Acidification	IDR	89.798,674	IDR	23.268,371
Eutrophication	IDR	2.619,846	IDR	1.359,907
Photochemical Oxidant Formation	IDR	3.757,411	IDR	5.842,946
Fine Dust	IDR	87.385,658	IDR	161.499,727
Human Toxicity	IDR	47.570,891	IDR	2.826,676
Ecotoxicity	IDR	4.550,259	IDR	2.533,667
Metals Scarcity	IDR	108.241,012	IDR	2.481,960
Oil&Gas Depletion excl Energy	IDR	25.681,387	IDR	2.723,261
Waste	IDR	-	IDR	-
Land Use	IDR	-	IDR	-
Water Stress Indicator	IDR	4.981,155	IDR	318,863
Total/batch	IDR	627.952,994	IDR	219.401,774
Total/product	IDR	12.559,060	IDR	4.388,020

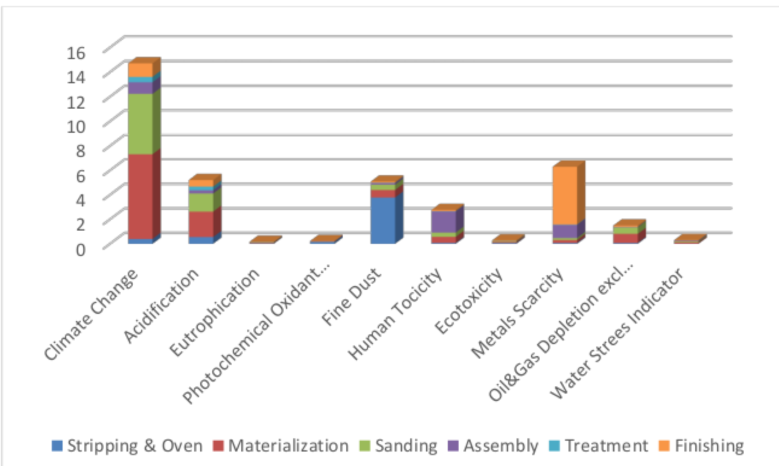

Figure 2. Single score

3.3. Eco-Efficiency Index (EEI)

The calculation of the eco-efficiency index aims to determine whether the hanger production (upcycle) is efficient from an economic and ecological perspective. This calculation refers to equation 2.

Firewood has an eco-efficiency index value of 3.816 and hanger products have an eco-efficiency index of 4.512. Firewood has less impact because it does not require materials and energy when disposed of. The upcycling process requires energy and other materials to become more valuable products. The calculation above found that firewood has a smaller eco-cost value than upcycle products. However, when firewood is upcycled, it can increase the value of the eco-efficiency index (EEI) even though it triggers a greater environmental impact due to energy and material consumption during production.

According to the eco-efficiency concept, the production process is included in the affordable and sustainable category [20].

Table 7. Eco Efficiency Performance

Indicator	Hanger (upcycle)	Firewood
Price (IDR)	6,750,000	837.187,5
Production cost	3,916,667.92	0
Net value (IDR)	2,833,332.08	837.187,5
Amount	50 unit	1116
Net (IDR) value/product	56.666.64	
Eco-cost (unit)	12,559.060	219.401,774
EEI	4.512	3,816
EVR	0.222	0.262
EER	77.83 %	73.8 %

Although based on the results of the EEI calculation, it is found that the hanger production process (upcycle & wood logs) does not harm the environment, but waste is still formed from the production process, which has an impact on the operation of the environmental ecosystem. The cost of environmental impact or eco-cost arising from the waste produced must be incurred by the company in order to overcome the impact that occurs on the environment. Hanger production has an EVR of 0.222 for upcycle products. The smaller the EVR, the better, and the hanger product is more feasible. The more efficient a production activity is, the lower the negative impact on the environment. Eco-efficiency ratio hanger rate is 77.837%. Efforts to increase the eco-efficiency rate can be made by increasing the net value or minimizing the contributors to production costs and environmental costs. Cost minimization can be done by minimizing the waste of production raw materials, using more environmentally friendly materials, and avoiding double or repeated processes in the production process.

Wood waste generated during production is better utilized in products with marketability value. The resulting sawdust can be recycled into fertilizer or sold to collectors to be used as particle board to generate profits for the company. In addition, sawdust can be used to make briquettes. If wood waste can be reduced, it will automatically reduce the environmental impact. The biggest impact of the hanger manufacturing process is in the manufacturing process caused by the use of electrical energy with fossil fuels. Therefore, based on LCA measurements, the improvement focus is on the improvement stage. More and more fossil fuels for power generation will produce hazardous chemicals and pollute the environment. Substitution towards renewable power generation needs to be done. Of the three renewable power plants, namely solar panels, biomass, and hydropower, it is known that solar panels impact climate change, carbon dioxide, methane, and nitrogen oxides which are 20 times lower than other renewable energies. A more in-depth study of solar energy as an energy source in the production process is needed.

4. Conclusion

Efforts to increase the lifespan of natural resources by using a circular economy often require additional energy and materials. In the upcycle process of tree branch waste into a hanger, it was found that the environmental impact of the production process was greater than if the waste was used as fuel. However, the upcycle effort has increased the net value so that the eco-efficiency index of upcycled products is more sustainable.

Waste recycling efforts should be carried out continuously to produce cleaner production. It can be done by reducing waste and production costs and environmental costs to improve the eco-efficiency index.

Further research on efforts to substitute energy sources from fossils to solar panels needs to be carried out to realize an increasingly environmentally friendly industry.

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