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Eco-Efficiency Ratio of Pencil Production Using Life Cycle Assessment for Increasing the Manufacture Sustainability

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Abstract: This study aims to measure the environmental costs (eco-cost) and the eco-efficiency ratio rate (EER) of the production of pencils and formulate some recommendations to improve the manufacture sustainability. The measurement of Eco-efficiency was performed using life cycle assessment (LCA) with the eco-cost method. The pencil manufacturer produces a waste of 20 %, and the product rejects 37 %. The material used is wood, slat, and chemical material for painting. The result of the data processing shows that the eco-costs of IDR 50.593.583 for 4200 grosses production lot size. The eco-efficiency index or EEI for pencil product was 1,69, which means that the products are affordable and sustainable. The eco-efficiency ratio rate (EER) is 41% means that pencil production processes need improvement. The single score Impact Category Diagram shows that the most significant environment impact category is climate change. The recommendation to improve the EER of pencil production based on Impact Category Diagram is (1) to increase the utilizing of wood waste and (2) to increase the capability of technicians and operators to reduce the product rejection. These recommendations aim to reduce the wood consumed in production.

Keywords: Eco-cost, eco-efficiency, life cycle assessment (LCA), sustainability.

Introduction

Life Cycle Assessment (LCA) identifies and quantifies the use of natural resources and energy, which is disposed into the environment. LCA also used in formulating the strategy to improve product quality. LCA is a compilation and evaluation of inputs, outputs, and the potential environmental impact of a product or service based on the life cycle [1]. Life cycle assessment is a tool for decision making and industrial policymakers in assessing the impact of cradle to grave product or process. Three forces play a role in the LCA evolution. The first force is government regulations that led to the "life cycle state responsibility", where manufacturing has a responsibility to the impact of production, transportation, and disposal phase. The second force is business participation in conserving the environment, as an example is the application of ISO 14000. Third, consumers and government procurement guidelines develop by placing LCA as a tool to identify the impact of cradle to grave based products and materials they create. Impact life cycle or cradle to grave was derived from activities ranging from raw material extraction, production process, delivery or distribution of products to consumers, the use of the product by the consumer, and the destruction or restoration of the product after the product life [2].

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Environmental Accounting since 1990 has been focusing on publishing The Greening of Accountancy by the Chartered Association of Certified Accountants (ACCA). Based on US Environmental Protection Agency (US EPA), Green Environmental Accounting has defined a function that environmental costs should be considered by the responsible party to reduce or avoid costs and improve environmental quality [3]. World Business Council for Sustainable Development (WBCSD) defines eco-efficiency as "increasing the production of goods and services with lower resource use, waste, and pollution " [4]. Eco-efficiency has three aspects: (1) improve the economic and environmental performance, (2) become imperative to compete, and (3) effort to support sustainable development [3].

WBCSD describes the eco-efficiency as a concept of reducing resource consumption, reduce environmental impact, and increase the value of products and services. Adoption of the principles of eco-efficiency in production patterns in public policymaking will increase the technological capabilities [5]. Eco-efficiency measurement carried out after obtaining the value of the environmental costs (eco-cost), the index of eco-efficiency, and eco-efficiency ratio. Eco-efficiency indexes used to assess the feasibility of a product from the economic aspect and ecologic aspect. Eco-efficiency ratio is a final calculation of eco-efficiency measurement using the Life Cycle Assessment (LCA). The implementation of eco-efficiency should consider the production costs obtained from the cost of goods manufactured (COGM) company.

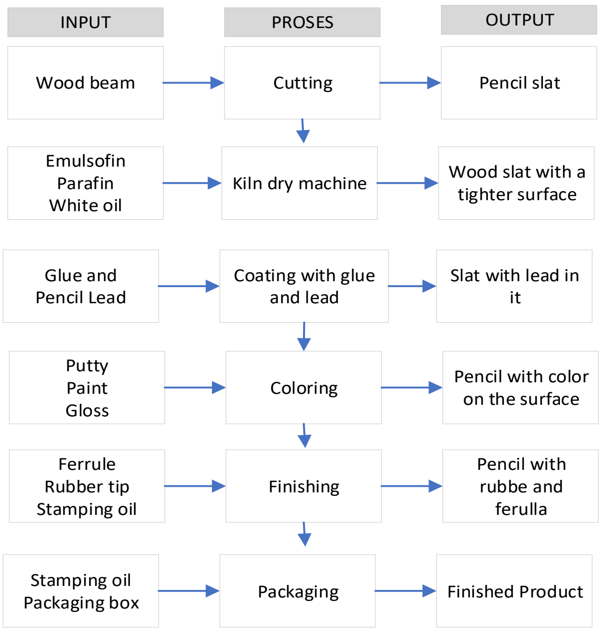

Figure 1. The production process stage

This study aims to determine the categories of environmental impacts arising from the wood pencil production process and measure the cost of the environment (eco-cost) for each category of impact.

Additionally, we also measure and analyze the eco-efficiency level and provide recommendations to improve the eco-efficiency of wood pencil manufacturing. Measuring the level of eco-efficiency was conducted to determine whether the pencils production can be said sustainable and affordable or not. It is the basis for interested parties to make a decision.

Methods

Pencil Production Process

This study was conducted in a pencil factory located in Cikupa, Tangerang. The factory uses wood to produce various types of pencils. The production processes also resulted in a waste of resources and environmental degradation. The production process is starting from the slat department, continue to the production department, and the packaging process. The slat department generates waste in the form of sawdust and small pieces of wood, reaching more than 20 % of all wood material. The production department outputs are raw pencil, paint, sawdust, and reject products. The packaging department also generated reject pencil-shaped almost 35 % of all products, but it will be rework. The waste produced is sorted to decide whether it will be reworked or will be burnt/destroyed. Waste that can be rework causes inefficiency of production processes and thus require more production resources. The inefficiency of the production process causes a loss for the industry.

Table 1. Material input for production process for 4200 grs (grosses)

	Input material	Unit	Conversion to unit product	Input quantity
Slat Production	Wood beam	M3	8471,413 grs	36,67
	Water	Liter	14080	5097,93
	Paraffin wax	Kg	1920	695,17
Raw Pencil Production	Slat	M3	6729,69 grs	29,13
	Lead	Kg	1 kg = 5,8 grs	1160,29
	Glue	Kg	1 kg = 25 grs	269,19
Painting Process	Pencil	M3	4200 grs	18,18
	Putty	Kg	1 kg = 40 grs	105
	Paint	Kg	1 kg = 50 grs	84
	Gloss	Kg	1 kg = 50 grs	84
Finishing Process	Ferrules	Kg	1 kg = 38 grs	110,53
	Rubber tip	Kg	1 kg = 8 grs	525
	Stamping foil	Roll	1 roll = 40 grs	105

Sawdust and the smoke from the burning of wood will result in environmental pollution and human health problems [6]. Figure 1 shows the process stage of pencil

production, and Table 1 shows the input material for a production process. The output of slat production that becomes wastes is 7,54 m3 scrap, and pulp and raw pencil production produce 10,95 m3 scrap and pulp.

The production process also consumes electrical energy that comes from the use of production machines. The amount of electrical energy produced is obtained from the amount of power needed by the production machine (kW) and the length of time the production machine operates (hours) so that the use of electrical energy is obtained in units (kWh). Table 2 shows the engine and the electrical power machine used for the production process.

The value of raw material input in Table 1 and the electrical energy consumption in Table 2 are input for LCA calculation in Simapro software.

Life Cycle Assessment

Life cycle assessment is a tool to assess the environmental impacts of the life cycle of products and activities from the retrieval/extraction of raw materials, production processes, transportation, use, and disposal. Today, LCA began to be applied in government policy, marketing, strategic planning, process improvement, and product design. It was also used as the basis for eco-labeling and consumer education program [7]. LCA is an Environmental accounting, a concept introduced by Hansen and Mowen [8]. The value a describe as eco-efficiency, which improves efficiency by improving the ability of the environment. DFS website of TUdelf [0] describes the eco cost in four groups, eco cost of resource scarcity, eco cost of carbon footprint, eco cost of the ecosystem, and eco cost of human health. Each group consists of some impact categories. The group of eco cost and their impact category describe in Figure 2.

Method of Life Cycle Assessment conducted to evaluate the environmental impact and provide an alternative improvement to reduce environmental impact [9]. Life Cycle Assessment can be used to evaluate the environmental impact of the use of raw materials such as coal and biomass fuels which the removal of these can lead to a problem of how big the emissions and other impacts resulted from the use of biomass fuels [10].

LCA Data Processing

This research was conducted by observation and interviews to collect data, both primary data and secondary data. Observation techniques are done directly and indirectly. Direct observation was done to measure the time process that will be used to measure some resources used, especially electrical energy, while indirect observations did use historical production data. Interview techniques conduct to get the data of the production stage, machine, materials used in production, and the source of electrical energy and other energy used. Data processing was done used Simapro 8.5.2 software by using eco-cost v.1.1. Figure 3 explains the flow of data processing in an LCA study.

Table 2. Engine and machine electrical power

Machine	Number of Machines	Engine Power (kWh)	Production (Hours) / machinery	Electric Power (kWh)
Proscut	1	3,7	9,75	36,09
Sugu	4	4,8	2,44	11,70
Broti	2	50	4,88	243,83
Molding	1	55	9,75	536,44
Zigsaw	2	13	5,39	70,11
Block cutting	2	11	1,18	12,98
Impragnating	1	100	11,68	1168,47
Stacking	2	11	1,57	17,26
Sizing	6	5	1,11	5,54
Grooving	6	7,5	7,69	57,68
Laying	6	2,2	7,69	16,92
Kiln dry	6	11	7,69	84,60
Shaping	4	15	11,22	168,24
Painting	16	3	2,75	8,24
Six	2	6	5,93	35,58
Stamping	15	2	6,71	13,43
Rubber Tipping	17	3	7,42	22,26
Sharpening	12	3,7	4,96	18,34
End cutting	2	2,2	16,29	35,84
Center cut	2	2	16,75	33,49
Data code	3	1	14,62	14,62
Total of electrical energy consumption				2611,27

Figure 3 explains the flow of LCA indicators measurement which consists of some phases:

The first phase is to define the purpose and scope to determine the direction of the research. The decisions to improve the production process will be made based on the results of the LCA indicators value. The scope of the assessment is the LCA evaluation process on a pencil production system starts from the resources entry the manufacture to the finishing product package. We can say the scope is a gate to gate type.

The second phase is the analysis of inventory (life cycle inventory/LCI) which identifies and collects data of the input and output of the production system and did some data processing through Classification, Characterization, Normalization, Weighting and define a Single Score. The result of the LCI phase is the Characterization of environment Impact category and Normalization value (in euro) after we input the number of resources uses for production to the software. Life-Cycle Inventory is a phase of measurement that describes the physical parameters.

The third phase is the environmental impact statement, which is intended to get the output of data processing in the form of a potential category to the damage of the environment. The output shows as Output of Impact Category Diagram. The diagram shows the environmental category impact of the production process. Sufficient information is needed in LCA measurement and makes the right decisions for improvement in the production process. Lack of understanding of the environmental impact is caused by the difficulty in interpreting the flow of raw materials and energy [7]. Therefore, many experts understand the importance of using LCA in assessing environmental impact. Based on the value of the total environment impact resulted from the LCI phase, we can define the value LCA indicators such as eco-efficiency index and eco-efficiency ratio.

Life Cycle Assessment (LCA) Indicators

LCA has some indicators on the economical aspect and ecological aspect. First, we do the cost-benefit analysis that performed to obtain the net value. The net value obtained by reducing the selling price by the cost of production. Cost-benefit analysis can also determine whether the product is eligible to be sold or not.

$$\text{Net Value} = \text{Selling price} - \text{Production Cost} \quad (1)$$

The net value then used to obtain the *Eco-efficiency index* or EEI. EEI conducted to determine the feasibility of the product in terms of ecological efficiency (sustainability) as well as economic efficiency (profitable). Eco-efficiency index value obtained by dividing the net value to the cost of the environment or eco-cost [5].

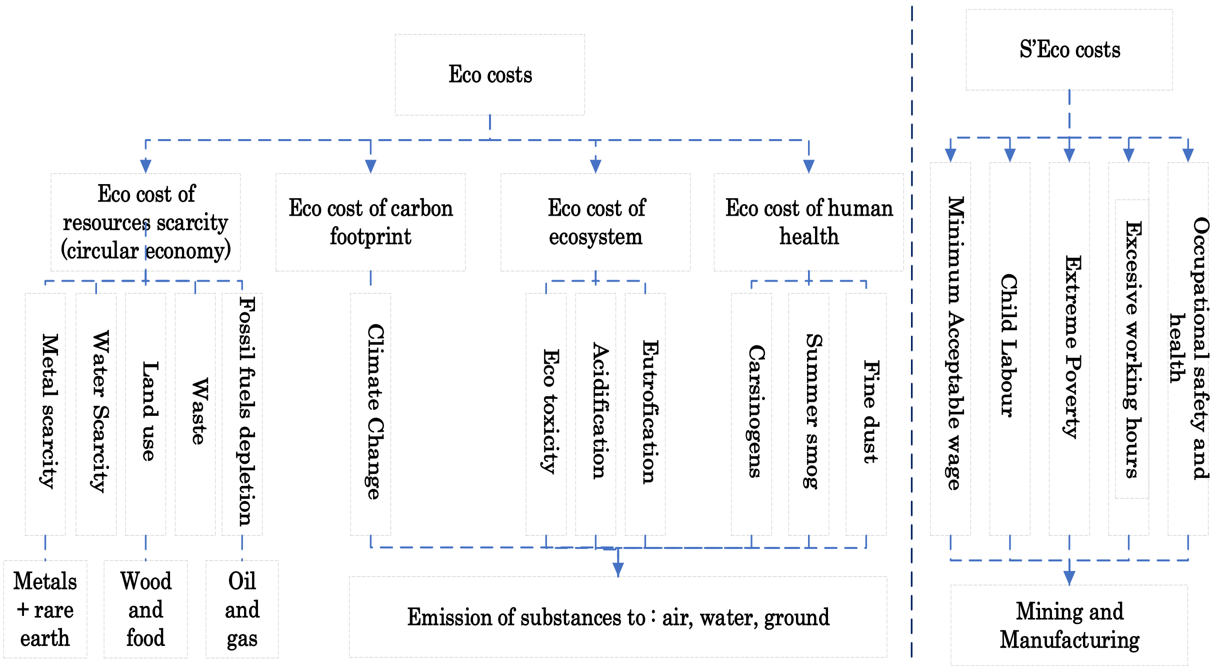

Figure 2. Eco cost category in Life Cycle Assessment (Source: www.ecocostsvalue.com)

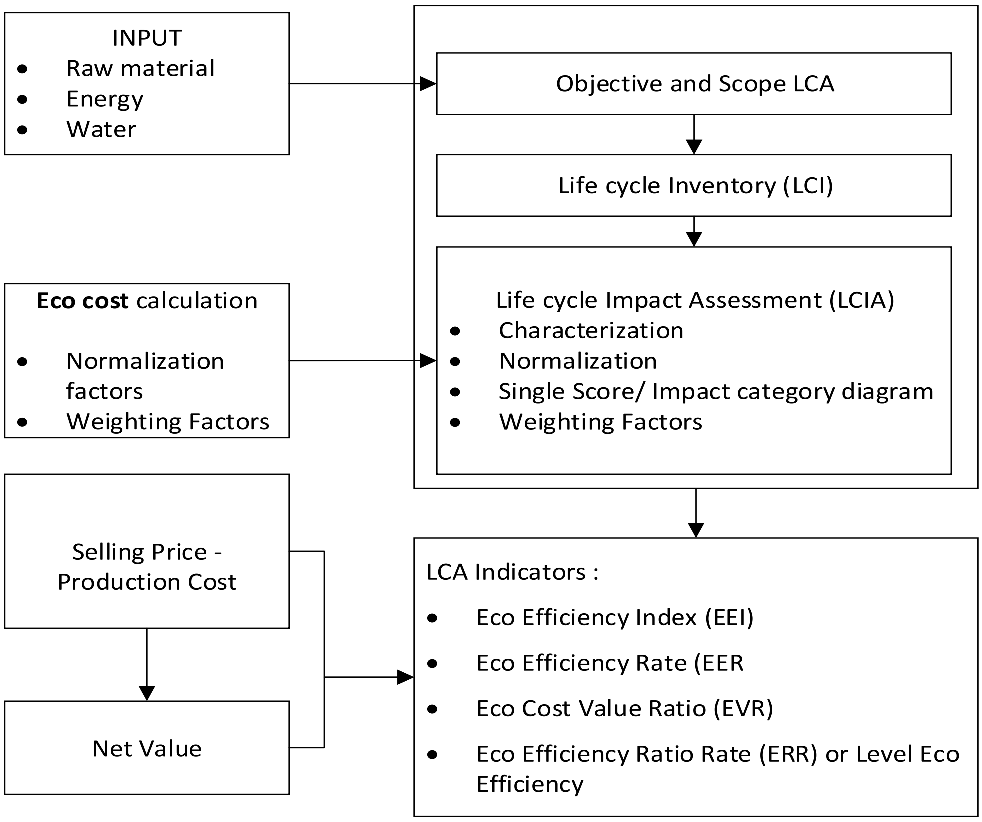

Figure 3. Flow data processing

$$EEI = \frac{Net\ value}{cost} \quad (2)$$

Eco-Efficiency Index (EEI) is used to categorize the product whether the product affordable and sustainable or not. Products categorized as affordable and sustainable if the value of EEI is more than 1, while affordable but not sustainable if the value of EEI is between 0 – 1. The product categorizes as not affordable and not sustainable if the value of EEI is less than 1 [11].

Table 3. The environment impact category of production process stage

Impact category	Unit	Slat	Raw pencil	Pencil	Total
Climate change	Kg CO2 eq	2479,25	821,20	4737,30	8037,76
Acidification	Kg SO2 eq	10,51	4,0073	29,24	43,76
Eutrophication	Kg PO4-- eq	12,29	2,36	5,68	20,32
Photochemical oxidant formation	Kg C2H4 eq	0,04	0,018	0,60	0,66
Fine dust	Kg PM2.5 eq	0,37	0,58	3,03	3,99
Human toxicity	Cases	0,00025	6,23E-05	0,00041	0,0007
Ecotoxicity (freshwater)	PAF.m3.day	13085571	2646631,9	25971336	41703539
Metals Depletion	Euro	0,78	0,22	536,38	537,37
Oil&Gas depletion excl energy	Kg oil equ	0	0	0	0
Waste	MJ	0	0	0	0
Land-use	Bio factor	0	0	0	0
Water stress indicator	WSI factor	11,38	1,84	12,14	25,36

Table 4. Characterization Impact category and Normalization value (in euro)

Impact category	Characterization		Normalization factors	Normalization (in Euro)
	Unit	Total		
Climate change	Kg CO_2 eq	8037.76	€ 0,116 / kg CO2 eq	932.38
Acidification	Kg SO2 eq	43.76	€ 8,83 / kg SO2 eq	386.36
Eutrophication	PO4 kg eq	20.32	€ 4,17 / kg PO4-- eq	84.75
Photochemical oxidant formation	Kg eq C2H4	0.66	€ 10,38 / kg C2H4 eq	6.82
Fine dust	PM2.5 kg eq	3.99	€ 34 / kg PM2.5 eq	135.68
Human toxicity	cases	0.0007	€ 919999,9775 / cases	666.49
Aquatic ecotoxicity	kg TEG eq	41703539	€5,54E-06/ PAF.m3.day	231.04
Metals depletion	Euro	537.37	€ 1 / euro	537.37
Oil & Gas excl energy depletion	Kg oil equ	0	€ 0,8 / kg oil equ	0
waste	MJ	0	€ 0,01125 / MJ	0
Land-use	Bio factor	0	€ 0,116 / kg CO2 eq	0
Water Stress Indicator	WSI factor	25.36	€ 8,83 / kg SO2 eq	25.36
Total				3006.25

After we have EEI value, then the EEI value used to calculate the EVR (*Eco-Cost Value Ratio).* EVR is an indicator that can be applied in cases when a designer is asked to design a product within a given price (budget). The issue then is to create maximum value for the end-user at a minimum of eco-costs (environmental burden). EVR is an indicator for sustainability in LCA related to the value of EER which obtain from EER.

EVR = Eco cost/ Net value (3)

The final calculation is the *Eco-Efficiency Ratio Rate* as the measurement of the eco-efficiency of roduction [12]. The formulation to calculate this indicator are state below.

$$EER = (1 - \text{EVR}) \times 100\% \quad (4)$$

Results and Discussions

Result of LCA measurement

LCI's first phase is characterization, which environmental impact categorized based on the method chosen. After inputting the number of production resources from Table 3 and the energy consumption from Table 4 above to the Simapro software input data, then the output is shown in Table 5. The calculation is done for volume production of 4200 grosses lot size of unit pencils product.

After summing the value of the environmental impact category of all the production stage, then values convert to the euro by the normalization process. Normalization is a stage when the impact category unit transform to the same unit (euro or USD). Normalization value is obtained based on the characterization value multiplied by normalization factors from the database of Simapro software. The normalization factors and the result of normalization are shown in Table 5.

After normalization, the next stage is weighting, which gives relative value to each impact category. Commonly, the relative value defines subjectively by an evaluator. In this study, the relative weights are the same for all of the impact categories.

Table 5. Net value, EEI, and EVR

Net Value	Unit	Value
Selling price	IDR	334.950.000
Production cost	IDR	249.542.281
Net Value	IDR	85.407.718,60
Eco cost	IDR	50.593.583
EEI		1,69
EVR		0.59
EER	%	41

Table 6. Increased production of eco-efficiency pencil

Recommendation	Description
Utilizing wood waste	Re-use waste wood by making collaboration with SMEs or artisan wood processing, which will utilize the waste as a production material of value-ble goods.
Efficiency in energy use	Minimize the product rework means minimize the product rejection
Improving the ability of operators and technicians	Skill and discipline improve-ment for operators and techni-cians by designing some train-ing programs to boost work performance.

Weighting value obtained by multiplying the weighting factor with the normalization value. If we argued that all of the impact categories are equal, we give the same relative value, then the result of the weighting stage will be the same as the normalization stage. Table 2 gives information that the total environmental impact from the manufacturing process as a result of normalization is 3006,25 Euro or equal to Rp 50.593.583 (used euro exchange rate IDR16.829/ euro).

The next step is defined as the Single Score of the environment impact categorized. Cost-benefit ana-lysis is used to identify the benefit value of the product compare to production cost. First, we defined the Net Value of the product from the value of the selling price reduced by the cost of production. The production cost was calculated by sum all of the cost used to produce 4200 gross lot size of unit pencils. Production cost for 4200 grosses of pencils is IDR 249.542.281 or cost per gross 59.415 IDR. The cost consists of the cost of material, energy, waste, and factory overhead. The selling price is IDR 334.950.000. Then the net value for 4200 grosses of pencils is IDR 85.407.718.-

The eco cost is IDR 50.593.583 resulted from the normalization phase in Table 5 (3006,25 Euro x IDR16.829/ euro). The selling price, cost of production and eco cost used to calculate the EEI based on formulation 2 above. We get the EEI value 1,69. The EEI value categorized the product as affordable and sustainable because the value of EEI is greater than 1. According to ESCAPE [13], eco-efficiency is a comparison between the economic value of the product indicated by the net value and the environ-mental cost to produce the product. Then, a product which has the eco-efficiency greater than 1 means that the economic value of the product is greater than the environmental cost to produce it. We can say the product is affordable and sustainable.

The EVR or Eco cost per value ratio, obtain from formulation 3, divide the eco cost by net value (50.593.583/ 85.407.718 = 0.59). The EVR of the pencils product is 0,59. The EVR value will be used to calculate the eco-efficiency ratio rate or EER. The value of EER is 1-EVR in percentage form. The EER value is 41 %. EER calculation is a final calculation to obtain the level of eco-efficiency of a manufacturing process in this case. The EER 41 % means that the eco-efficiency of a production system is low and needs to be increased. All value calculate from this measu-rement is shown in Table 6.

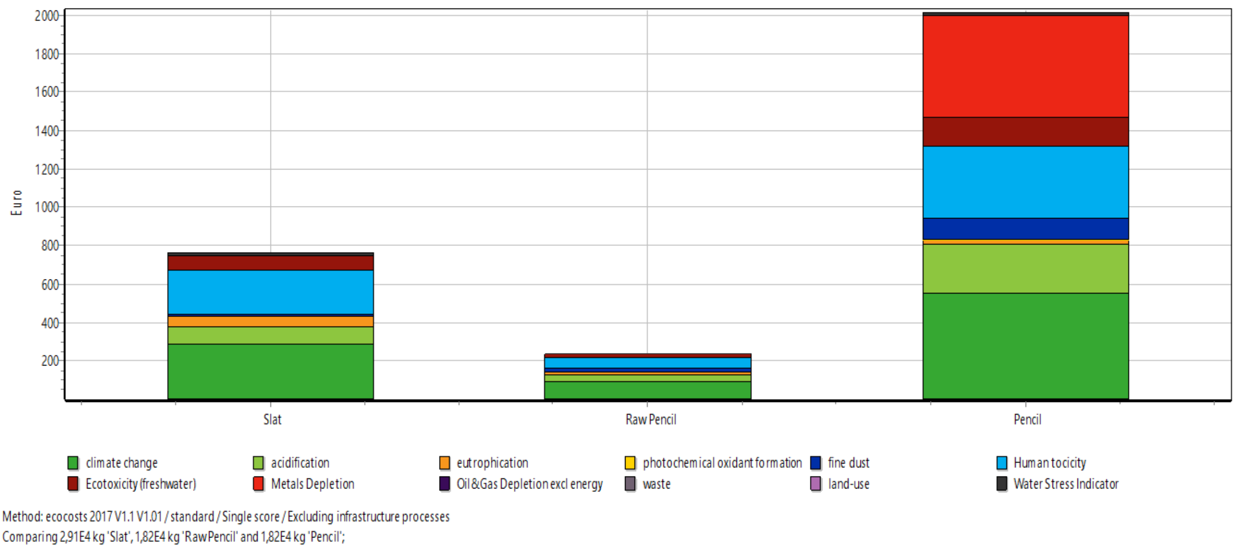

Figure 4. The output of the impact category diagram

Recommendations to Increase the value of Eco-efficiency

Eco-efficiency represented by EER is an integral indicator that is simultaneously quantifying the economic and environmental performance of industrial symbiosis (IS) networks. World Business Council for Sustainable Development defines the eco-efficiency indicators as one economic indicator and three generally applicable simplified environmental indicators: raw material consumption, energy consumption, and CO^2 emission [14]. The principle of eco-efficiency is a concept of ecological and economic efficiency based on the use of natural resources. The pencil production using some primary materials: wood, slate, and paint. Slat is made from a mixture of graphite and clay that are placed into the grooves. Graphite is made of pure carbon. Figure 4 describes the single score result that explains the impact category on pencil production.

Figure 3 shows that the most significant impact category to the environment is climate change. The volume of wood as raw material which inputted to the software recognized it as a significant impact on climate change, also energy (watt of electricity). The second-highest impact category is metal depletion which resulted from the material used in the painting process.

Deforestation in the rainforest is a major cause to climate change due to the decreasing number of trees available to capture increasing carbon dioxide levels in the atmosphere. According to the result of a single score, the formulation of recommendations needs to focus on the reduction of wood usage by increasing the utilization of wood waste and decrease product reject to reduce wood consumption. Based on interviews with enterprise management, many defective products on pencils are caused by machines set up errors caused by a lack of expertise from operators who set up the machine. The capability of the machines, technicians, and operators need to be improved to decrease the product rejection. The increase in wood waste utilization can be achieved by making collaboration with other industry who can rework or reuse of wood waste. Small and medium enterprises (SME) and artisans need a smaller component in their product. The recommendation is given in Table 6. The category of climate change impacts is also caused by the contribution of the use of electrical energy to drive the engine. Reducing or minimizing the use of electricity has the effect of reducing the combustion process of coal, petroleum and natural gas.

Utilizing wood waste as raw materials for wooden based SME or artisan can improve the eco-efficiency. The efficient use of wood would indirectly affect the natural ability to minimize environmental damage. Economically also would minimize the cost incurred for the purchase of raw materials. Utilization of waste (non-product output) can also be performed to minimize wood waste being burned because the burning process can give a negative impact on the environment. Improving the ability of operators and technicians can also minimize waste from the production process by reducing the reject product produced from lack of accuracy and the ability of the operator and technicians. Table 6 gives two recommendations for manufacture management to improve the eco-efficiency of the production process.

Conclusion

The result of data processing of the life cycle assessment concluded that the value of eco-costs of the impact category is IDR 50.593.583 and the most significant impact is on climate change. The eco-efficiency index or EEI is 1,69 means that the pencil product is in the category of sustainable and affordable, which means that the products have a positive value from the economic aspect compare to environment cost to produce it. Otherwise, the value of EER of pencil production is 41% which means that the improvement reduces the cost of the environment is necessary. The effort to reduce raw material consumption can be done by reducing waste and product rejection. The recommendation to reduce the product reject is to improve the ability of operators and technicians due to product reject which needs to be rework. Reducing the product reject also reduce the rework process and reduce the energy consumption. The third recommendation is to utilize wood waste as raw material for SME or artisan to make valuable products.

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References

1. Lehtinen, H., Saarentaus, A., Rouhiainen, J., Pitts, M., and Azapagic, A., A Review of LCA Methods and Tools and Their Suitability for SMEs. *Manchester: Europe Innova Biochem*, 2011.
2. Yan, J. *Handbook of Clean Energy System.* Retieved from Wiley Online Library:

http://onlinelibrary.wiley.com/doi/book/10.1002/9781118991979, Mei 4, 2015.

3. Basuki, B., Eco-Efficiency and Sustainable Development as Efforts to Produce Environmentally Friendly Product: An Exploratory Case Study. *Social and Environmental Accounting*, 2015, 199-218199-218.
4. Lehni, M., *Eco-Efficiency Creating More Value with Less Impact.* Switzerland: World Bussiness Council for Sustainable Development (WBCSD), 2000.
5. Ichimura, M., Nam, S., Bonjour, S., Rankine, H., Carisma, B., Qiu, Y., and Khrueachotikul, R., Measuring Resource-use Efficiency and the Impact of Economic Activities, *United Nations Economic and Social Commission for Asia and the Pacific*, Bangkok, 2009.
6. Purwaningsih, R., Cahyantari, A, E., Ariyani Z., Susanty, A., Arvianto, A., and Santoso, H., Product-service System Method to Measure Sustainability Level of Traditional Smoked Fish Processing Industries, *MATEC Web of Conferences*, 154, 01062, 2018.
7. Lewis, H., and Demmers, M., Life Cycle Assessment and Environmental, *Australasian Journal of Environmental*, 2013, 110-123.
8. Hansen Don R., and Mowen M. M., *Managerial Accounting*, Eighth Edition, Thompson, USA, 2007.
TuDelf, *The Model of the Eco-costs / Value Ratio* (EVR), Retrieved from: https://www.ecocosts-value.com/
9. Pringgajaya, K. A., and Ciptomulyono, U., Implementasi Life Cycle Assessment (LCA) dan Pendekatan Analytical Network Process (ANP) untuk Pengembangan Produk Hetric Lamp yang Ramah Lingkungan, *Jurnal Teknik ITS*, 1(1), 2012,pp. A515-A520.
10. Harjanti, T. R., Fahrurrozi, M., and Bendiyasa, I. M., Life Cycle Assessment Pabrik Semen PT Holcim Indonesia Tbk. Pabrik Cilacap: Komparasi antara Bahan Bakar Batubara dengan Biomassa, *Jurnal Rekayasa Proses,* 6(2), 2012,pp.51-58.
11. Sari, D. P., Hartini, S., Rinawati, D. I., and Wicaksono, T. S., Pengukuran Tingkat Eko-Efisiensi Menggunakan Life Cycle Assessment untuk Menciptakan Sustainable Production di Industri Kecil Menegah Batik, *Jurnal Teknik Industri*, 14(2),2012, 137-144.
12. Vogtlander, *Bamboo a Sustainable Solution for Western Europe, Design Cases, LCAs and Land Use*, Delft University of Technology, Nederland, 2009.
13. UNO, ESCAP 2009 Eco-e_ciency Indicators: *Measuring Resource-use E_ciency and the Impact of Economic Activities on the Environment,* United Nations Ecoomic and Social Commisions for Asia and the Pasific.
14. Park Hung-Suck, and Bahera, S. K., Methodological Aspects of Applying Eco-efficiency Indicators to Industrial Symbiosis Networks, *Journal of Cleaner Production*, 64, 2014, pp 478 -485.