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"Gheorghe Asachi" Technical University of Iasi, Romania

ASSESSMENT OF MANUFACTURING PROCESSES ECO-EFFICIENCY BASED ON MFA-LCA-MFCA METHODS

Aldona Kluczek*

Institute of Organization of Production Systems, Faculty of Production Engineering, Warsaw University of Technology, 86 Narbutta Street, Warszawa, 02-521, Poland

Abstract

The objective of this paper is to investigate eco-efficiency in a durable goods manufacturing system. It is intended to apply a method used in a company producing heating devices within the boiler sector. A hybrid methodology is used to assess the eco-efficiency of manufacturing processes, based on combining Material Flow Analysis, Life Cycle Assessment, and Material Flow Cost Accounting. This provides an effective approach to evaluate environmental and economic performance in the context of process improvement. To demonstrate the method, it is used a case study for comparing the eco-efficiency for baseline and improvement scenarios in a company producing central heating boilers.

All of the suggested improvements were directed toward reducing the overall environmental impact of the plant without sacrificing in-process quality and increasing eco-efficiency. The results indicate higher eco-efficiency for cutting measured in terms of energy use. For the manufacturing processes, the greatest benefits came from eco-efficiency improvements in the cleaning phase. Eco-efficiency analysis revealed that the total cost of material losses could be reduced by 2% against current processes. Unfortunately, due to the high cost of processing fuel, painting creates the highest utilities costs. It illustrates a significantly less eco-efficiency (3%) compared to the current process.

This method may serve as a useful foundation for enterprises to make viable decisions regarding material selection, whilst considering environmentally beneficial technologies and greater financial benefits at the same time.

Keywords: eco-efficiency, life cycle assessment, manufacturing processes, material flow analysis, material flow cost accounting

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1. Introduction

Governmental regulations have been the main drivers of environmental initiatives in industry, and have encouraged manufacturers to evaluate their production processes. In recent years the central heating manufacturing sector has increased its economic and political relevance, attracting the attention of policy makers.

Manufacturing in the heating sector produces adverse environmental impacts such as waste generation, energy consumption, and the release of hazardous substances. The topic of improvements to the production and environmental aspects of central heating device manufacturing has been covered in two papers (Kluczek, 2014; 2017). Improving environmental performance has also gained attention as a business strategy for improving economic performance. While short term improvements in environmental efficiency from modifying existing technologies or introducing new ones may lead to increased cost in some areas, in the long term it may lead to improved economic performance. Evidence supporting this positive relationship between financial and environmental performance has been established (Hazi and Hazi, 2017; Rosen and Kishawy, 2012).

The design of eco-efficiency processes with reduced total energy and material demand and losses

*Author to whom all correspondence should be addressed: e-mail: aldona.kluczek@gmail.com; a.kluczek@wip.pw.edu.pl; Phone: +48 222348133; Fax: +48 228499390

as well as the minimization of emission and waste is a target of *industrial ecology* (Lifset, 2009). In order to make effective decisions regarding investments to production technologies, materials and processes for improving economic and environmental performance, a relevant and useful assessment tool is beneficial.

This study is designed to apply an integrated method involving standardized Material Flow Analysis (MFA), Life Cycle Assessment (LCA), and Material Flow Cost Accounting (MFCA) to assess the eco-efficiency of the manufacturing processes. This combination couples both economic and environmental performance into an easily used assessment tool for quantifying eco-efficiency.

2. Literature review

2.1. Eco-efficiency

The term eco-efficiency was first used by Schaltegger and Sturm (1990; 2016) as a "business link to sustainable development" for sustainability in manufacturing. Eco-efficiency is offered as an effective approach for the improvement of environmental and economic performance at the enterprise level (ISO 14045, 2012; Verfaillie and Bidwell, 2000).

The World Business Council for Sustainable Development (WBCSD, 2000) and Dewulf and Duflou (2005) defined categories for eco-efficiency including material and energy reduction, toxic substances reduction, recycling, renewable energy, and extending product life cycles. Concepts of eco-efficiency can be transferred from the policy level and applied at the manufacturing process level (UN, 2009). In this regard, the application of eco-efficiency is useful for integrating environmental and economic performance into core business processes (Cucek et al., 2015). The WBCSD has developed ways of measuring and reporting the overall performance of a company using eco-efficiency ratios (Verfaillie and Bidwell, 2000; WBCSD, 2000).

Eco-efficiency is commonly measured as the ratio between product system value generated and environmental resources used (Koskela and Vehmas, 2012; Ueda et. al., 2009; Winter, 2015). It can also be represented as annual production divided by total material requirements, in terms of direct material input + indirect flows + unused domestic extraction (Sendra et al., 2007). Zhang et al. (2008) defines eco-efficiency as the ratio between the added value of what has been produced and the added environmental impacts of the product or service. Eco-efficiency may be also calculated as the net sale value per environmental impact within one aspect or an aggregated value. Magerholm-Fet (2003) and Huppes et al. (2012) argued that weighting between the impact categories is needed, while Johnsen et al. (2013) examined criteria for evaluating LCA weighting methods.

Manufacturing impact studies are typically focused on the evaluation of a single process (e.g., grinding, drilling (Gutowski, 2010; Li et al., 2012), and are often limited to individual categories (e.g., CO_2) (Kellens et al., 2012; Narita et al., 2008; Winter, 2015). The emphasis on specific impacts is often motivated by incomplete available data on manufacturing processes. The focus is often limited to estimated energy consumption, and data on potential process emissions are rare (Kellens et al., 2012). Additionally, the complexity of production processes including different process parameters (performance dimensions) does not allow for assessing them at the same time.

In the calculation of eco-efficiency, a complex evaluation of manufacturing processes is needed. Several established methods such as environmental impact assessment (EIA), environmental management systems (EMS), design for the environment (DfE) and Life Cycle Assessment (LCA), Material Flow Analysis (MFA) have been suggested for eco-efficiency analysis by Finnveden and Moberg (2005) and Kuosmanen (2005), and their combination require high-level expert competence (Sevigné-Itoiz et al., 2015; Schaltegger and Synnestvedt, 2002). The overview of potential use of life-cycle-assessment based environmental methods on various processes was presented in the study by Burchart et al. (2016), and Jacquemin et al. (2012).

In fact, the environmentally intended approaches mentioned above support the minimalizing of environmental damages. Unfortunately, there is a lack of monetary value data for material flows, as their economic relevance still determines what is done with these materials (Schmidt and Nakajima, 2013). Additionally, approaches do not make clear contributions to cost savings or industrial plant profits. Likewise, standalone methods do not integrate the economic and environmental performance for manufacturing process. Using MFCA, this method would allow to achieve monetary effects of reducing material and energy use/losses and increase production eco-efficiency (Seager and Theis, 2002). More, MFCA can contribute to LCA based improvement assessments by quantifying and presenting the contribution of material to processes, physical flow and environmental impact. On the other hand, MFCA does not provide detailed analysis of the cost and considerations of energy flows and energy loss flows by alternatives (Sygulla et al., 2011).

Calculating eco-efficiency based on the Life Cycle Cost/Life Cycle Assessment (LCC/LCA) ratio is an alternative method (Kicherer et al., 2007; Li et al., 2012). Three indicators are used to measure environmental impact (Seppälä et al. (2005): "pressure indicators (e.g., emissions of CO_2), impact category indicators (e.g., CO_2 equivalents in the case of climate change), and a total impact indicator (aggregating different impact category indicator results into a single value)". In this case, the annual net sale value is represented as the inverse of yearly production costs.

In summary, it should be pointed out that the mentioned methods neglect the complexity of each established method. The available approaches mainly differ depending on analyzing and assessing quantified flows and the use of monetary evaluation criteria. The connection of the MFA-LCA-MFCA methods approach eliminates the mentioned shortcomings and it is therefore more suitable for assessing eco-efficiency of processes.

2.2. Methods for evaluating eco-efficiency improvement

Significant effort has been made for measuring the environmental and economic performance of manufacturing processes. Efficiency improvement is realized by implementing technological changes or process improvements (Yeo et al., 2016). Methods for eco-efficiency are based on these evaluation results, where the flows for the existing processes are quantified with respect to their resource and cost efficiency. Thus, eco-efficiency is measured using following methods:

Life Cycle Assessment (LCA) is a comprehensive approach that encompasses the environmental impact throughout product life cycle phases and extends beyond manufacturing. LCA, based on material flow, focuses on the identification and quantifying of environmental loads, the potentiality of these loads and proposing environmental impact reduction (Finnveden et al., 2009; Glavic and Lukman, 2007). “Materials used in manufacturing are also major sources of the environmental impact, not only from the materials themselves but also from the embedded energy and resources used to produce these materials” (Yuan et al., 2012). This limits LCA's usefulness as the sole basis for comprehensive assessments and the comparisons of alternatives. So as LCA may identify potential issues from a system wide perspective, more focused assessments using other analytical techniques are often necessary to resolve the issues (Comăniță et al., 2018; Mbohwa, 2013).

Material Flow Analysis (MFA), in turn, can be seen as an instrument for aggregating various environmental impacts into a few strategic indicators such as the total throughput of materials, and energy intensity per unit. This method can also be used to develop strategies for improving material flow as well promoting technological changes (Brunner and Rechberger, 2004; Moreau and Massard, 2017). This data can be used for establishing an inventory for LCA and MFCA.

Material Flow Cost Accounting (MFCA), in turn, is a tool for presenting process costs including material, energy and waste, disposal. Under MFCA, the flows materials within a company are traced and quantified in physical units and the costs associated with these material flows are also evaluated. The costs may be expressed as profit or loss, based on the production volume. MFCA can be used to reduce waste and thereby improve resource efficiency and environmental performance (Jasch, 2009). The advantage lies in the fact that MFCA method conveys the information about value losses over various process steps and makes it transparent (Schmidt and Nakajima, 2013). The resulting information can act as a motivator for industrial plans to seek opportunities to simultaneously generate economic benefits and reduce adverse environmental impacts.

None of these methods allow for a comprehensive approach in calculating eco-efficiency for manufacturing processes. To address this shortcoming, an integrated approach for assessing the eco-efficiency of the manufacturing processes is proposed, based on a Material Flow Analysis (MFA), Material Flow Cost Accounting (MFCA), and Life Cycle Assessment (LCA). The approach identifies the most effective, relevant manufacturing technologies and offers an easily used metric for improving manufacturing practices. A combination of the MFA, LCA, and MFCA seems interesting in order to overcome the problems of limitation in application for three tools. Additionally, this method is introduced to fill gaps in the assessment of homogeneous manufacturing processes with various functional units. To do so, it is necessary to be able to compare existing with improved processes by quantifying the environmental and economic effect in all relevant dimensions. The illustrate the relevance of this research, the welding, cleaning, cleaning and painting processes are studied at a heating boiler manufacturing facility in Poland.

3. Material and methods

3.1. Methodology

The aim of this chapter is to outline the three analytical tools that have been used in this study to calculate eco-efficiency in heating boiler manufacturing: MFA, LCA, and monetary MFCA. It introduces a hybrid method called MFA-LCA-MCFA. This hybrid assessment tool can be used to measure eco-efficiency in order to determine which processes are responsible for the largest environmental impacts and if a process is improved after upgrades.

In evaluation of eco-efficiency, four major steps are applied to the study (ISO 14040, 2006):

(1) identifying the boundaries, within the processes to be assessed are defined, as well as the context of the assessment to be made;

(2) collecting and analyzing inventory data to establish the material flow diagram. This inventory analysis collects all data of manufacturing processes and relates it to the functional unit of the study, it examines the inputs and outputs (materials and energy consumed) during the manufacturing processes from and to the environment;

(3) analyzing eco-efficiency (LCA + MFCA) – during the evaluation of significance of potential environmental impacts based on the inventory flow results. The following sub-steps are taken:

- classification and aggregation of environmental impact categories:
- the inventory parameters (inventory results) are selected and assigned to specific impact

categories; therefore, a common unit is defined for each category,

- impact measurement: - the categorized LCI flows are characterized into common equivalent units that are then calculated to provide an overall impact category,
- cost appraisals of the quantified flows,

(4) interpretating the results.

To analyze the data inventory and evaluate the information for assessing the environmental impact, LCA and MFA are appropriate for comparing aggregate, disparate material flows within the manufacturing processes. Additionally, the MFA-LCA is used to capture the upstream environmental burdens associated with manufacturing processes, according to recommendations in ISO/TR 14025 (2006). The environmental impact is expressed in impact categories, such as global warming, health impairment and energy footprint. Production, material loss, waste and emission costs are calculated in MFCA.

Once inventories are established, the environmental impact is evaluated using Eco-indicator 95. Eco-Indicator 95 is chosen in this paper, since it allows for an easy demonstration of the proposed hybrid method, based on indicators for the most globally relevant categories for energy, materials and processes. Eco-Indicator 99 requires greater detail in a microcosmic scale that adds complexity, but not greater utility, to the objective of this study. For this paper, the differences between 95 and 99 are superficial and using 99 would be over-elaborated. By using Eco-indicator 95, it is easily made combinations and carried out an LCA, so no outside expert or software was needed.

The hybrid approach calculates the environmental impact by integrating various contributions into a single analysis. The core of the approach is to calculate a single indicator for each manufacturing process. These must be further balanced against an economic analysis using MFCA to complete the calculation of eco-efficiency.

So far, no MFA-LCA-MFCA study has been performed for assessing eco-efficiency of manufacturing processes in the heating device sector. LCA is applied to quantify the environmental impacts of boiler production. In the combined MFA-LCA approach, however, the method is based on material balancing, which is often not the case in LCA studies (de Haes et al., 2000). The material flow balance is summed up to show how much of the purchased materials are actually processed into product sold and how much is discharged as waste, or emissions (Jasch, 2009). Additionally, MFA data can be used for MFCA, which serves as the economic indicator within the model. It is used to represent production costs. These include material, energy and waste cost. Therefore, the three analyses (MFA-LCA-MFCA) are combined and adapted to the case study as an analytical tool for the assessment of the eco-efficiency of production. This structured assessment method is needed to embody both environmental and economic performance in manufacturing process for quantifying eco-efficiency.

3.2. Industrial case study

An industrial case study has been carried out to evaluate the eco-efficiency of manufacturing processes using the MFA-LCA-MFCA method. The company was chosen due to its high interest in environmental performance analysis and improvement programs. The interviews with three production managers and company employees at different level were used to provide a foundation for developing this case. In addition, plant visits were conducted to create a current state map and collect data. Furthermore, the data analysis and performance with regard to processes and equipment are carried out in collaboration with the plant's management (Muchiri et al., 2011).

As illustrated in Fig. 1, the production process consists of six processes that are cutting, bending, welding, cleaning, painting, and final assembly. The scope of the case study encompasses material and energy use, emission and wastes involved in the production system. All materials and energy required for the improvement scenario, and descriptions of waste, emissions generated from these processes are depicted in Fig. 1. The input-process-output diagram also shows how processes are interconnected through commodity flows. Cutting, welding cleaning, painting is evaluated for the production of 4000 central heating boilers per year. The annual electricity use of 100 520 kWh is allocated to the production process.

With reference to the processes listed above, the MFA-LCA-MFCA study carried out aiming at improving eco-efficiency of the manufacturing processes, with a particular focus on investigating the environmental and economic performance in the plant. The analysis is framed in terms of mapping technological changes in manufacturing processes for an enterprise (baseline scenario and improvement scenario) as shown in Table 1.

Based on the inventory data for the both scenarios placed in Table 2, environmental impact can be quantified for all six boiler manufacturing processes. Table 2 summarizes all of the material, energy and waste flows shown in Fig. 1. Material consumption and material waste, dust, and pollution emissions for the both scenarios were taken from plant data. Energy consumption [kWh] was calculated using energy use per machine [kW], process specific data and operation time [h].

3.3. System boundaries

The system boundary determines which manufacturing processes will be investigated (Ekvall and Weidema, 2004; Suh et al., 2004). The different manufacturing processes and their interrelationships are described to define where each intended unit process starts, which operations take place and where unit processes end (Kellens et al., 2012). The omission of inputs or outputs for selected manufacturing processes is only recommended if it does not significantly change the overall conclusions of the study. The processes investigated do not take into account emissions from transport, bending and final assembly. The following inputs are included in the inventories:

- materials,
- electricity input,
- fuel burned during the painting process.

The following outputs are considered:

- emissions to air from manufacturing processes and energy combustion,
- waste generated during the work processes.

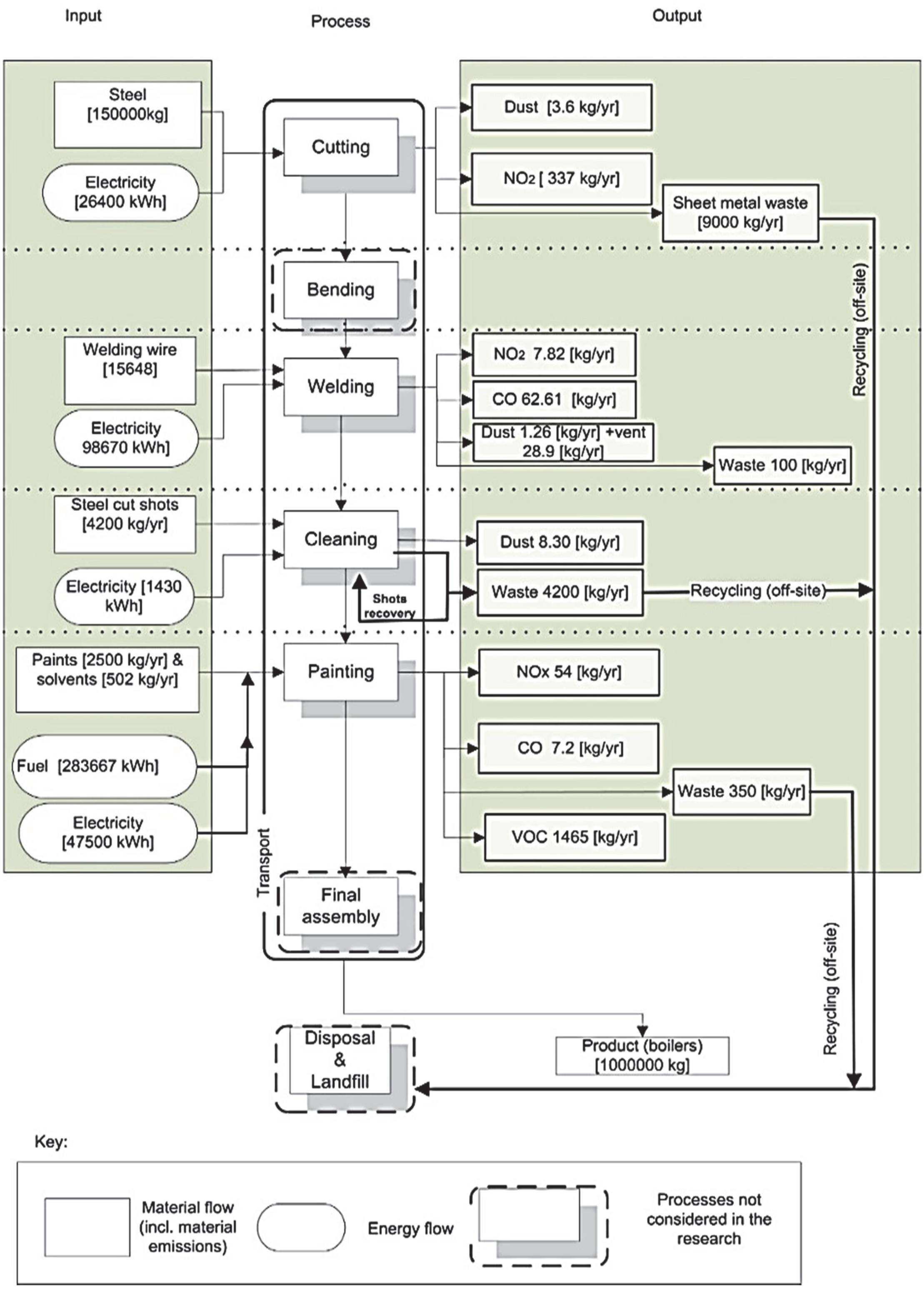


Fig. 1. Improved scenario: life cycle diagram, including Material Flow Analysis for production of 4000 units (Kluczek, 2014)

Table 1. Basic vs. improved scenario

Manufacturing processes	*Existing techniques (baseline scenario)*	*Proposed solutions (improvement scenario)*
Cutting (M1)	Sheet steel is plasma cut, using a computer control system which accurately produces the shapes designed in a CAD / CAM system. This technique enables cutting arbitrary, complex parts which do not require further finishing.	Laser cutting machine: workplaces converted to laser cutting will be equipped with a separate ventilation system (filtering system)
Welding (M2)	Boiler bodies welded with semi–automatic MIG/MAG in a CO_2 shield, using SpG3S-wire with a diameter of ϕ 1.2 mm. Due to the high versatility of the process, MIG/MAG allows performing a variety of functions with different metals and alloys in workshop and assembly conditions, in all positions. The burner is cooled with ethylene glycol. Welding stations are equipped with jigs, fixtures, and lifts point.	Push–Pull welding ventilation system: Install central filtering systems with cartridge filter units to reduce welding fumes and gases released into general ventilation.
Cleaning (M3)	The painting process is preceded by a thorough cleaning of parts by sandblasting, and sometimes degreasing.	Install a dust-free, shot blasting booth with a closed circuit steel shot system: The shot blast booth will be equipped with an integral filter absorbing dust emissions.
Painting (M4)	Solvent-based paints are applied to the cleaned parts using a pneumatic spraying method, releasing a large amount of VOCs into the atmosphere.	Use a paint spraying and drying cabin with an air recirculation loop, with hydrodynamic spraying as the application technique.

Table 2. Baseline scenario vs. improvement scenario: life cycle production inventory data assuming production volume of 1000 tons and manufacturing time of 1000 hours for M1, M2, M3 and 800 hours for M4

	Material consumption [kg]		*Energy consumption [MJ]*		*Waste [kg/yr]*		*Emission to air [kg/yr]**		*CO_2 eq emissions [kg]*	
unit of process	existing processes	improvement scenario	existing processes	improvement scenario	existing processes	improvement scenario	existing processes	improvement scenario	Existing processes	improvement scenario
M1	150000	150000	217800	95040	12000	9000	696	340.20	38720	16896
M2	15648	15648	130680	322920	100	100	322.40	100	23232	57408
M3	258384	4200	9504	7920	258384	4200	335	8.25	1690	1408
M4	3002	3002	3888	171072	350	350	1526	1526	691.20	30413
				1021200						64.80

** sum of overall emissions including CO, NOx, NO_2, VOC, dust*

3.4. Inventory analysis - input and output indicators

Inventory analysis quantifies the amount of material and energy used as inputs at each manufacturing process in the baseline and improvement scenarios. Furthermore, it quantifies the outputs, including released CO_2, wastes and emissions within the system boundaries.

The inventory data used for estimating the environmental impacts are presented in the Table 1, which contains a summary of input and output flows for production. The information is aggregated at the production level, meaning all inputs and outputs released to the environment are summed. Data on input and output for baseline and improvement scenarios are driven from the company. It is important that the data for the four processes are represented in units that allow for comparable evaluation of environmental performance.

Inputs are represented by energy consumption (kWh/yr), fuel consumption (MJ) and material consumption (kg/yr). Outputs are amount of emissions (kg/yr), carbon dioxide (CO_2) and waste generated (kg/yr). Air pollutants and production wastes are calculated, aggregated and summed by the annual production for each manufacturing process, (Table 2). Data on volatile organic emissions (VOCs) obtained from the company are summed. A wide range of emissions were considered in this study: including nitrous oxide (NOx), carbon monoxide (CO), carbon monoxide (CO), and sulfur dioxide (SO_2).

Since no measurement of the actual electricity consumption of the in-line manufacturing processes is done by the company, the electricity usage is approximated using the power requirements declared on the machines and processing time (Table 1). The times do not include changeovers, program changing and non-production activities.

Data on fuel consumption in MJ in the painting process are given in liters per year (l/yr). By multiplying the values given in l/yr by the specific liquid fuel gas density (25.53 MJ/l), a value for the fuel consumption for the painting process was obtained. The quantity of electricity is reported as kWh/yr, but it is also expressed in MJ, as the electricity use (kW) multiplied by annual operation hours (h) and by the conversion factor (3.6 MJ/kWh). The following equation is used for calculating the carbon dioxide CO_2 emissions (Eq. 1):

$$CO_2 = \Sigma \text{ (emission factor (kg/m}^3 \text{ * GWP of GHGs)) *fuel (m}^3\text{)/1000} \quad (1)$$

The following details will be considered in calculating performance values for both baseline and improvement scenarios.

According to IPPC (IPPC, 2013) the propane (LPG) emission factors for the main greenhouse gases (CO_2, N_2O and CH4) emitted to the atmosphere during the combustion of natural gas are 1530; 0.23; 0.03 (kg/m$^{3)}$ respectively. The global warming potential (GWP) values for these gases are 1; 310 and 21 respectively. Fuels come from a variety of sources whose CO_2 contribution varies relative to the producing country. The CO_2 equivalent emissions are determined by multiplying the quantity of each gas emitted by its GWP emissions relative to its source. The value factor for electric power in Poland is 0.065 kg per kWh, (Brander et al., 2011). The price of 1 kWh at the time of writing is US$0.189 per kWh, and is the sum of the distribution charge and electricity price.

3.5. Aggregation of the Environmental Impact Categories

A single environmental impact indicator in each environmental impact category is used, based on Eco-indicator 95 (Goedkoop, 1995), which encompasses:

- global warming (in terms of CO_2);
- health impairment (emissions into air as the sum of VOC components and dust);
- energy footprint.

The global warming metric is an eco-efficiency indicator. It reflects the potential contribution of different greenhouse gas (GHG) emissions from the production process affecting the environment. The health impairment eco-efficiency indicator reflects the potential risk of emitted toxic substances to human health. Energy footprint is an eco-efficiency indicator that takes into account energy and fuel demand of manufacturing processes (Stoeglehner, 2003). Fig. 2 indicates the relative size of the environmental impact of processes (baseline vs. improvement scenario) expressed as a coefficient of variation (CV) in each of the environmental impact categories considered. CO, SO_2, NOx are not considered in the calculation of environmental impact in Fig. 2, because these emissions are unchanged in the improvement scenario.

3.6. Cost appraisals of the quantified flows

After developing the flow model, the material flows are determined on a quantitative basis.

Material loss, energy, labor, emission and waste management costs are calculated in MFCA in the following way:

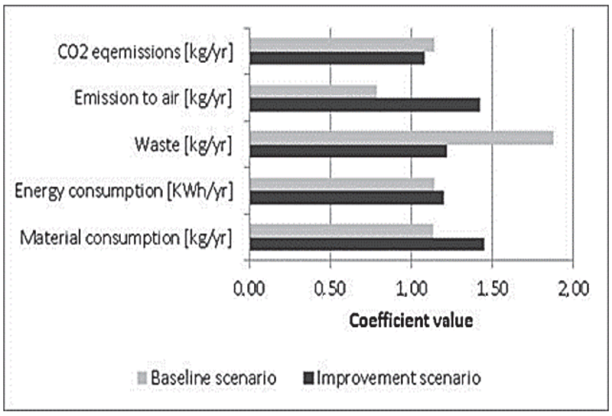


Fig. 2. Environmental impact categories: Global warming, Health impairment, and Energy footprint in terms of Eco-indicator 95

- Material costs: cost are determined by multiplying the amount of the particular materials by their specific prices and summing up the results (Sygulla et al.,2011);
- Labor costs: labor costs are calculated in the man-hours required by each machine: *labor cost per year* (1+f)/average hours per year*, where f is a social cost of labor;
- Energy costs: electricity and fuel costs are included in the calculation. The energy consumption of each examined process is allocated to each quantity center by machine-hour. Energy is often subsumed under the term of material, the energy costs are treated as part of the material costs; (Jasch, 2009);
- Waste management costs: waste cost are all expenses which occur in the context of handling waste losses within a particular quantity center (Sygulla et al., 2011);
- Emission cost: emissions (CO, NO2, dust, VOC, NOx) are calculated similar to the waste.

Based on the MFCA calculation, the data collected within these boundaries are summarized in monetary units as shown in the in Table 3.

Application of the MFCA showed that a large part of the costs is connected with the material losses due to defective products, wastes, emission etc. for each process. Table 4 shows the material flow cost matrix by type of process and its cost. Application of the MFCA showed that a large part of the costs is connected with the material losses due to defective products, wastes, emission etc. for each process. Table 4 shows the material flow cost matrix by type of process and its cost.

The benefits from applying the proposed solutions (Table 1) are slightly significantly decreased waste and emissions, reducing total costs associated with regulatory fees by 0.12%. By using recycled steel shot resulting in dust-free cleaning, the company is able to reduce $US667.29 paid to the government. The company spends $US484857.86/yearly on materials used, however runs into cost losses of 8% of material used to the amount of $US443535. For energy consumption, the electricity and fuel cost are about $US66463 year, a cost demand of 3% of the energy consumption costing of $US15364.50/year.

3.7. Calculation of eco-efficiency

Eco-efficiency ***EE*** is calculated to obtain understanding on a per kg CO_2 and per Pt of the environmental and economic impacts. Eco-efficiency demonstrates which manufacturing process is the most cost-efficient. To assess existing vs. improved process, a MFA-LCA-MFCA is carried out. The annual product costs in terms of volume serves as the economic component in this calculation. Based on the results of the analysis of environmental performance (LCA+MFA) and economic performance (MFCA), eco-efficiency of manufacturing processes for both baseline and improvement scenarios are expressed by the ratios as follows:

- expressed in terms of GWP (Eq. 2):

*EE = (1/(annual product costs/production volume) * GWP indicator))* (2)

- expressed in terms of Health Impairment (Eq. 3):

EE = (1//(annual product costs/production volume) Eco-indicator 95))* (3)

A higher indicator value means higher efficiency.

- expressed in terms of energy footprint (Eq. 4):

EE = 1/annual product cost /total energy consumed in MJ (4)

In Table 5 it is depicted impact categories using GWP and Eco-indicator assessment method for baseline and improvement scenario. The greatest impact on CO_2 equivalent relates to cleaning, where 1689.60 kg CO_2 per 1 Mg of production is released in the atmosphere. Using Eco-indicator 95 method cleaning with value of 3662 Pt/kg has more environmental impact than the same process in the improvement scenario (41.50 Pt/kg). The same impact value (3662 Pt per kg of production) has the painting process in the two scenarios.

The results of the existing manufacturing methods are clearly separated from those of the improved manufacturing ones (alternative processes) with regard to the environmental impact factors used. The most favorable processes are located top right of the portfolio, the least favorable one’s bottom left. The most efficient processes have the least environmental impact in a category and the greatest economic benefit. The distance of the alternatives to the portfolio diagonal is a measure of the respective eco-efficiency (Saling et al., 2002).

Table 3. Environmental and production cost groups based on the MFCA data collection

No	*Environmental related cost groups*	*Improvement scenario*	*Baseline scenario*
		Total Cost [$/yearly]	*Total Cost [$/yearly]*
1	**Production Cost**	**534998.30**	**532081.66**
	Electricity	34463.30	19098.80
	Fuel	32000	0
	Materials	443535	484857.86
	Employee cost	25000	28125
2	**Waste and Emission Cost**	**667.29**	**4119.95**
	Waste	-2195.29	1103.06
	Overall Emissions	2862.58	3016.89
	Total	**535665.59**	**536201.61**
3	**Material Loss Cost**	**12775.52**	2%
	Materials	41322.86	8%
	Fuel	-32000	1%
	Waste	3298.35	0.12%
	Emission	154.31	-6%
4	Electricity	-15364.5	-3%

Table 4. Material flow cost matrix by type of process and its cost

Process / *Cost*	*Electricity*	*Fuel*	*Materials*	*Labor*	*Waste*	*Emission*	*Total production cost*
Improvement scenario							
M1	5016	0	128500	4687.50	-2340	56.96	138203.50
M2	18747.30	8932	212966.40	7812.50	100	21.94	248458.20
M3	1672	0	8106	6250	15.71	4,14	16028.00
M4	9028	32000	93962.60	6250	29	2779,54	141240.60
Baseline scenario							
M1`	11495	0	128500	4687.5	-3120	60.41	144682.50
M2`	6897	8932	212966.4	7812.5	100	32.07	236872.03
M3`	6897	8932	212966.40	7812.50	100	32.07	236872.03
M4`	205.20	0	93962.60	6250	29	2776.86	106029.52

The results of calculations using the hybrid method indicate a higher eco-efficiency of improved manufacturing processes when measured in terms of GWP: cutting, cleaning and painting process. For manufacturing measured in terms of Eco-indicator 95, a higher eco-efficiency presents cutting and cleaning. Moreover, relative eco-efficiency values for the two scenarios where economic performance is measured in USD/Mg, and environmental impact is measured in kg CO2 eq. and Pt, is shown in portfolio plots (Figs. 3-4). Also, using this method to present the results of LCA+ MFCA analysis allows comparison of eco-efficiency of the manufacturing processes examined.

So, the results demonstrate that alternative cleaning is the most eco-efficient, based on its low cost, it also shows that it has less overall environmental impact than the alternative processes. The cost of raw materials has a great impact of the total cost, and therefore the eco-efficiency. Based on the results of environmental and economic analysis is calculated eco-efficiency values for the two scenarios (Table 6). A higher value of indicator indicates a higher eco-efficiency. The results demonstrate that the alternative cleaning alternative is the most eco-efficient measured in terms of GWP Eco-indicator 95 than that of baseline scenario.

Table 5. Environmental impact assessment in impact categories for baseline and improvement scenario

Environmental impact categories	***M1***	***M2***	***M3***	***M4***	***M1`***	***M2`***	***M3`***	***M4`***
Global warming (GWP) [kg CO2 eq/Mg]	16.90	63.19	5.63	30.48	38.72	23.23	1689.60	691.20
Eco-indicator 95 [Pt/kg]	18	151.50	41.50	3662	36	301.50	1675	3662

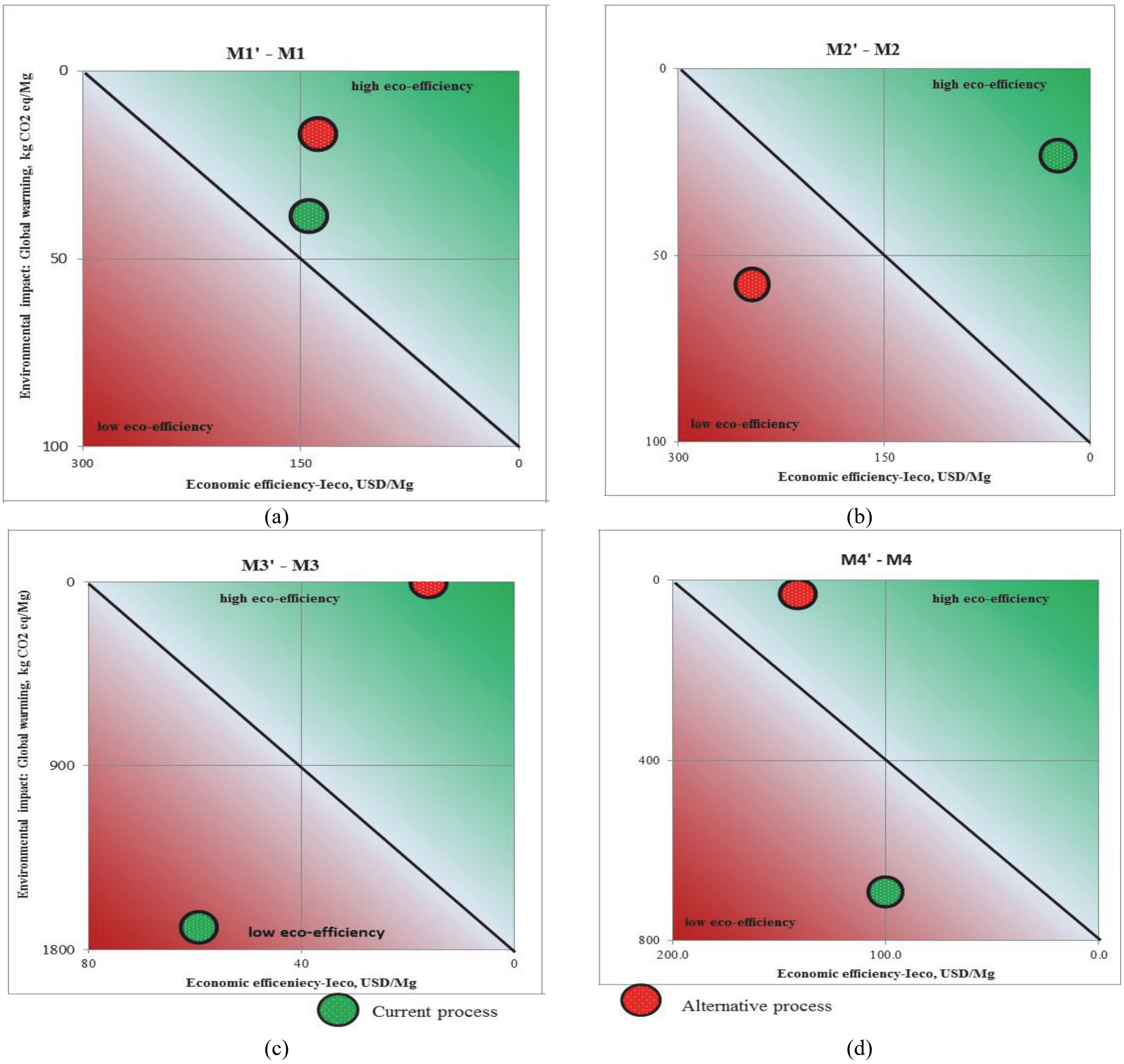
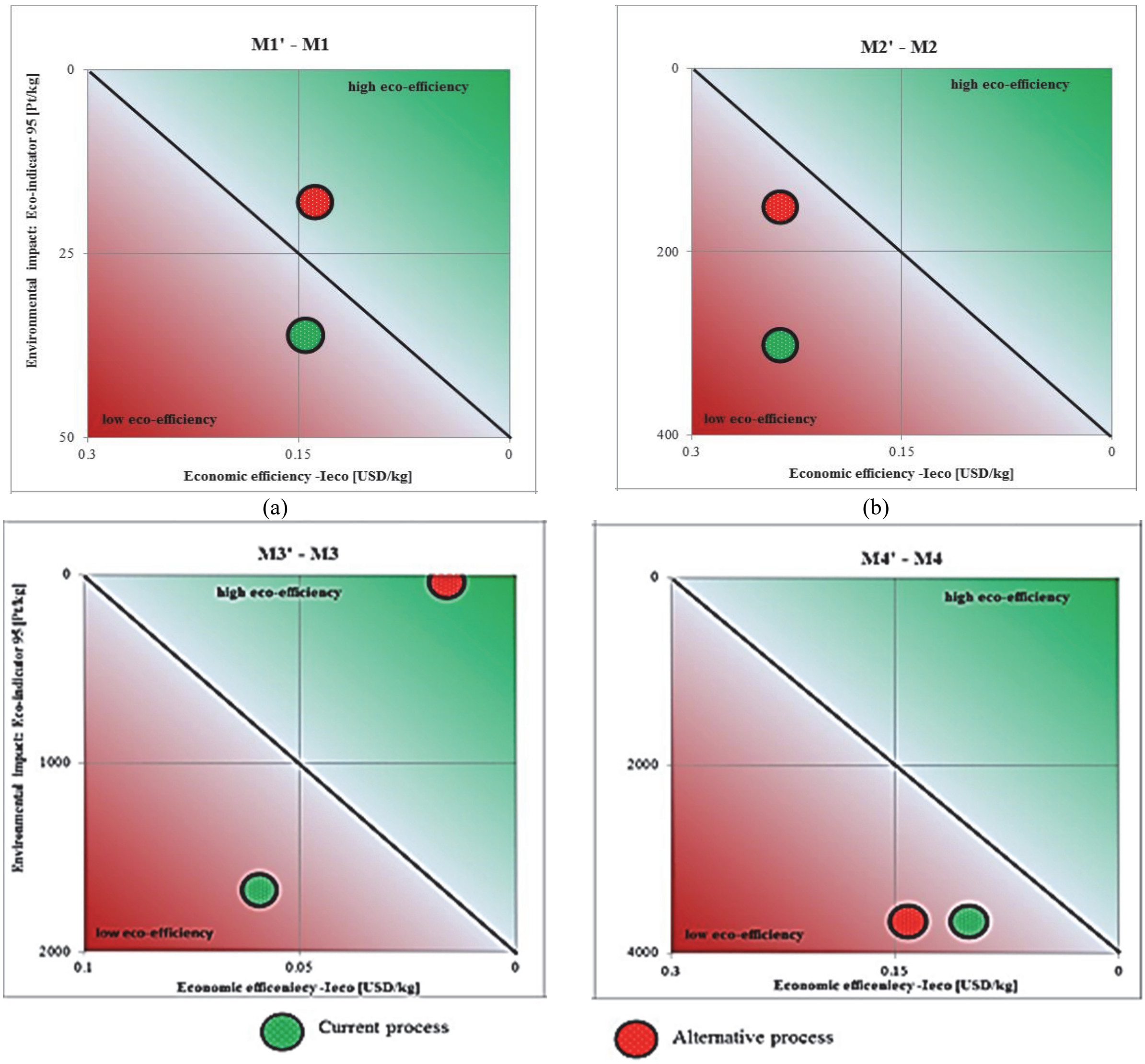


Fig. 3. Relative eco-efficiency values measured by environmental and economic performance and calculation of CO_2 eq in the scenarios (baseline – improvement)(a) Represents cutting process (M1`-M1); (b) Represents welding process (M2`-M2); (c) Represent cleaning process (M3`-M3); (d) Represents painting process (M4`-M4)

The energy footprint provides additional information for the environmental impact considered (Table 6). A comparison of the eco-efficiency of the baseline and – improvement scenarios shows that the alternative cutting has, relatively to other manufacturing processes, a higher eco-efficiency than the process for the baseline scenario.

Due to the high processing energy, alternative painting has the least indicator, but the highest utilities costs: 32000 liters of fuel are burned to paint heating boilers and dry cabin. It represents a significantly less eco-efficiency to the current process. Fig. 5 visualizes environmental impact under the category of energy footprint.



(c) (d)

Fig. 4. Relative eco-efficiency values measured by environmental and economic performance and Eco-indicator 95 in the scenarios (baseline – improvement) (a) represents cutting process (M1`-M1); (b) represents welding process (M2`-M2); (c) represents cleaning process (M3`-M3); (d) represents painting process (M4`-M4)

Table 6. Results of relative eco-efficiency values for the baseline and improvement scenario

Environmental impact categories	*M1*	*M2*	*M3*	*M4*	*M1`*	*M2`*	*M3`*	*M4`*
Global warming (GWP) *[kg CO2 eq/Mg]*	4.28E-04·	6.37E-05	1.11E-02	2.33E-04	1.79E-04	1.82E-04	9.98E-03	1.44E-02
Eco-indicator 95 *[Pt/kg]*	4.02E-01	2.66E-02	1.51E+00	1.93E-03	1.92E-01	1.40E-02	1.01E-02	2.72E-03
Energy footprint	6.88E-04	5.26E-04	1.98E-03	1.21E-03	1.51E-03	5.52E-04	1.60E-04	3.87E-05

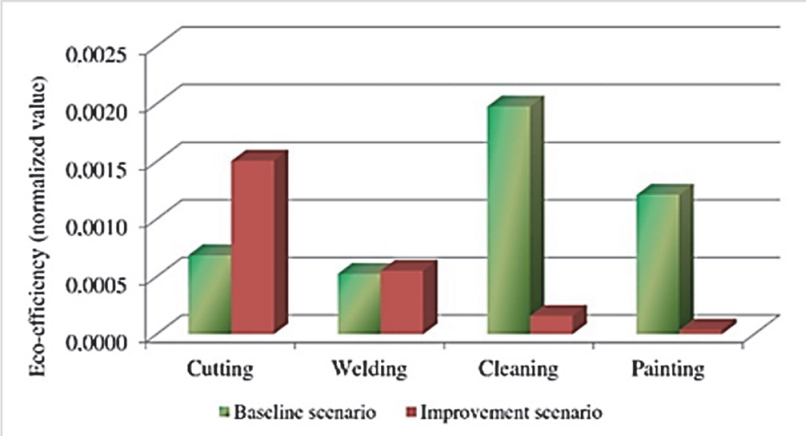


Fig. 5. Eco-efficiency for processes in terms of energy footprint

4. Results and discussion

The case study shows that the method combining MFA-LCA-MFCA is a viable and effective tool of assessing the eco-efficiency of a manufacturing system. It is used for assessing a baseline and improvement scenarios in terms of cost and environmental benefits. In the case study used in this paper, the production costs in the improvement scenario are greater than the baseline due in part to investment in new equipment. Investments in equipment are amortized and will eventually have no permanent costs associated with production. A look at the eco-efficiency of electricity reveals that there is more electricity consumption between current and alternatives processes, resulting in cost increase of 3%. Fuel expense was increased in the painting process, but the elimination in VOC emissions released to the atmosphere is seen as a desirable tradeoff.

The calculated results for the improvement scenario indicate higher eco-efficiency in GWP for cleaning and painting. For health impairment, calculated using Eco-indicator 95, the largest gain in eco-efficiency was presented by improvements to the cleaning process. These results are congruent with the data shown in Fig. 1, which indicates that dust emissions are highest in these processes (335 kg and 60.3 kg/yr) before improvements. For an economic analysis from the MFA-LCA-MFCA, the greatest benefits are also provided by the cleaning process. The welding process in the improvement scenario shows an increase in electricity consumption of 273% from the base scenario from the addition of the new filtration system.

Painting has the highest environmental impact of any of the processes in production. This is due to the high energy demand for painting and curing as well as the emissions of different pollutants. With respect to energy consumption, the improvement scenario results are not as positive as was with pollution reduction. Annual LPG fuel consumption increased 100% and electricity was 363% greater after improvements.

The results indicated higher eco-efficiency for cutting in terms of energy use. In terms of health impairment and GWP, the greatest increase in eco-efficiency comes from improvements to the cleaning process. The eco-efficiency values may vary considerably depending on what type of electricity is used, how recycling is done, etc. Such variation points to the flexibility of using eco-efficiency as an indicator for assessing and improving environmental performance in manufacturing. Since improving eco-efficiency involves cost and benefit tradeoffs, if the improved technologies within production process are beneficial to the environment, or even merely better than existing systems, then, eco-efficiency may decrease. This would be despite an overall improvement on environmental impact. Many types of efficiency measures can have this result. An example of the greater demands in assessment would be the incorporation of overseas supplier logistics into a manufacturer's environmental footprint. The combined MFA-LCA-MFCA method can serve as a flexible foundation, incorporating other impact categories and indicators, such as Eco-Indicator 99 and ReCipe, for more complex assessment needs (Verbitsky and Pushkar, 2018).

It is anticipated that future improvements in the manufacturing processes of heating boilers will provide more systematic information, thus allowing the combined MFA-LCA-MFCA method to play a greater role in eco-efficiency assessment.

5. Conclusions

The application of the MFA-LCA-MFCA was provided a comparable tool to assess the eco-efficiency of processes enabling the enterprise to gain a higher transparency of material use / losses, and to identify options to reduce their costs in order to minimize environmental impacts and enhance economic performance. The study revealed that the total cost of material losses could be reduced by 2% against current processes. The cleaning is the most eco-efficient, based on its low cost and environmental impact.

Further work is required to expand the hybrid method by strengthening simultaneous analysis of various features of the flows and integrating the method with standardized assessment methods.

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