Thesis for the Degree of Master of Management of Technology

Developing an Eco Design Method for Energy-Related Products Using Environmental, Economic, and Functional Assessment Techniques

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(환경적, 경제적, 기능적 평가기법을 통한 친환경 제품 개발 방법)

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ABSTRACT

Recently, new product development is being forced to move toward considering more various and different performances. Especially, assessing environmental impacts of product systems becomes significant with emphasis on the reduction of carbon dioxide emission in line with the new climate change regime. For these reasons, selecting the best product among product candidates remains more troublesome to product developers. However, relevant studies regarding environmental assessment on the product development phase do not much combine the aspects of cost and function simultaneously. The present work proposes an environmentally-conscious (eco-) design methodology that integrates environmental, economic and functional analysis with consideration of product's predefined requirements. This methodology consists of four phases: (1) compliance checklist to ensure that energy-related products fulfill the legislation formalized by ErP Directive 2009/124/EC enacted from European Union, (2) environmental assessment to evaluate the product's environmental impacts by using simplified Life Cycle Assessment (LCA), which is suggested by ISO standard, (3) economic assessment to calculate the total cost during the product lifecycle by using Life Cycle Cost (LCC) concept, and (4) functional assessment

to check the ability of the product during the period of time. Ultimately, the proposed methodology provides an analytical method for determining the most appropriate product in terms of those three aspects. The present work includes a case study to show the effectiveness of the proposed methodology, demonstrated by comparing energy-related products, specifically two vacuum cleaners respectively made by Germany and Korea. This study expectedly helps product developers make an eco-decision on selecting the best product among product candidates through the checking mechanism for complying with such environmental legislation as well as the integrated thinking for quantifying environmental, economic and functional performances.

환경적, 경제적, 기능적 평가기법을 통한 친환경 제품 개발 방법

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요약

지난 한 해 동안, 신제품 개발은 다양성과 효율성을 중심으로 끌려 오고 있었다. 특히 제품 생산에 배출된 이산화 탄소를 줄이기 위한 기후변화대응대책 평가를 집중적으로 하고 있었다. 따라서 개발할 의향이 있는 제품들 중에 위에 같은 요건과 일치하는 제품생산 시스템을 개발하기가 쉽지 않다. 심지어 제품생산에 생긴 비용편익과 환경적인 효과에 대하여 적절한 평가 과제나 논문이 많이 없었다. 본 연구는 제품의 사전 정의 된 요구 사항을 고려하여 환경, 경제 및 기능 분석을 통합하는 환경 친화적 (에코) 설계 방법을 제안합니다. 이 방법론은 다음과 같은 4 단계로 구성되어 있다: (1) 에너지 관련 제품이 EU 에서 지정된 ErP 지침 2009 / 124 / EC 에 의하여 법적으로 준수하는지 보장하기 위한 체크리스트, (2) ISO 표준 제안을 따라 단순화 된 LCA (Life Cycle Assessment)을 사용하여 제품의 환경 영향을 평가, (3) LCC (Life Cycle Cost) 방법을 사용하여 제품 수명주기에 총 비용을 계산하도록 하는 경제적 평가, (4) 일정한 기간 동안 제품의 기능 평가. 제안 된 방법론은 이 세 가지 측면에서 가장 적절한 제품을 결정하기 위함이다. 본 연구는 에너지 관련 제품, 구체적으로 독일과 한국에서 생산된 두 개의 진공 청소기를 비교하여 제안된 방법론의 효과를 보여주기 위한 사례를 포함되어 있다. 또 환경, 경제 및 기능적 성능에 관한 점검 구조가 개발할 제품 후보 중에서 제일 적합한 제품을 선택하는 데에 친환경적인 결정을 내리기에 도움이 될 것으로 기대된다.

1. INTRODUCTION

Nowadays there are so many new technologies as well as new products emerging and exist in the marketplace where all products and services are fully focused to meet product development goals. New product development is being forced to move toward considering more various and different performances. Therefore, the designer of a new product is one of the important roles in the product life cycle especially in the design stage (Kazimierska & Grebosz-Krawaczyk, 2017).

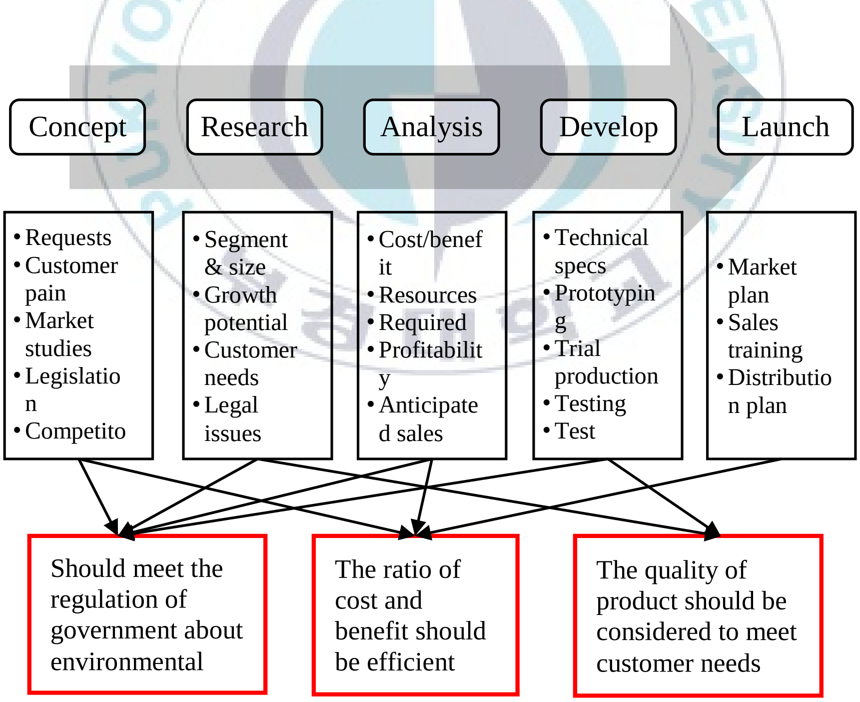

Figure 1.1 New product development process

As shown in Figure 1.1. The snew product development process consists of several parts such as concept, research, analysis, development, and launching. All these stages, has different objectives or tasks ranging from identifying demand, finding out customer needs, fulfill the regulations given by the government, evaluating the feasibility of costs and benefits, etc. This is become a challenge for designers to fulfill all those goals.

Especially, assessing environmental impacts of product systems becomes significant with emphasis on the reduction of carbon dioxide emission in line with the new climate change regime (Lindow, et al., 2018). Every product that comes from natural resources is processed into ready-made products through rapid technological improvements, the quantity of products increases dramatically over time.

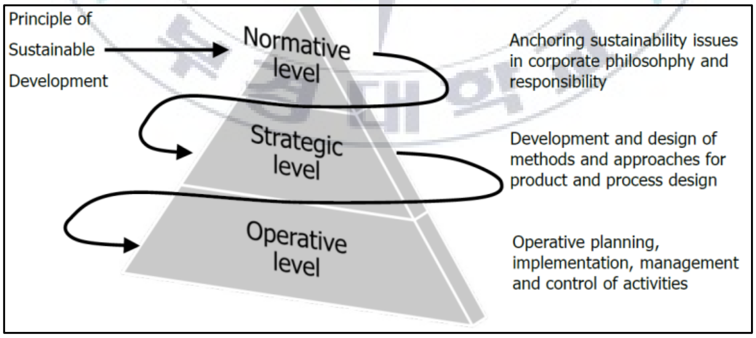

Figure 1.2 Approach to implement sustainable thinking

The production process requires energy and materials. Therefore, if the quantity of production increases then the need for energy and raw material increases as well and those things are closely to related environmental sustainability (Hahlen, 2005).

Recently, environmental sustainability is becoming the most important issue in the world because every company focuses only on customer needs without considering the impact of production on the environment (Pereira, 2015). The sustainable area covers the environment, economy, and society. These three are the 3 main pillars to build sustainability and one of the 3 pillars is the environment (Grossman & Fellow, 2018). Current environmental impacts such as; acidification, biodiversity, climate change / global warming, land degradation, ozone depletion, water pollution, water pollution, etc., need to be addressed. Manufacturing has a big contribution to environmental aspect. Therefore, research in the field of manufacturing to reduce negative environmental impact is needed. There have been many previous studies that discussed the formation of methodologies to prevent excessive environmental impacts, applied the methods found in case studies in industry, however, previous studies concerned with environmental assessment of products rarely combine these analyzes with analysis of functions and costs . In this case the function of the product is durability which means that the characteristics of those objects or materials that maintain their properties are over time (Mora, 2007).

Due to this issues become more important, there is a regulation issued by the European Union called Eco design directive.

This is a framework that aims to reduce total carbon dioxide emissions and energy use by 20% and increase the use of renewable energy by 20% by 2020 (Directive 2009/125/EC, 2009). This means that all products that consume energy circulating in the European market must meet the standards provided by this framework. Given the market in Europe has a high consumer level. According to data from the World bank. Europe ranks second in the world's largest consumer list based on their household final consumption expenditure that represents consumer spending in nominal terms (Anon., 2016).

This work aims to find a new methodology in the field of product design in the manufacturing process to achieve environmentally friendly products and optimize the use of energy and raw materials as efficiently as possible. Furthermore, The present work proposes an environmentally-conscious (eco-) design methodology that integrates environmental, economic and functional analysis with consideration of product's predefined requirements. This methodology consists of four phases: (1) compliance checklist to ensure that energy-related products fulfill the legislation formalized by ErP Directive 2009/124/EC enacted from European Union, (2) environmental assessment to evaluate the product's environmental impacts by using simplified Life Cycle Assessment (LCA), which is suggested by ISO standard, (3) economic assessment to calculate the total cost during the product lifecycle by using Life Cycle Cost (LCC) concept, and (4) functional assessment to check the ability of the product during the period of time. The study also provides a case study demonstrated on one of energy-related products which is a vacuum cleaner and compared it from two products from two different manufacturers namely Germany and Korea respectively to see the feasibility of this proposed methodology.

Finally, this study provides a framework that combines three aspects including environment, economy, and function of a product. This approach is very useful for designers in order to determine the best product from several product candidates in considering these three aspects more specifically to make an eco-decision. Although this study does not recommend the best products specifically, however this study allows companies, manufacturers or designers to evaluate products at the design stage to adjust product standards according to existing conditions.

This thesis is structured as follows:

Chapter 2 Literature review, that identifies related work to this study and finds a gap between this study and the previous study, Chapter 3 Methodology, provides the proposed method and explains the every sections and sub-sections of the method, Chapter 4 demonstrates the proposed method in a case study of a vacuum cleaner, Chapter 5 discusses the results of the research and includes the implications of the entire study, and finally Chapter 6 conclusions.

2. LITERATURE REVIEW

Environmentally-conscious (eco-) design is a concept that combines process design and consideration of environmental issues from a product life cycle that aims to reduce the impact on the environment (Anon., 2018). According to (Navarro, et al., 2005) there are seven main activities in eco-design including; prepare the project, explain the problem from an environmental and social perspective, set and develop ideas, design concepts, determine the final design, execute the plan, and finally evaluate the process.

There are many studies that deal with this issue including; (Shi, et al., 2017) provides an eco-design framework to control solid waste in chemical industries and this method was applied to the analysis of waste due to coal fly ash (Litos , et al., 2017) developed a methodology for life-cycle analysis called EVSM and this method was implemented to a flooring manufacturing industry in the United Kingdom and as a result the company was able to reduce costs by switching off the control panel. Another example of eco-design method from (Kazulis, et al., 2017) they were analyzed the environmental effects of xylan production using eco design analysis and the results they identified the main factors that produced the greatest environmental impact.

From all of these studies it can be said that implementing the eco-design concept in an industry or organization is able to help stakeholders especially designers in the design stage to design products and processes more efficiently and can reduce the impact on the environment as much as possible.

One of the most commonly used concepts is life cycle design (LCD). this concept assesses the entire product life cycle from "cradle to grave" including raw material, manufacturing, assembly, distribution, usage, and end of life. While, this concept assesses each phase from an economic and environmental standpoint and each assessment has its own indicators (Favi, et al., 2012). The most famous method developed based on this concept for environmental issues is Life Cycle Assessment (LCA) and for the economic side, namely Life Cycle Cost (LCC).

Many studies have been carried out in terms of applying the life cycle assessment method on energy-related products including: (Egede, et al., 2015) demonstrating the development of the LCA method in electric vehicles, (Benton, et al., 2017) applying LCA to diesel generator sets, to see the amount of energy consumption in the entire product life cycle, (Zanghelini, et al., 2014) assesses the environmental impact of air compressors in Brazil focusing on comparing three types of waste management scenarios. (Bhakar, et al., 2015), assesses the impact on the environment of three types of monitor waste, (Soo & Doolan, 2014) comparing several types of mobile phone waste treatment from several countries using LCA. And (Gallego-Schmid, et al., 2018) evaluates the effect of ErP directive on the production of emissions and energy consumption of kettles.

Based on all previous studies, when an environmental assessment is carried out they only assess the impact of a process and product on the environment without considering the ability of the product to work according to its function over a period of time, or in other words the durability of the product. Environmental assessment provides a database that contains many emissions factors for each product and process so that users can choose the type of material or process that has the least adverse impact on the environment. However, in terms of choosing material, it has an influence on the durability and quality of the product structure (Poulikidou, et al., 2015).

There has been an environmental assessment that also considers the durability of the product (Ardente & Mathieux, 2014). They made a methodology for environmental assessment and considered aspects of durability by identifying how the environment would benefit if the product's lifespan could be extended. However, this method is only based on the scenario of time differences without specifically analyzing the factors causing the extension or reduction of product life.

Therefore when assessing the environmental impact of a product we must also focus on the ability of the product, in order to be able to provide options in the form of several product candidates with different environmental impacts and durability and determine which products are most in accordance with the required specifications. Therefore, this becomes a gap between the previous study and the present study. This study provides an analytical approach that allows designers to design products by considering the impact on the environment as well as analyzing the ability of the product without ignoring the standard requirements provided. In this study we adopted standard requirements based on the ErP directive standard. And economic assessment is also done in addition to identify cost efficiency.

3. METHODOLOGY

For the development of the present methodology, an iterative approach was followed. There is three phases of research activities has conducted as illustrated in the Fig. 3.1.

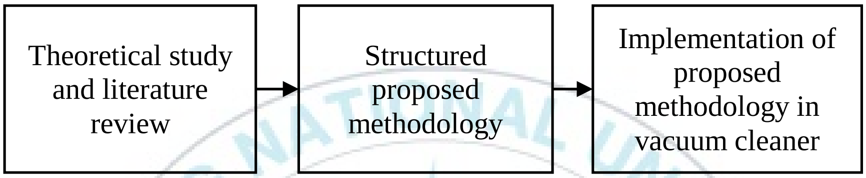

Figure 3.1 Research phases for the development of methodology.

In the first phase, related theory and literature were searched to find the gap of current and previous studies, and to determine the equations used in the proposed methodology. Then in the next phase, the proposed methodology was structured based on the theories and literatures. Ultimately the validation of proposed methodology was implemented in case study with vacuum cleaner from to different manufacturer which are Samsung vacuum cleaner and *Allgemeine Elektricitäts-Gesellschaft* (AEG) vacuum cleaner. The aims of the implementation methodology into two manufacturers is to compare Europe product which has fulfilled the ErP directive and Korean product which has not.

The structure of the proposed methodology in this study for the integrating of Environmental, Economical, and Functional assessment in Energy-related products is presented in the Figure 3.2.

This methodology consists of four main steps: First, Compliance checklist of Energy-related products standard to qualify that the product fulfill the standard which given by ErP directive from European Union.

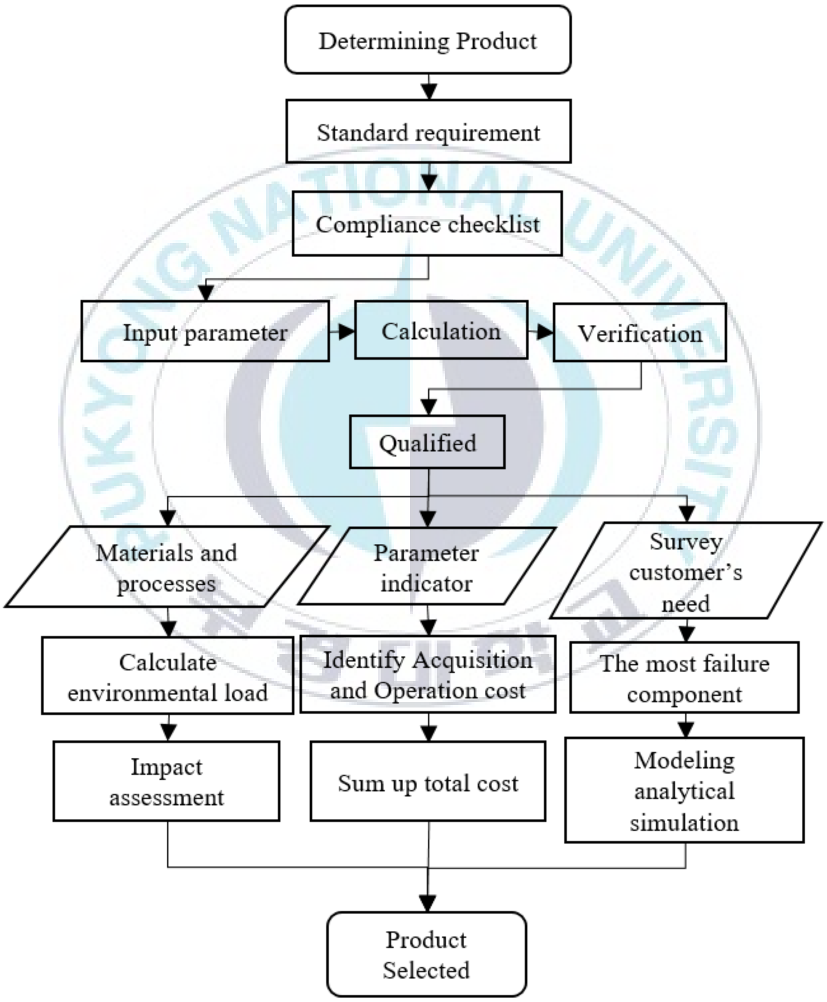

Figure 3.2 A proposed methodology for integrating Environmental, Economical, and Functional techniques.

Second, Environmental assessment to assess the impact of product by using Life Cycle Assessment (LCA) tool which suggested by ISO standards (Lee & Inaba, 2004)). Third, Economical assessment to calculate the total cost in the product life cycle by using Life Cycle Costing (LCC) methodology suggested by (Kara, et al., 2017). Finally, the functional analytical model is used to see the ability of the product during the period of time.

Each main step has specific activities to perform. An explanation of each step and its specific activities are presented in the description below.

3.1 Compliance checklist of Energy-Related Products

Energy related product, (a product) means any good that has an impact on energy consumption during use which is placed on the market and/or put into service, and includes parts intended to be incorporated into energy-related products. (Commission Regulation, 2013).

There is world-wide demand for more efficient products to reduce energy and resource consumption. The EU legislation on Eco-design and energy labelling is an effective tool for improving the energy efficiency of products. It helps eliminate the least performing products from the market, significantly contributing to the EU's 2020 energy efficiency objective. It also supports industrial competitiveness and innovation by promoting the better environmental performance of products throughout the Internal Market**. (**European Union). Because of this reason, the European Union establishes a framework for the setting of eco design requirements for energy-related products with the aim of ensuring the free movement of such products within the internal markets.

This Directive provides for the setting of requirements which the energy-related products covered by implementing measures must fulfil in order to be placed on the market and/or put into service. It contributes to sustainable development by increasing energy efficiency and the level of protection of the environment, while at the same time increasing the security of the energy supply.

3.1.1 Determining product

The first activity in this step is to determine which product will be assess through this methodology. There are more than twenty products are covered in this directive such as, air heating and cooling products, air conditioner and comfort fans, circulators, electric motors, computers, washing machines, vacuum cleaners, refrigerators and freezers, external power supplies, household dishwashers, industrial fans, power transformers, local space heaters, solid fuel boilers, televisions, ventilation units, water pumps, external power supplies, lighting products in the domestic and tertiary sectors, etc.

3.1.2 Requirement standard

The European Union has announced standard requirement for every energy-related products in official journal of European Union. In this compliance checklist there are three specific processes in order to figure out the qualification. The first is input parameter consists with collecting preparation data. In order to calculate the requirement standard several parameters are needed. Every products has their own parameter depend on what kind of product will be assess in section 3.1.1, it provided by ErP directive. For instance: power, time use, sound power level, electricity consumption, etc. The data was obtaining by experiment through direct measurement, assumption as well as simulation.

Once the parameter has obtained, the next activity is to calculate the requirement standard based on those parameters. It aims to fulfill the regulation of European Union. The example of vacuum cleaner regulation is shown below.

- Annual energy (AE) consumption shall be less than 43.0 kWh/year
- Rated input power shall be less than 900 W
- Sound power level shall be less than or equal to 80 db(A)
- The hose, if any, shall be durable so that it is still usable after 40,000 oscillations under strain
- Operational motor life time shall be greater than or equal to 500 hours.

Sound power level was measured through direct measurement using sound measurement software which is amplitude measures how forceful the wave is. It is measure in decibels or dBA of sound pressure. 0 dBA is the softest level that a person can hear. Normal speaking voices are around 65 dBA. Sounds that are 85 or above can permanently damage human ears. Frequency is measured in the number of sound vibrations in one second. The sound level measurement software can be seen in the figure 3.3.

Figure 3.3 Sound level measurement software

DC power measurement is relatively simple as the equation is simply watts = volts x amps. For AC power measurement, the power factor (PF) introduces complexity as watts = volts x amps x PF. This measurement of AC power is referred to as active power, true power or real power. In AC systems, multiplying volts x amps = volt-amps, also called apparent power. However the power data was obtaining using power measurement device and simulated in the software to reduce the complexity of collecting data. The collecting data process will be discuss more detail in case study of vacuum cleaner to see the installation of device, wiring cables, installation of software and so on. The figure of power measurement device and its software can be seen in the figure 3.4.

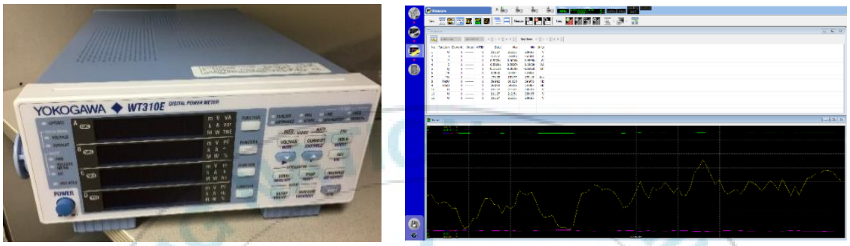

Figure 3.4 Power measurement device and its software

The last activity in this compliance checklist is verification. Once the standard requirement of product has generated, it is necessary to do verification meaning that confirmation by examination and evaluation of objective evidence that generated

Parameter	Verification tolerances
Annual energy consumption	The determined value (1) is not more than 10 % higher than the declared value.
Dust pick up on carpet	The determined value (1) is not more than 0,03 lower than the declared value.
Dust pick up on hard floor	The determined value (1) is not more than 0,03 lower than the declared value.
Dust re-emission	The determined value (1) is not more than 15 % higher than the declared value.
Sound power level	The determined value (1) is not higher than the declared value.
Operational motor lifetime	The determined value (1) is not more than 5 % lower than the declared value.

Table 3.1 Verification tolerances value for vacuum cleaner

requirements meets all the standard input nor exceeding the generated standard. All verification tolerances value are provided in the ErP directive. It depends on what product has assessed. For instance, the limit of every standard is shown in table 3.1.

3.2 Environmental Assessment

Currently the view of sustainability is one of the objectives of product production and consumption. because mass production contributes to an increase in adverse impacts on the environment. in general, the development of a product only focuses on meeting the needs of consumers without considering the impact of the overall process by the product on the environment.

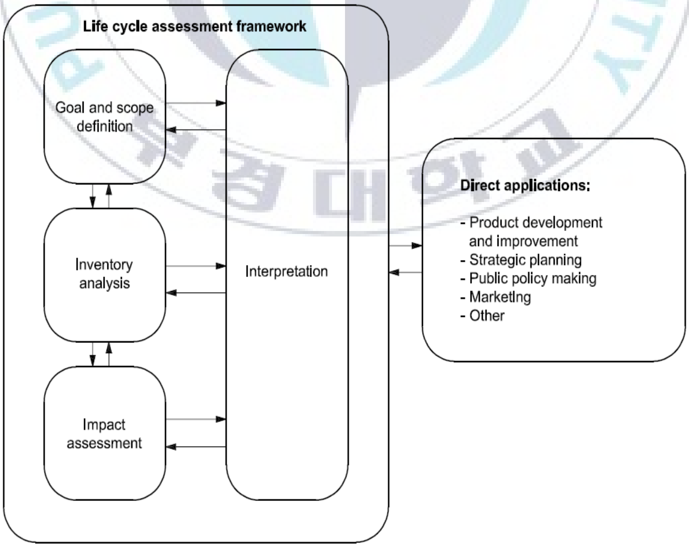

Fig 3.5 Phases of LCA (ISO 14040)

Therefore, many regulations have been set in reducing the environmental impact of product life cycles including manufacturing, acquisition, distribution, use and disposal. In order to do so, a tool is needed to assess the environmental impact of the product life cycle.

Life cycle assessment (LCA) is the best tool for assessing the impact on the environment of the product life cycle provided by ISO 14040. there are four main phases in this tool; goal and scope definition, life cycle inventory analysis (LCI), impact assessment life cycle (LCIA) and life cycle interpretation. these four main phases can be seen in the picture 3.5.

3.2.1 Goal and scope definition

The goal and scope definition aims to addressed the reason why to perform this tool, who are the target audiences, and what is the product under this study?. This phase should explain those aspects. First, identify what products will be assessed in this analysis.

Furthermore, the explanation of the product process both the upstream process and downstream process includes the type of material used for the product, the manufacturing, distribution, use and disposal processes is needed. An explanation of the use of energy and natural resources is also needed.

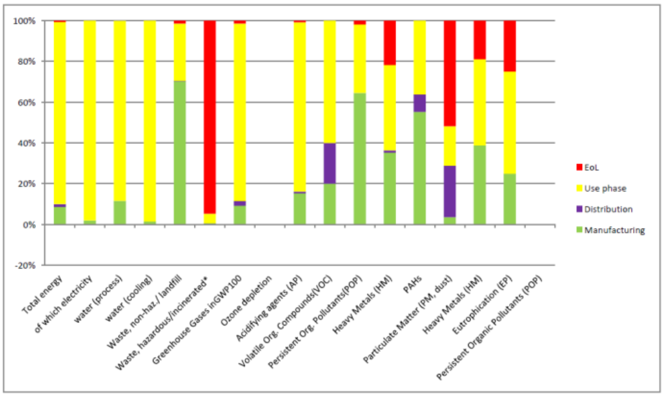

Fig 3.6 Contribution of each phase ErP in environmental impact (Bobba, et al., 2015)

However, this study only focuses on two stages, manfacturing and use phase. According to the European Commission's report that the highest contribution of energy-related products to the environment comes from the manufacturing and use phases as shown in figure 3.6. The next step is to explain the use of the product and how much the product is used in a certain period.

3.2.2 Environmental load

Second is Life cycle inventory analysis. The main activity in this phase is data collection and environmental load quantification. It aims to quantify inputs and outputs of materials and energy associated with a product system under study. In this case, all inputs and outputs of the product system and process are related to the output of final product.

Collecting data is the activity of collecting input data needed as a parameter to perform calculation. There are several ways to collect data. include; direct measurement, database data, literature review, etc. Data retrieval based on product life cycle from raw material to disposal. Generally data for the Manufacturing stage, including processing to usable raw materials such as bill of material, iron, pilypropylene, and energy such as diesel and electricity. However, data retrieval must be taken into account when using a database data or assumptions because it might not match the specific LCA tool. Usage data comes from customers. This data can be in the form of scenarios or assumptions, survey data, and literature review. The parameters in this section are the amount of product usage time, energy consumption, total emissions, the number of components replaced during maintenance, etc.

When data collection is complete, the next step is to calculate the environmental load per unit/process which means preparing the life cycle inventory table of a product system. As mentioned earlier, this study focuses on only two phases which have the highest contribution to environmental impacts, they are manufacturing and use phase. Furthermore, all of data that comes from manufacturing and use phase should be calculated in environmental load which means the process of dividing input and output data for each unit/process by weight of energy content of the product in orer to identify the contribution of each parameters in environmental impact. For instance, if the weight of a product is 10 kg and one part of the product weight's 100 g with the type of material is iron, the environmental load per functional unit is the input weight divided by the total weight of output. 100 g / 10 kg = 10 g/kg. So the contribution of 100g iron in the product is 10 g/kg.

Figure 3.7 Korea life cycle Inventory database

3.2.3 Environmental impact

The next step is to calculate the environmental impact of each functional unit/process. To calculate the environmental impact, the Life cycle impact (LCI) database is needed as a basis for information to find out what outputs each parameter will produce because life cycle impact database provide basic referential data to calculate environmental impact of a product include, Energy resources (coal, oil, etc.), mineral resources (iron, cooper, etc.), emission (to air or water), and waset. There are several life cycle impact databases provided by organizations such as; eVerdEE database, Environmental impact statement (EIS) database, and so on. However, this study uses the environmental impact database life cycle provided by Korea Life cycle impact database as shown in the figure 3.7.

Inventory data of common materials (e.g., steel plate, copper wire, Polyethylene), energy (e.g., electricity, diesel), land processes (11 ton truck transportation) are often available in the form of LCI DB. The system boundary of the LCI DB usually spans from raw material acquisition to manufacturing of the materials, energy and processes.

Parameter	Upstream	Manufacturing	Distribution	Use	Disposal		Sum of EL (g/hair drier)	
					Scenario A	Scenario B	Scenario A	Scenario B
Crude oil	2.62E+02		4.00E+01		2.21E+00	-3.48E+01	3.04E+02	2.67E+02
Coal	1.39E+02	1.61E+01		4.95E+03	1.10E-01	3.82E+00	5.10E+03	5.11E+03
Iron ore	7.34E+01					-5.03E+01	7.34E+01	2.32E+01
CO_2	1.26E+03	9.43E+01	1.32E+02	2.90E+04	3.52E+02	-8.46E+01	3.08E+04	3.04E+04
Methane	9.78E-01	1.73E-01		5.32E+01	1.46E+00	9.36E-01	5.58E+01	5.53E+01
CO			7.24E-01				7.24E-01	7.24E-01
VOC	3.63E+00						3.63E+00	3.63E+00
NO_x (Air)	2.00E+00				7.48E-02	6.03E-02	2.07E+00	2.06E+00
SO_x (Air)	3.96E+00	3.84E-01		1.18E+02	7.18E-02	1.54E-02	1.22E+02	1.22E+02

Table 3.2 Example of environmental impact.

impact database. Once environmental load for each functional unit/process has been obtained and environmental impact data from reference databases have been obtained, then the environmental impact can be calculated from the multiplication between environmental load per functional unit and environmental impact value from the database. The example of Environmental impact value can be seen in the table 3.2.

There are two more phases in Life cycle assessment process which are Life cycle impact assessment and Interpretation. Significant potential of the environmental impact of a product system based on the results of the life cycle inventory analysis can be seen using life cycle impact assessment. Life cycle impact assessment consists of several points, namely classification, characterization, normalization, and weighting. all these aspects aim to see the contribution of life cycle inventory parameters to the environmental impact categories that are divided into this LCIA process. the categories of environmental impacts include; abiotic and biotic resource depletion, global warming, ozone depletion, photochemical oxidant formation (ozone) or smog formation, acidification, eutrophication, human toxity, ecotoxicity, solid waste, hazardoous and radioactive waste. And the last phase in this LCA study is Life cycle interpretation. Results of life cycle inventory analysis and life cycle impact assessment are analyzed with respect to various aspects such as completeness, sensitivity, and consistency. And for additon this phase also identify the key issues that has highest contribution to the environmental impact of product system. Finally this phase describe the explanation of the whole

LCA study and figure out the conclusions and recommendations to the users. The result shows the contribution of products and processes into environmental impact in detail. It also can be a useful information for producer and consumer to decide which product or process that need improvement in environmental issue, or it depends on it's goal of the LCA study.

However, this study does not include the last two phases which are Life cycle impact assessment and interpretation in order to simplify calculations. This only shows parameters that contribute to the environmental impact based on the data that comes from inventory analysis and life cycle impact database.

3.3 Economic Assessment

The lifecycle cost is often referred to as the sum of all costs incurred during an asset's useful life and allows for a more appropriate cost-benefit analysis. The 'realistic appraisal' conducted through LCC analysis is further reinforced by considering the time value of money. This method assists in the reduction of the total cost of a product, identification of high-cost components in a product's lifecycle, and comparison of competing products. (Kara, et al., 2017)

Generally, this method is used to identify the total cost of a product as long as the life cycle starts from the processing of raw materials, production, use, and disposal. The application of this model can influence decision makers in the design stage to determine the relationship between costs and design parameters and identify the highest cost contributions during the product life cycle. As with the life cycle assessment that assesses the highest contribution of a product life cycle to the environment, life cycle costing can assess the highest contribution of a product life cycle in terms of costs.

According to (Kumaran, et al., 2001), there are many features that can be learned using LCC, including; a combination of rising inflation, cost growth, reduced purchasing power, budget constraints, increased competition, etc. Furthermore, according to his study that LCC is a systematic analytical process for evaluating various designs or alternative courses of actions with the objective of choosing the best way to employ scarce resources. The ultimate objective of the LCC of any product is to provide a framework for finding the total cost of design/development, production, use and disposal of the product with an intention of reducing the total cost.

In previous studies, LCC has been applied to electric vehicle as energy-related products with the aim of identifying the key input parameters that make the electric vehicles less competitive in relation to conventional vehicles. The LCC framework was applied to quantify the economic impact of a 2011 Nissan leaf under Australian conditions and provide a comparison with an equivalent conventional vehicle, the Toyota corolla. The result was the selected vehicle Nissan leaf performed worse in terms of total life cycle cost compared to Toyota corolla. The prime contributor to the life cycle cost is the operation phase.

This economic assessment in this study is based on the framework in the case study of electric vehicle above. This method can be used in the current study because both products in previous study and current study have similar characteristics that is a product that uses energy. It's called the consumer LCC framework which consists of three main phases; acquisition phase, operating phase, and disposal phase. The framework can be seen in the figure 3.8.

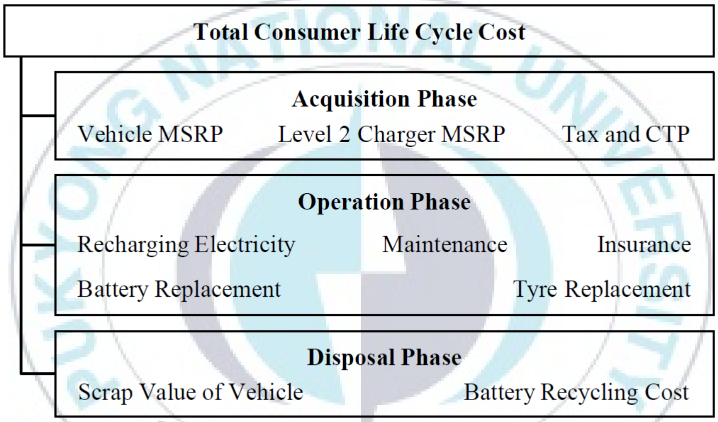

Figure 3.8 Consumer LCC framework (Sami Kara et al. 2017)

Acquisition phase is all the costs that exist from the production process to the finished product. However, the purchasing price (usually) comprises all costs for producing the respective product plus a certain profit margin. (Quack, et al., 2010). The cost of purchase is relevant. Additional installation costs might incur in some cases. For example, in case of heating device that needs the installation process which is take costs.

Costs incurred during the product use stage also known as operational costs. Generally, the costs incurred when using especially for energy-related products are very significant. examples of these costs include; electricity costs for electronic goods, fuel for vehicles, consumptive costs such as detergents for washing machines, and any oher costs, such as; taxes, insurance fees, and so on. The last is disposal costs. For some of the product groups the costs (or fees) for the disposal of waste strongly depend on current regulations. For example, waste electrical and electronic equipment (WEEE) can be disposed free of charge in the EU if this waste is similar in nature and quantity to that of private households. However, as mentioned in section 3.2.3, this study does not include disposal phase due to simplification of the calculation. Furthermore the total of life cycle cost will be calculated in the equation below

Total cost = Acquisition costs + Operational Costs…………….3.1

3.4 Functional Assessment

In this study the meaning of functional assessment is the process of analyzing the function of a product in this case energy-related products that aim to see the ability of the product to be used in accordance with its function for a certain period of time. It is also can be known as durability which means the characteristic of those objects or materials that maintain their properties over time. The focus on properties is especially common in standards defining the characteristics that the product/material should fulfil (e.g. the tensile strength of materials) and the testing conditions to identify them (Ardente & Mathieux, 2014).

The durability of a product is often expressed in terms of lifetime, which can be differentiated between; first, technical lifetime, which is the time span or number of usage cycles for which a product is considered to function as required, under defined conditions of use, until a first failure occurs. Second, functional lifetime, which is the time a product is used until the requirements of the user are no longer met, due to the economics of operation, maintenance, and repair or obsolescence (EEA, Environmental indicator report, 2014).

As explained in the introduction where the purpose of this study is to combine environmental assessment, economic assessment and functional assessment to identify products with the best scenarios of these three aspects. Furthermore, this part shows the explanation of functional assessment in this figure 3.9.

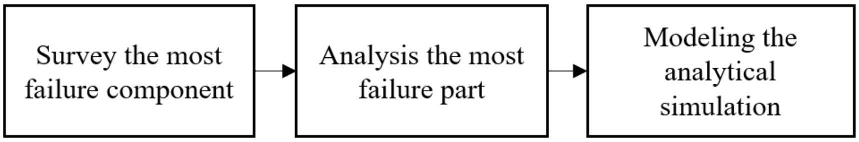

Figure 3.9 Functional Assessment

A product will be able to work according to its function all the time when all the components in the product run well. If there are one or more components that are damaged or have a problem, the system of the product will not work properly. Therefore the initial step of this assessment is to identify what components are most often damaged. To identify this problem, it can be done by surveying customers who use the product to be assessed in order to find the most common component damage problems. Another way is to do a literature study or test directly on the product to be assessed. However, taking data by conducting a direct test is quite difficult to do because it requires adequate facilities and a supportive environment but the results of this test might be more accurate.

When the initial steps have been taken and the components that are most often damaged have been obtained, the next step is to identify cause of the component's failures. It includes local effects, end effects, and cause of failures. The most common tool to analyze the failure of products or processes is Failure mode effect analysis (FMEA). FMEA is a systematic method for identifying potential failure modes and prioritizing them. (J. Sakamoto et al. 2018) FMEA involves as many components, sub-systems and devices as possible to identify errors, including the causes and their effects in the process. Every component, failure, and effect caused in the system will be written in a special FMEA worksheet. This method is applied in product development, engineering systems, and operational management.

Ultimately, the last step in this functional analysis is modeling the analytical simulation. At this stage the results of the FMEA analysis which is part of a component that has the most damage will be simulated using a model simulation to determine the degradation process of that part. Because all the degradation processes lead to the reduction of the insulation lifetime. Many methods of lifetime estimation based on the accelerated electrical, thermal and mechanical tests.

Type	Examples
Mechanical	Cracking, Tensions, Vibrations
Electrical	Overvoltage, Tracking, Partial Discharges, Electrical Trees, Electrochemical Trees
Thermal	Oxidation, Hydrolysis

Table 3.3 Ageing Factors

In general, degradation occurs due to the stress applied to the material beyond the limit of the material strength. The stress usually comes from mechanical stress that occurs due to vibration or any other force, or the initial crack in the material that makes the component fail, or the heat load received by the structure as shown in table 3.3. To find out the degradation process during the run time on the material some simulations were carried out based on the model obtained from the literature study. Including the aging model because of the heat load, the aging model due to the electrical load, and the aging model due to mechanical loads.

To validate this methodology, this method will be applied to energy-related product case studies. One of the products chosen is a vacuum cleaner product. Vacuum cleaner is one of the household appliances included in the group of energy-related product that has a significant level of sales both in Europe and outside Europe. In this case study, the methodology will be implemented in a vacuum cleaner from two different manufacturing companies. The first is AEG which is a product from Europe and the second is SAMSUNG which is a product from Korea. Both of these vacuum cleaners will be compared in terms of environmental, economic, and functional based on the proposed methodology. A more detailed explanation of this case study will be explained in the next chapter.

4. CASE STUDY

This section shows the implementation of the proposed methodology by demonstrating the method to one of the energy-related products, which is a vacuum cleaner. This product was chosen because it is one of the products included in the energy-related products category and is also an uncomplicated product for demonstration. This implementation is carried out to validate the feasibility of the proposed method. The selected vacuum cleaner are two vacuum cleaners from two different manufacturers which are AEG made in German and SAMSUNG made in Korea as shown in figure 4.1. The purpose of selecting products from two manufacturers in different countries is to compare the products, one of which is a European-made product that meets the standards of eco-design directive already.

Figure 4.1 Vacuum cleaners from two different Countries

The differentiation of those vacuum cleaner can be seen in the specification of each products. (1) SAMSUNG VCM2110LP with a total weight of 5.3 kg and the average input power is 1200 W, dust capacity is 1.5 L, noise level 77 dBA, and the frequency of motor is 60Hz. (2) AEG VX6-1-ÖKO with a total weight of 4.7 kg, the average input power is 600 W, dust capacity 3.5 L, noise level 76 dBA and the frequency of motor is 50Hz. These data specification is obtained from manufacturer's information. The application of the proposed methodology in the case study of vacuum cleaner then carried out by following the steps as described in section 3.

4.1 Obtaining data

To implement the proposed methodology, several parameters and data are needed for calculation. The first data collection is data of components, weight, and type of material used in each vacuum cleaner.

Figure 4.2a Disassembled of AEG vacuum cleaner

Figure 4.2b Disassembled of SAMSUNG vacuum cleaner

Dismantling has been carried out on the product in order to retrieve weight of each component as shown in figure 4.2a for AEG vacuum cleaner, and figure 4.2b for SAMSUNG vacuum cleaner. The total weight of AEG is 4762 g, while, total weight of SAMSUNG is 5358 g. Type of material used for each product, include; Polypropylene (PP) (motor case, nozzle, and inside case), Acrylonitrile butadiene styrene (ABS) (main case at the top and bottom) Polyamide Steel (motor), brass (motor brass), Stainless steel (vacuum cleaner handle), Nylon (hose) Polyurethane (include small plastic components). HDPE (filter), and folding box made for the package of the product.

Second, data from the production process. This data is very difficult to obtain because it requires tight access to get information from the production plant directly. Because of this limitation, we therefore use data from the literature review as shown in table 4.1 for both AEG and SAMSUNG products.

Process	Energy	Data	Source
Injection moulding	Electricity	17.3 MJ	Literature
Injection moulding	Heat	14.4 MJ	Literature
Metal stamping	Electricity	5.6 MJ	Literature
Metal stamping	Heat	2.5 MJ	Literature
Screen printing	Electricity	0.2 MJ	Literature
Power cord, plug and wire cables	Electricity	2.1 MJ	Literature
Power cord, plug and wire cables	Heat	0.3 MJ	Literature
Assembly and packaging	Electricity	26.3 MJ	Literature
Assembly and packaging	Water	13 L	Literature

Table 4.1 Data from manufacturing processes

Based on this assumption data, injection molding is assumed to be a processing for all plastic materials, metal stamping is assumed to be the process of processing all materials made of metal including iron and aluminum, and packaging processing is assumed to use cardboard materials respectively. The parameters selected from each production process are electricity and heat consumption.

Third, data on electricity consumption in the usage phase. This data collection has done by directly measuring the amount of electricity consumption of the product using a power analyzer.

Figure 4.3 Power data retrieval

The tools needed in this measurement are; the product to be analyzed which is a vacuum cleaner, a power analyzer in this case we use the yokogawa power analyzer WT310E which is a measurement device that provides a method that facilitates data retrieval. This tool also provides software to simplify data processing in Microsoft Excel format. Figure 4.3 shows the data retrieval process

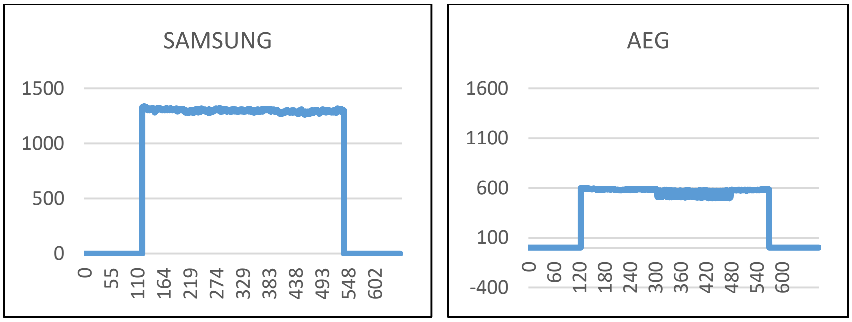

Figure 4.4 Power of SAMSUNG and AEG vacuum cleaners

The results of power data retrieval shows that the SAMSUNG vacuum cleaner consumes as much as 1290 Watts of electricity, the result of which is twice as large as the AEG vacuum cleaner, which is only 545 Watts as shown in Figure 4.4.

AEG Manufacturing phase	Value	Unit
Polypropylene (PP)	0.817	kg
Acrylonitrile butadiene styrene (ABS)	1.384	kg
Polyamide	0.330	kg
Steel	0.900	kg
brass	0.376	kg
Stainless steel	0.489	kg
Nylon	0.655	kg
Polyurethane	0.476	kg
Folding box	0.695	kg
Injection moulding (electricity)	4.805	kWh
Injection moulding (heat)	4.000	kWh
Metal stamping (electricity)	1.555	kWh
Metal stamping (heat)	0.694	kWh
Screen printing (electricity)	$5.5x10^{-5}$	kWh
Power cord, plug and wire cables (electricity)	0.583	kWh
Power cord, plug and wire cables (heat)	0.083	kWh
assembly and packaging (electricity)	7.305	kWh
assembly and packagingc (water)	13	L
Use Phase		
Electricity	26.16	kWh
Maintenance (filter replacements)	0.378	kg

Table 4.2a Life cycle inventory data for AEG vacuum cleaner

This is due to AEG products from Europe already meet the standards provided by ErP directive where the rated input power for all vacuum cleaner products sold in Europe should not exceed the maximum limit of 900 Watts since September, 2017.

SAMSUNG Manufacturing phase	Value	Unit
Polypropylene (PP)	1.013	kg
Acrylonitrile butadiene styrene (ABS)	2.013	kg
Polyamide	0.223	kg
Steel	0.950	kg
brass	0.376	kg
Stainless steel	0.234	kg
Nylon	0.288	kg
Polyurethane	0.476	kg
Folding box	0.695	kg
Injection moulding (electricity)	4.805	kWh
Injection moulding (heat)	4.000	kWh
Metal stamping (electricity)	1.555	kWh
Metal stamping (heat)	0.694	kWh
Screen printing (electricity)	$5.5x10^{-5}$	kWh
Power cord, plug and wire cables (electricity)	0.583	kWh
Power cord, plug and wire cables (heat)	0.083	kWh
assembly and packaging (electricity)	7.305	kWh
assembly and packaging (water)	13.00	L
Use Phase		
Electricity	61.2	kWh
Maintenance (filter replacements)	0.378	kg

Table 4.2b Life cycle inventory data for SAMSUNG vacuum cleaner

Power data obtained in watt (W) is then converted to kilowatt hour (kWh) in order to determine annual electricity consumption. The calculation is done as follows;

Annual energy consumption

Input power (W) x Number of use in hour per year (Hour) / 1000…………………………………………………………..4.1

Where, the power input (W) is the average power value measured from each vacuum cleaner when it works. SAMSUNG has 1290 watts of power and the AEG has 545 watts of power. In this case we assume that the average use of a vacuum cleaner is 1 hour per week based on JRC science and policy report 2015 as shown in table 4.8, therefore the number of vacuum cleaner uses in one year is 48 hours. And the value 1000 represents the conversion from wattage to kilowatt. The results of each calculations are shown in table 4.2a for AEG and table 4.2b for SAMSUNG in use phase respectively.

4.2 Compliance checklist

As explained in section 3.1, this process consists of 3 specific stages, namely determining input parameters, determining the values obtained based on input parameters and verifying the values set in accordance with the standards provided by ErP directive. In this case there are 3 generated parameters based on the standards provided by ErP directive, namely; annual energy consumption, rated input power, and sound power level. The results of the first parameter are obtained from calculations according to formula 4.1 and the results are shown in Figure 4.5 respectively for each products. The result of the rated input power and sound power level can also be seen in the picture above. According to table 3.1 regarding the tolerance value, the value of annual energy consumption should not exceed 10% of the standard value given,

Input Parameter

Determination

AEG	Value	Unit
Annual energy consumption	26.16	kWh/year
Rated input power	700	watt
Sound power level	76	dB
Operational motor life-time		Hour

SAMSUNG	Value	Unit
Annual energy consumption	61.2	kWh/year
Rated input power	1200	watt
Sound power level	77	dB
Operational motor life time		Hour

Verification

AEG	Standard Value	Value	Unit	Tolerances	Compliance
Annual energy consumption	43	26.16	kWh/year	23.544	YES
Rated input power	900	700	watt	700	YES
Sound power level	80	76	dB	74.86	YES

SAMSUNG	Standard Value	Value	Unit	Tolerances	Compliance
Annual energy consumption	43	61.2	kWh/year	55.08	NO
Rated input power	900	1200	watt	1200	NO
Sound power level	80	77	dB	76.8845	YES

Figure 4.5 Compliance checklist process

while the value of the sound power level and the rated input power must not exceed the exact value given by the standard value.

The result shows that the AEG vacuum cleaner meets all standards. However, the SAMSUNG vacuum cleaner only meets one of three standards provided ErP directive.

4.3 Environmental assessment

This calculation has done manually by following the lifecycle assessment method provided by ISO 14041. According to impact assessment methods in lifecycle assessment (Aitor P. et al, 2015) there are several impact indicators consist in the LCA methodology. However, in this case we used 4 emission factors to indicate the environmental impact of vacuum cleaners include; CO_2 Emission representing climate change, SO_2 NO_X representing acidification and H_2O representing depletion of abiotic resources.

The vacuum cleaner that is considered is a vacuum cleaner with 700 and 1400 input power for each product respectively, functional units are 1 vacuum cleaner with 48 hours usage in 1 year according to the initial scenario. The scope of this study considers two phases are manufacture phase and use phase as described in section 3.2.1. The inventory data for this vacuum cleaner are explained in detail in tables 4.2a and 4.2b for each product. Calculations are carried out as explained in section 3.2 using the environmental impact database life cycle provided by Korea Life cycle impact database as shown in the figure 3.7.

AEG	Value	Unit	Environmental Impact			
Manufacturing phase			CO_2	NO_X	SO_2	H_2O
Polypropylene (PP)	0.817	kg	$9.9x10^{-4}$	$1.6x10^{-6}$	$1.1x10^{-7}$	$1.7x10^{-3}$
Acrylonitrile butadiene styrene (ABS)	1.384	kg	$3.9x10^{-3}$	$1.0x10^{-5}$	$1.9x10^{-6}$	$2.0x10^{-2}$
Polyamide	0.330	kg	$6.0x10^{-1}$	$1.7x10^{-3}$	$2.5x10^{-4}$	16.2081
Steel	0.900	kg	2.14920	$3.7x10^{-3}$	$2.7x10^{-3}$	3.52640
brass	0.376	kg	$6.6x10^{-4}$	$2.1x10^{-6}$	$1.2x10^{-6}$	0
Stainless steel	0.489	kg	$1.3x10^{-3}$	$2.9x10^{-6}$	$4.4x10^{-5}$	$1.7x10^{-5}$
Nylon	0.655	kg	0	0	0	0
Polyurethane	0.476	kg	$1.1x10^{-3}$	0	0	0
Folding box	0.695	kg	0	0	0	0
Injection moulding (electricity)	4.805	kWh	2.37875	$2.0x10^{-5}$	$2.8x10^{-5}$	0
Metal stamping (electricity)	1.555	kWh	$7.7 x10^{-1}$	$6.6x10^{-6}$	$9.1x10^{-6}$	0
Screen printing (electricity)	$5.5x10^{-5}$	kWh	$2.7x10^{-5}$	$2.3x10^{-10}$	$3.2x10^{-10}$	0
Power cord, plug and wire cables (electricity)	0.583	kWh	$2.8 x10^{-1}$	$2.5x10^{-6}$	$3.4x10^{-6}$	0
assembly and packaging (electricity)	7.305	kWh	3.61625	$3.1x10^{-5}$	$4.2x10^{-5}$	0
assembly and packaging (water)	13	L	1.45262	0	0	0.39
Σ			11.2637	$5.5x10^{-3}$	$3.1x10^{-3}$	20.1469
Use Phase						
Electricity	26.16	kWh	12.9492	$3.1x10^{-1}$	$4.2x10^{-2}$	0
Maintenance (filter replacements)	0.378	kg	$8.9x10^{-4}$			0
Σ			12.9500	$3.1x10^{-1}$	$4.2x10^{-2}$	0

Table 4.3a Result of life cycle assessment for AEG vacuum cleaners

SAMSUNG	Value	Unit	Environmental Impact			
			CO_2	NO_X	SO_2	H_2O
Manufacturing phase						
Polypropylene (PP)	1.013	kg	$1.2x10^{-3}$	$2.0x10^{-6}$	$1.4x10^{-7}$	$1.7x10^{-2}$
Acrylonitrile butadiene styrene (ABS)	2.013	kg	$5.7x10^{-3}$	$1.5x10^{-5}$	$2.9x10^{-6}$	$2.0x10^{-2}$
Polyamide	0.223	kg	$4.0x10^{-1}$	$1.1x10^{-3}$	$1.7x10^{-4}$	16.2081
Steel	0.95	kg	2.2686	$4.0x10^{-3}$	$2.9x10^{-3}$	3.52640
brass	0.376	kg	$6.6x10^{-4}$	$2.1x10^{-6}$	$1.2x10^{-6}$	0
Stainless steel	0.234	kg	$6.5x10^{-4}$	$1.3x10^{-6}$	$2.1x10^{-5}$	$1.7x10^{-5}$
Nylon	0.288	kg	0	0	0	0
Polyurethane	0.476	kg	$1.1x10^{-3}$	0	0	0
Folding box	0.695	kg	0	0	0	0
Injection moulding (electricity)	4.805	kWh	2.37875	$2.0x10^{-5}$	$2.8x10^{-5}$	0
Metal stamping (electricity)	1.555	kWh	$7.7x10^{-1}$	$6.6x10^{-6}$	$9.1x10^{-6}$	0
Screen printing (electricity)	$5.5x10^{-5}$	kWh	$2.7x10^{-5}$	$2.3x10^{-10}$	$3.2x10^{-10}$	0
Power cord, plug and wire cables (electricity)	0.583	kWh	$2.8x10^{-1}$	$2.5x10^{-6}$	$3.4x10^{-6}$	0
assembly and packaging (electricity)	7.305	kWh	3.61625	$3.1x10^{-5}$	$4.2x10^{-5}$	0
assembly and packaging (water)	13	L	1.45262	0	0	0.39
Σ			11.1898	$5.2x10^{-3}$	$3.1x10^{-3}$	20.1469
Use phase						
Electricity	61.2	kWh	30.294	$7.3x10^{-2}$	$9.9x10^{-2}$	0
Maintenance (filter replacements)	0.378	kg	$8.9x10^{-4}$	0	0	0
Σ			30.2948	$7.3x10^{-2}$	$9.9x10^{-2}$	0

Table 4.3b Result of life cycle assessment for SAMSUNG vacuum cleaners

Detailed analysis results from the environmental impact assessment are shown in table 4.3a and 4.3b for each product respectively. It shows that based on the functional unit scenario, AEG produces emissions of 11.26 kg CO_2 eq. in manufacture phase and 12.95 kg CO_2 eq. in the use phase for each unit annually.

Emission	AEG		SAMSUNG	
	Manufacture	Use	Manufacture	Use
CO_2	$1.13x10^{1}$	$6.48x10^{1}$	$1.12x10^{1}$	$1.15x10^{1}$
NO_x	$5.59x10^{-3}$	$3.12x10^{-2}$	$5.25x10^{-3}$	$7.30x10^{-2}$
SO_2	$3.15x10^{-3}$	$4.26x10^{-2}$	$3.19x10^{-3}$	$9.96x10^{-2}$
H_2O	$2.77x10^{1}$	0	$2.01x10^{1}$	0

Table 4.4 Summarize of life cycle assessment for AEG and SAMSUNG vacuum cleaners

While, SAMSUNG produces 11.18 kg of CO_2 emissions in manufacture phase and 30.29 kg CO_2 eq. in the use phase for each unit annually.

Table 4.4 summarizes the results of the environmental impact assessment. According to the result, CO_2 is the main and the most emission produced compared to other emissions following by H2O, SO_2 and NO_X. This is due to the use of electricity in the use phase which become a major contributor to CO_2 emission. According to the Korea Life Cycle Environmental Impact Database, the process of electricity production uses several types of natural resources Including anthracite, bituminous coal, heavy oil, gas, gas composite, light oil composite, internal strength, hydropower, nuclear power generation that generates a lot of CO_2 emissions.

Environmental impact from both AEG and SAMSUNG vacuum cleaners shows quite similar results. Where, the use phase contributes more environmental impact than the manufacture phase.

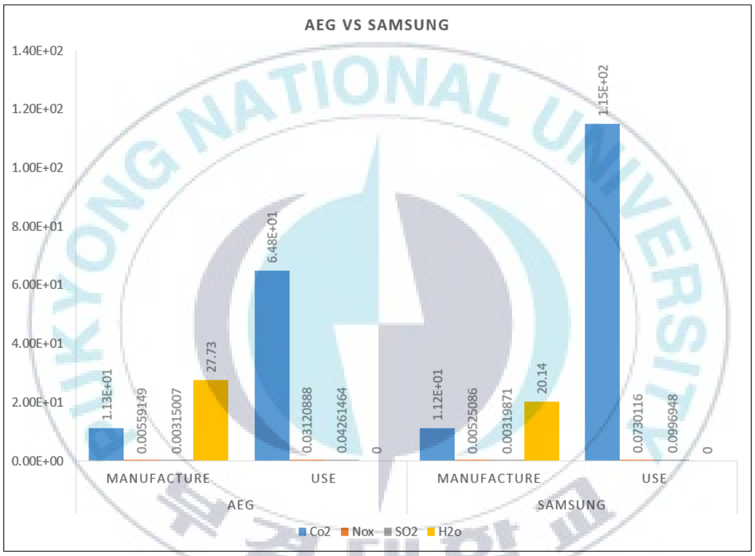

Figure 4.6 Comparison of environmental impact between AEG and SAMSUNG vacuum cleaners

Figure 4.6 shows a comparison between two products on the environmental impacts from two phases. Based on the results we can see how the effect of implementing ErP directive on a vacuum cleaner. AEG which is a product from Germany that have complied with European Commission regulations as shown in Figure 4.5, produce emissions specifically CO_2 emissions of more than twice less than SAMSUNG in terms of electricity consumption.

4.4 Economic assessment

As we discussed in section 3.3, the economic assessment in this study adopts life cycle cost which means the sum of all costs incurred during product life cycle. In this case product life cycle including manufacture phase and use phaseThe parameters to be calculated are the sum of all costs incurred both from the manufacturing phase and the use phase which includes the costs of material depending on the type of material used, and material costs taken from several sources in units of USD per kilogram.

AEG	Value	Unit	Cost	Unit
Manufacturing phase				
Polypropylene (PP)	0.817	kg	0.898	USD
Acrylonitrile butadiene styrene (ABS)	1.384	kg	1.038	USD
Polyamide	0.330	kg	1.419	USD
Steel	0.900	kg	0.225	USD
brass	0.376	kg	0.827	USD
Stainless steel	0.489	kg	1.320	USD
Nylon	0.655	kg	1.277	USD
Polyurethane	0.476	kg	1.904	USD
Folding box	0.695	kg	0.695	USD
Injection moulding (electricity)	4.805	kWh	0.961	USD
Metal stamping (electricity)	1.555	kWh	0.311	USD

Screen printing (electricity)	$5.5x10^{-5}$	kWh	$1.1x10^{-5}$	USD
Power cord, plug and wire cables (electricity)	0.583	kWh	0.116	USD
assembly and packaging (electricity)	7.305	kWh	1.461	USD
assembly and packaging (water)	13	L	0	USD
Σ			12.45	USD
Use Phase				
MSRP	1	pcs	200	USD
Electricity	26.16	kWh	5.232	USD
Maintenance (filter replacements)	1	pcs	20	USD
Σ			225.232	USD

Table 4.5a Result of economic assessment for AEG vacuum cleaners

Furthermore, the costs of the production process such as injection moulding, metal stamping, screen printing, and assembly mostly come from the use of machines that consumes electrical energy. And the cost for electricity is assumed to be 0.2 USD per kWh. In the use phase, the amount of costs derived from the use of electrical energy as long as the vacuum cleaner works and the costs that come from maintenance in this case is filter replacement. Functional unit and scope in this assessment is a vacuum cleaner that is used for one year and assumed that this vacuum cleaner works as much as 1 hour per week and in one year the filter is replaced once.

SAMSUNG	Value	Unit	Cost	Unit
Manufacturing phase				
Polypropylene (PP)	1.013	kg	1.114	USD
Acrylonitrile butadiene styrene (ABS)	2.013	kg	1.509	USD
Polyamide	0.223	kg	0.958	USD
Steel	0.950	kg	0.237	USD
brass	0.376	kg	0.827	USD
Stainless steel	0.234	kg	0.631	USD
Nylon	0.288	kg	0.561	USD
Polyurethane	0.476	kg	1.904	USD
Folding box	0.695	kg	0.695	USD
Injection moulding (electricity)	4.805	kWh	0.961	USD
Metal stamping (electricity)	1.555	kWh	0.311	USD
Screen printing (electricity)	5.5×10^{-5}	kWh	1.1×10^{-5}	USD
Power cord, plug and wire cables (electricity)	0.583	kWh	0.116	USD
assembly and packaging (electricity)	7.305	kWh	1.461	USD
assembly and packaging (water)	13	L	0	USD
Σ			11.29	USD
Use phase				
MSRP	1	pcs	100	USD
Electricity	61.2	kWh	12.24	USD
Maintenance (filter replacements)	1	pcs	30	USD
Σ			142.24	USD

Table 4.5b Result of economic assessment for SAMSUNG vacuum cleaners

The value of parameters in this assessment can be seen in table 4.5a for AEG products and table 4.5b for SAMSUNG products respectively. And the summary between two products can be seen in table 4.6. Afterwards, a comparison between the two products is based on the results of the economic assessment was performed.

AEG	
Raw material	9.604
Production	2.850
MSRP	200
Electricity	5.232
Maintenance	20

SAMSUNG	
Raw material	8.440
Production	1.880
MSRP	100
Electricity	12.24
Maintenance	30

Table 4.6 Summarize of economic assessment for AEG and SAMSUNG vacuum cleaners

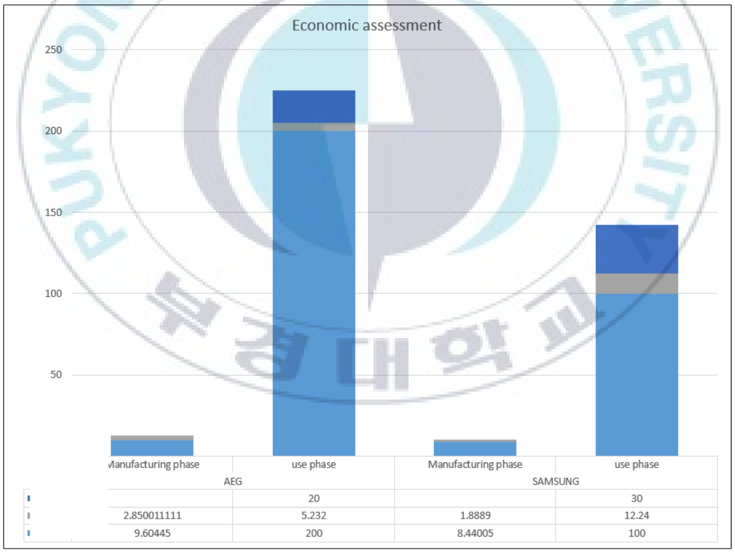

Figure 4.7 Comparison of economic assessment for AEG and SAMSUNG vacuum cleaners

Figure 4.7 shows that generally, AEG products have a higher cost rather than SAMSUNG. This is due to the biggest costs come from the use phase which is the costs of MSRP have a large value compared to other costs. However, for example in terms of the use of electrical energy AEG has a lower value than SAMSUNG. This is because SAMSUNG consumes more electricity compared to AEG. In other parameters, the value of the total cost is almost the same because the assumptions given are not much different for the two products.

Based on the results of this economic assessment, we can identify how the impact of each aspect of costs is spent on each life cycle stage and find the key contributors.

4.4 Functional assessment

The last assessment is functional assessment. This stage aims to predict how long the product can last to do work in accordance with its functions for a certain period of time. As discussed in section 3.4, there are 3 sub sections consisting of (1) Survey the most failure component, (2) Analyze the most failure part in its component and (3) Modeling the analytical simulation based on the analyzed part. Firstly, we determined what components are most often damaged. This can be done in various ways, one of them is surveying the reason why the vacuum cleaner is damaged and determining which components are most often damaged in a vacuum cleaner. According to a report from AEA Energy and

Environment 2009, the reason of vacuum cleaner damaged is most often due to suction and motor problems as shown in table 4.7.

Reason for breakdown	Upright	Cylinder
Split/broken hose	21%	25%
Suction	19%	15%
Motor	16%	-
Broken casing	-	11%
Power cable	-	11%

Table 4.7 The most of breakdowns component in vacuum cleaners (AEA Energy & Environment 2009)

Electric motor became one of the causes of damage to the vacuum cleaner and it affects the suction capability of the product decrease over time. Once we already know which component is most often damaged, furthermore it is to analyze the component and identify what is causing the component damage. In order to do so, based on the previous discussion in section 3.4, this analysis is carried out using failure mode and effect analysis method as shown in figure 4.8

This methodology identifies all possible failures that will occur in the structure or component of a product or system. This is intended to provide information to designers to prevent possible failures. In the previous study (R. A. Munteanu, et al. 2013) they compiled an algorithm to predict the possibility of failure on all electric motors. And the result was that the bearing elements in the electric motor become the most frequently damaged elements due to several causes including; excessive loading, temperatures that exceed the limit, often starting and stopping, etc.

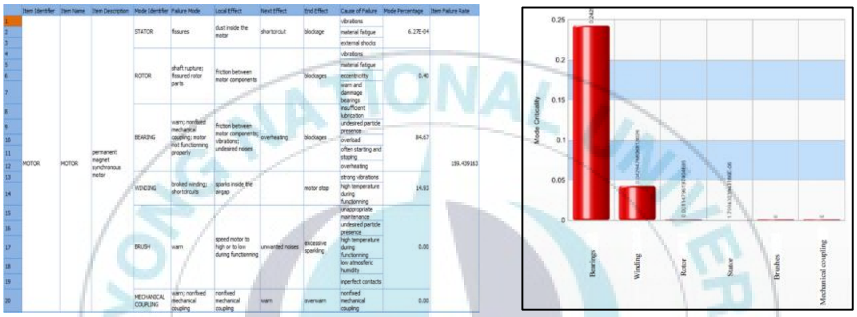

Figure 4.8 Failure mode and effect analysis for bearing motor (R. A. Munteanu, et al. 2013)

Finally, once we get the main cause of the vacuum cleaner damage in this case is the element of bearing, then modeling analytical simulation was performed to predict how long the bearing life time in the electric motor based on the given situation. The bearing age calculation uses the formula provided by ISO standard 281. To calculate bearing life with 90% reliability can be seen in formula 4.1, while the formula used to calculate bearing life based on operating time is shown in formula 4.2.

Durability of motor bearing

$$L_{10} = \left(\frac{C}{P}\right)^{p} \quad \text{………………………………………….……4.1}$$

$$L_{10h} = \frac{10^6}{60\ x\ n}\ x\ L_{10} \quad \text{……………………………….………4.2}$$

$$P = X.Fr + Y.Fa \quad \text{……………………………..…………..4.3}$$

Where,

L_{10} = nominal life in rev x 10^6

L_{10h} = nominal lifetime in hours

P = equivalent dynamic load

C = dynamic load rating

p = exponent; 3 for ball bearings and 10/3 for roller bearings

n = rotational speed, rpm

Fr,Fa = radial and axial force

X,Y = Constants from table

The bearing used in this study was 608-z single row deep groove ball bearing which is type of bearing commonly used in electric motors in vacuum cleaners with specifications as shown in figure 4.9.

This model was applied to two products which are AEG and SAMSUNG to compare the life time of those two products with three different usage pattern scenarios as shown in table 4.8, consists of; light which are consumers who operates

Pattern	Hour	Week
Light	0.25	1
Heavy	4	1
Average	1	1

Table 4.8 The amount of time spent cleaning (JRC science and policy report 2015)

Specification of bearing 608-z

Parameter	Symbol	Value	Unit
Outer diameter	D_a	20	mm
Inner diameter	d_a	10	mm
Basic dynamic load rating	C	3.45	kN
Basic static load rating	C_0	1.37	kN
Fatigue load limit	P_u	0.057	kN
Reference speed		7500	rpm
Limiting speed		4800	rpm
Calculation factor	k_r	0.025	
Calculation factor	f_0	12	
Mass		0.013	kg
Radial and axial force	Fr,Fy	0.3	kN

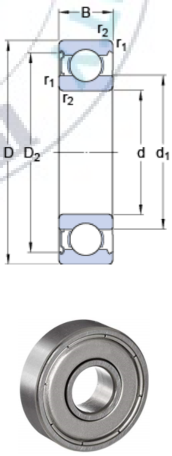

Figure 4.9 Specification of bearing

AEG	509 hours	Light	42.4638
		Heavy	2.65399
		Average	10.6159
SAMSUNG	424 hours	Light	35.3865
		Heavy	2.21165
		Average	8.84663

Table 4.9 Summarize of functional assessment for AEG and SAMSUNG vacuum cleaners

a vacuum cleaner 0.25 hours for one week, heavy which are consumers who operate a vacuum cleaner 4 hours in one week, and the last is an average pattern for those who use a vacuum cleaner for one hour a week.

In this calculation the specifications and parameter assumptions used for the two products are the same. However, the parameter that distinguishes the calculation result is which parameter of rotating speed (n), this parameter is used to calculate bearing life time based on operating time. In accordance with the specifications of each product especially for rotating speed of motor, the AEG has a rotation of 3000 rpm and SAMSUNG has a rotation of 3600 rpm. The results of calculations for each product are shown in table 4.9 respectively and the result is that the AEG can last 509 hours while SAMSUNG can only last 424 hours.

Referring to the standards provided by ErP directive where, the standards for each vacuum cleaner's motor must last more than 500 hours for operating time and we can see that AEG product have met the given standard.

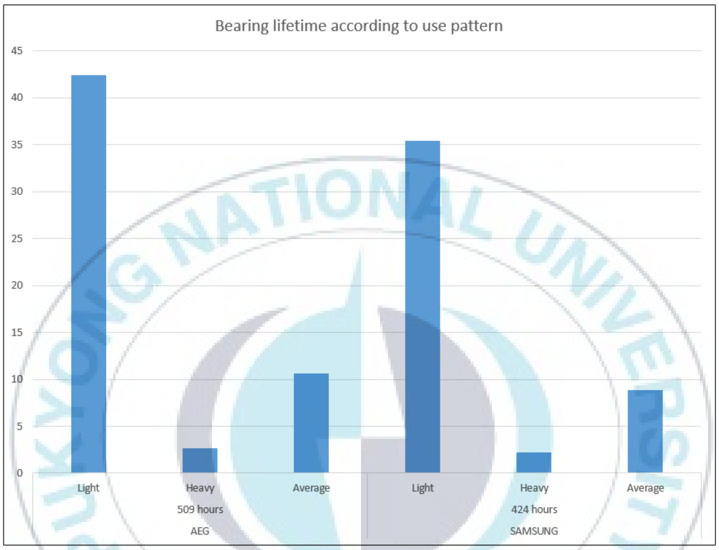

Figure 4.10 Comparison of functional assessment for AEG and SAMSUNG vacuum cleaners

In comparison with the given pattern scenario as shown in Figure 4.10, we can see that based on the three scenarios for AEG, light pattern of consumer can use a vacuum cleaner for approximately forty-two years. However, heavy pattern of consumers can only use a vacuum cleaner for approximately two years and average users can use the product for more than ten years. For SAMSUNG, light pattern of consumers can use products for thirty-five years while heavy pattern of consumers can only use products for two years and average users can use products for more than eight years.

4.4.1 Suction performance measurement

Generally, many people think that in the case of a vacuum cleaner the greater input power, leads to the greater of suction power. However, according to (Gehring, 2011) There is no clear relationship between input power and cleaning efficiency. To prove this statement, an experiment was conducted on two vacuum cleaners in this study

Figure 4.11 State of experiment

This experiment shows the performance of the suction power of two vacuum cleaners, namely AEG with an average input power of 545 W and SAMSUNG with an average input power of 1290 W. As shown in figure 4.11, experiments were carried out on two different products which cleaning up two surfaces with the same amount of areas and dust.

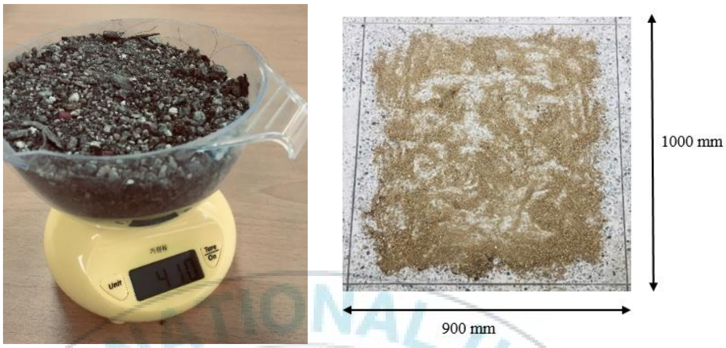

Figure 4.12 Weight of dust and Cleaning area

The area to be cleaned was 1000 mm x 900 mm or 0.9 m^2. And the amount of cleaned dust was 872 gr which is spread out in the area for both products. The way to clean the surface area of the floor was moving the nozzle horizontally according to the instructions given by ErP directive.

	Area	Dust	Time
AEG	0.9 m^2	872 gr	1.018 min
SAMSUNG	0.9 m^2	872 gr	3.139 min

Table 4.10 Comparison of vacuum performance

The time spent by each product was measured until the product has finished cleaning dust on the surface of floor. As shown in the table 4.10, the result is AEG's product could be able to clean up the surface areas almost three times faster than SAMSUNG's product.

5. RESULT AND DISCUSION

Based on the discussion, we can find out the analysis results of the three aspects that cover the environment, economy, and function of the product. In terms of environmental impacts as shown in figure 4.11a, between both AEG and SAMSUNG products we can see that SAMSUNG has a larger environmental impact, more specifically the impact of carbon dioxide emissions. This is because the electricity consumption of the product in the usage phase is almost twofold greater than other products. On the other hand, existing AEG products that meet ErP directive standards as shown in the compliance checklist which requires this product to use electrical energy below the given limit.

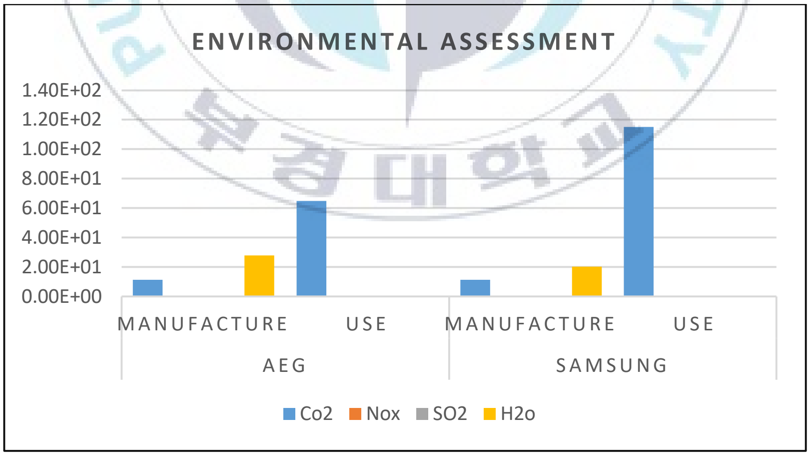

Figure 5.1a Environmental assessment of AEG and SAMSUNG vacuum cleaners

This means that the standards have a significant impact in decreasing environmental impacts through reducing carbon dioxide emissions.

Despite the results of such environmental impacts, in terms of economic assessment AEG has a higher cost compared to SAMSUNG as shown in figure 4.11b. This is because the costs that come from purchasing (MSRP) which the price of AEG products are more expensive than SAMSUG. However, the cost of electricity consumption which shows that SAMSUNG's electricity consumption costs are greater than other products.

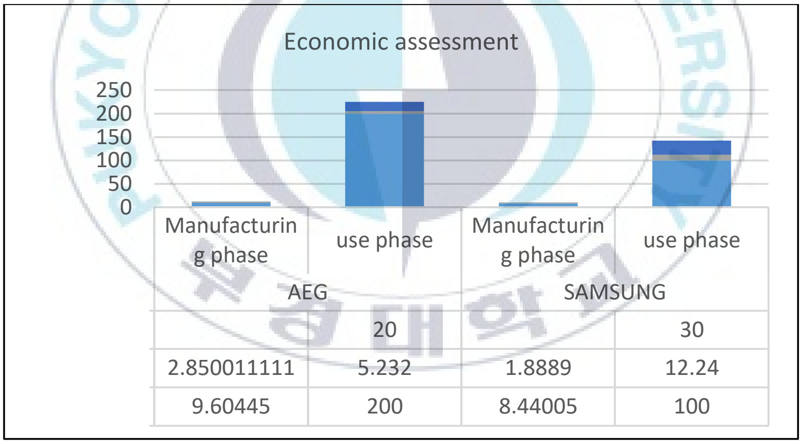

Figure 5.1b Economic assessment of AEG and SAMSUNG vacuum cleaners

For functional assessments as shown in figure 4.11c, we can see based on the prediction analysis of bearing life on an electric motor in a vacuum cleaner that the AEG could be able to running for 509 hours of work operation while SAMSUNG could only able to run 424 hours. This result does not mean that the vacuum cleaner damages are always occurs in electric motor bearings but we assume the age of the vacuum cleaner can be determined from how long the components that are most often damaged can hold out based on existing conditions. Based on this result also we can concluded that AEG has qualified with ErP standard according to standard for motor operating life time is 500 hours.

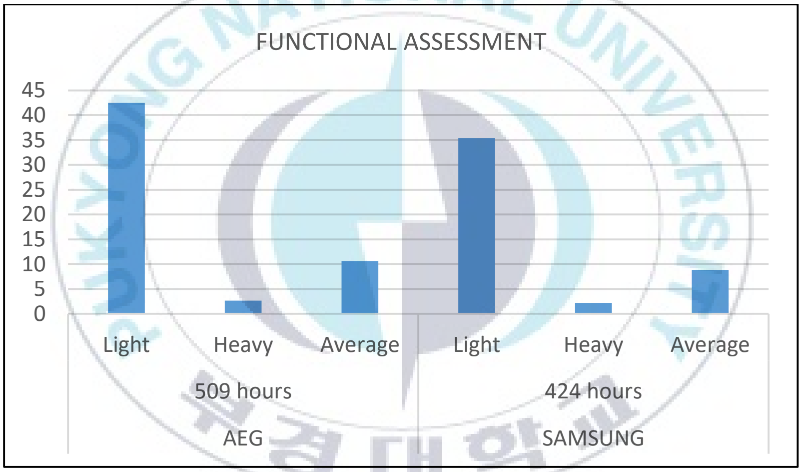

Figure 5.1c Functional assessment of AEG and SAMSUNG vacuum cleaners

Based on the results that have been obtained we can assess what parameters cause the high environmental impact and how to reduce it, we can even adjust the design that must be made whether it aims to meet customer needs, meet government regulations and or adjust to market demand. This approach is very useful to support the decision-making process for designers in the design phase, determine what aspects to optimize whether it is about the economy related to the market situation, or optimize the best product from several product candidates in terms of determining the least environmental impact, even determining the type of material on components in order to make the product more durable or vice versa.

The contribution of this study is to provide a framework that integrates three assessment techniques that include environmental, economic, and functional with the addition of a compliance checklist to a standard to help designers in companies, organizations and manufacturers make an eco-decision or in other words make a decision which not only considers the quality and economic efficiency of a product but also considers the impact of the product life cycle on the environment. The proposed methodology does not provide suggestions for choosing a specific type of product but shows critical points based on three perspectives to determine the best product based on the comparison between several product candidates according to the needs of the designer.

This research was conducted based on real data obtained from the experiment so that the results obtained approached the actual results. However, some other data such as data from the production process and data from the load given to motor components are data derived from literature and assumptions so that this method requires more application to several other case studies.

The calculations from this study are still done manually on Microsoft Excel and for functional analysis can only be done on certain case studies in this case motor bearings. Because each component or structure of the product has a different type of load. Therefore the future work will integrate this manual calculation into the software and for functional analysis it will focus more on the parameters of material types that are more detailed because the type of material has a large effect on the durability of a product from the existing load or condition.

		AEG		SAMSUNG	
Environmental	CO_2	1.13×10^{1}	6.48×10^{1}	1.12×10^{1}	1.15×10^{2}
	NO_x	5.59×10^{-3}	3.12×10^{-2}	5.25×10^{-3}	7.30×10^{-2}
	SO_2	3.15×10^{-3}	4.26×10^{-2}	3.19×10^{-3}	9.96×10^{-2}
	H_2O	2.77×10^{1}	0	2.01×10^{1}	0
Economical	Raw material	9.6		8.4	
	Production	2.9		1.9	
	MSRP	200.0		100.0	
	Electricity	5.2		12.2	
	Maintenance	20.0		30.0	
Functional	Light	509 hours	42.463	424 hours	35.386
	Heavy		2.653		2.211
	Average		10.615		8.846

Table 5.1 Critical point of view

Input power is a key issue that affects product's performance in terms of the three aspects analyzed. In the case of environmental assessment, electricity consumption affects the high level of impact in the use phase due to high energy consumption, in the case of economical electricity consumption affects the significant difference in electricity price, and in the case of durability the high rated input power of Samsung affects high frequency of motor.

6. CONCLUSION

The present work proposes an environmentally-conscious (eco-) design methodology that integrates environmental, economic and functional analysis with consideration of product's predefined requirements in this case, the standard used is a standard adopted from ErP directives provided by the European Union. This approach was demonstrated in one of the products included in the category of energy-related products, which is a vacuum cleaner. In this study we were implementing proposed methodology with comparing two vacuum cleaners from different manufacturers made in Germany and Korea respectively, to see the difference between products that have met ErP directive standards and products from outside Europe that have not met these standards.

The results show that in the environmental view, AEG products produce less environmental impact compared to SAMSUNG where the most emissions are carbon dioxide emissions. The most environmental impact comes from the use phase for both products respectively and this shows that the biggest contributor to the environment comes from a more specific use phase due to electricity consumption. In contrast to economic valuation results, AEG has a higher cost compared to SAMSUNG which comes from the usage phase which is cost of purchasing. However, for the cost of electricity consumption, SAMSUNG has a larger cost. Finally, in functional assessment, AEG is able to run as its function during 509 hours and SAMASUNG is less than 424 hours based on simulation model. And also based on the experiment, AEG can perform three times faster than SAMSUNG in terms of suction performance. According to the results of this study, designers can use this approach to optimize the product with adjusting the designer's needs which related to the environment, economy and functional aspect to generate the most appropriate product.

Based on the results of this study using the analytical approach through the proposed methodology is closely related to the regulations provided by the European commission regarding the use of energy in electrical products. It was proven that the amount of energy use specifically high level of electrical consumption contributes to high environmental impacts and large costs and also affects to the product’s age.

This study expectedly helps product developers especially designers in the design stage to make an eco-decision in order to determine which products are closest to the provisions based on the three aspects discussed.

Functional analysis is a challenge in this study. Because each structure of the product has a different type of component and loading. Therefore it is difficult to predict the age of the product. In this case the simulation model that is applied can only be used on specific components, especially on electric motor bearings

The formalized calculation was a manual calculation completed with Microsoft Excel. However, for future work the calculation will be carried out by integrating the use of software with the aim of solving more complicated problems. Furthermore, functional analysis will focus more on the effect of different type material on environmental impacts, costs, and loading that affect the product's life.

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APPENDIX

Table A1. Life cycle inventory of Electricity

번호	방향	그룹	환경	명칭	양	
				명칭	단위 기호/명칭	값
1	INPUT	Resource	Soil	Bauxite(Al_2O_3)	g	0.001
2	INPUT	Resource	Soil	Biomass	g	0.000
3	INPUT	Resource	Soil	Caliche	g	0.007
5	INPUT	Resource	Soil	Coal	g	175.625
6	INPUT	Resource	Soil	Crude oil	g	21.752
9	INPUT	Resource	Soil	Natural gas	g	22.500
11	INPUT	Resource	Soil	Sodium chloride(NaCl)	g	0.014
12	INPUT	Resource	Soil	Uranium(U)	g	0.012
14	INPUT	Resource	Water	Water	g	20.749
15	OUTPUT	Product	Technosphere	Electricity	kWh	1.000
17	OUTPUT	Emission	Air	Ammonia(NH_3)	g	0.001
21	OUTPUT	Emission	Air	Carbon dioxide(CO_2)	g	487.218
22	OUTPUT	Emission	Air	Carbon monoxide(CO)	g	0.049
24	OUTPUT	Emission	Air	Dust	g	0.108
27	OUTPUT	Emission	Air	Hydrocarbons	g	1.007
34	OUTPUT	Emission	Air	Methane	g	0.353
35	OUTPUT	Emission	Air	Nickel(Ni)	g	0.000
36	OUTPUT	Emission	Air	Nitrogen oxides(NO_X)	g	1.193
37	OUTPUT	Emission	Air	Nitrous oxide(N_2O)	g	0.002
40	OUTPUT	Emission	Air	Sulfur oxides(SO_X)	g	1.629
41	OUTPUT	Emission	Air	VOC	g	0.017
43	OUTPUT	Emission	Water	Aluminium(Al)	g	0.001
49	OUTPUT	Emission	Water	BOD	g	0.001
51	OUTPUT	Emission	Water	Chloride(Cl^-)	g	1.308

54	OUTPUT	Emission	Water	COD	g	0.009
57	OUTPUT	Emission	Water	Dissolved solids	g	3.155
58	OUTPUT	Emission	Water	Fluoride(F-)	g	0.001
67	OUTPUT	Emission	Water	Oil	g	0.026
72	OUTPUT	Emission	Water	SS	g	0.024
74	OUTPUT	Emission	Water	Sulfate(SO42-)	g	0.294
79	OUTPUT	Waste	Technosp here	Hazardous wastes(foreign)	g	0.002
80	OUTPUT	Waste	Technosp here	Hazardous wastes(domesti c)	g	13.441
81	OUTPUT	Waste	Technosp here	Industrial wastes(domesti c)	g	251.998
82	OUTPUT	Waste	Technosp here	Unspecified wastes	g	45.770

Table A.2 Life cycle inventory of Polyprophelyne

번호	방향	그룹	환경	명칭	양	
				명칭	단위 기호/명칭	값
1	INPUT	Energy ware	Techno sphere	Unspecified energy	kg	0.004266
2	INPUT	Raw material	Techno sphere	Unspecified chemicals	kg	0.008515
3	INPUT	Raw material	Techno sphere	Unspecified materials	kg	0.486640
4	INPUT	Resource	Air	Air	kg	0.106921
5	INPUT	Resource	Soil	Baryte(BaSO4)	kg	0.000121
6	INPUT	Resource	Soil	Bauxite(Al2O3)	kg	0.000564
7	INPUT	Resource	Soil	Coal	kg	0.028562
8	INPUT	Resource	Soil	Copper ore(0.14%)	kg	0.000000
9	INPUT	Resource	Soil	Copper(Cu)	kg	0.000000
10	INPUT	Resource	Soil	Crude oil	kg	1.403610
11	INPUT	Resource	Soil	Natural gas	kg	0.079860
12	INPUT	Resource	Soil	Sodium chloride(NaCl)	kg	0.000713

13	INPUT	Resource	Soil	Soft coal	kg	0.000049
14	INPUT	Resource	Water	Water	kg	12.28046
15	OUTPUT	Emission	Air	Air	kg	0.000678
16	OUTPUT	Emission	Air	Carbon dioxide(CO2)	kg	1.217856
17	OUTPUT	Emission	Air	Carbon monoxide(CO)	kg	0.098067
18	OUTPUT	Emission	Air	Dust	kg	0.000136
19	OUTPUT	Emission	Air	Exhaust	kg	0.006133
20	OUTPUT	Emission	Air	Vapor	kg	0.026142
21	OUTPUT	Emission	Water	Dissolved solids	kg	0.000513
22	OUTPUT	Emission	Water	Steam condensate	kg	0.064651
23	OUTPUT	Emission	Water	Water	kg	0.089037
24	OUTPUT	Product	Techno sphere	Propene	kg	1.000000
25	OUTPUT	Waste	Techno sphere	Hazardous wastes(domestic)	kg	0.002777
26	OUTPUT	Waste	Techno sphere	Industrial wastes(domestic)	kg	0.044857
27	OUTPUT	Waste	Techno sphere	Industrial wastes(foreign)	kg	0.000299
28	OUTPUT	Waste	Techno sphere	Unspecified wastes	kg	0.007438

Table A.4 Life cycle inventory of Stainless steel

No	방향	그룹	환경	명칭	양	
				명칭	단위	
					기호/명칭	값
1	INPUT	Resource	Air	Air	kg	0.279
2	INPUT	Resource	Soil	Bauxite ore	kg	0.432
3	INPUT	Resource	Soil	Brown coal	kg	0.157
4	INPUT	Resource	Soil	Chromium ore	kg	0.306
5	INPUT	Resource	Soil	Coal	kg	0.671
6	INPUT	Resource	Soil	Crude oil	kg	0.028
7	INPUT	Resource	Soil	Iron ore	kg	0.664
8	INPUT	Resource	Soil	Limestone	kg	0.034

9	INPUT	Resource	Soil	Natural gas	kg	0.301
10	INPUT	Resource	Soil	Nickel ore	kg	0.102
11	INPUT	Resource	Soil	Oil	kg	0.284
12	INPUT	Resource	Soil	Pyrite(FeS_2)	kg	0.054
13	INPUT	Resource	Water	Water	kg	2.730
14	INPUT	Resource	Soil	Wood	kg	0.006
15	OUTPUT	Product	Technosphere	(Stainless steel)	kg	1.000
16	OUTPUT	Emission	Air	Air	kg	0.028
17	OUTPUT	Emission	Air	Carbon dioxide(CO_2)	kg	2.800
18	OUTPUT	Emission	Air	Carbon monoxide(CO)	kg	0.001
19	OUTPUT	Emission	Air	Dust	kg	0.004
20	OUTPUT	Emission	Air	HC except CH_4	kg	0.002
21	OUTPUT	Emission	Air	Hydrocarbons	kg	0.001
22	OUTPUT	Emission	Air	Methane	kg	0.005
23	OUTPUT	Emission	Air	Nitrogen oxides(NOX)	kg	0.006
24	OUTPUT	Emission	Air	Sulfur oxides(SOX)	kg	0.092
25	OUTPUT	Emission	Water	BOD	kg	0.002
26	OUTPUT	Emission	Water	Calcium ion(Ca^{2+})	kg	0.001
27	OUTPUT	Emission	Water	Chloride(Cl^-)	kg	0.014
28	OUTPUT	Emission	Water	COD	kg	0.003
29	OUTPUT	Emission	Water	Dissolved inorganic matter	kg	0.003
30	OUTPUT	Emission	Water	Iron ion(Fe^{2+}/Fe^{3+})	kg	0.001
31	OUTPUT	Emission	Water	Magnesium ion(Mg^{2+})	kg	0.001
32	OUTPUT	Emission	Water	Sodium ion(Na^+)	kg	0.006
33	OUTPUT	Emission	Water	SS	kg	0.004
34	OUTPUT	Emission	Water	Sulfate(SO_4^{2-})	kg	0.006
35	OUTPUT	Emission	Water	Waste water	kg	0.074
36	OUTPUT	Waste	Technosphere	Hazardous wastes(domestic)	kg	0.009
37	OUTPUT	Waste	Technosphere	Industrial wastes(domestic)	kg	0.411
38	OUTPUT	Waste	Technosphere	Industrial wastes(foreign)	kg	0.085

Table A.5 Life cycle inventory of ABS

번호	방향	그룹	환경	명칭	양	
				명칭	단위	
					기호/명칭	값
1	INPUT	Energy ware	Technosphere	Unspecified energy	MJ	0.015
2	INPUT	Raw material	Technosphere	Unspecified chemicals	kg	0.194
3	INPUT	Raw material	Technosphere	Unspecified materials	kg	0.601
4	INPUT	Resource	Air	Air	kg	1.779
5	INPUT	Resource	Air	Nitrogen(N2)	kg	0.757
6	INPUT	Resource	Soil	Coal	kg	0.156
7	INPUT	Resource	Soil	Copper ore(0.14%)	kg	0.000
8	INPUT	Resource	Soil	Copper(Cu)	kg	0.000
9	INPUT	Resource	Soil	Crude oil	kg	0.314
10	INPUT	Resource	Soil	Dolomite(CaMg(CO3))	kg	0.000
11	INPUT	Resource	Soil	Feldspar	kg	0.000
12	INPUT	Resource	Soil	Ferro manganese(Fe-Mn)	kg	0.000
13	INPUT	Resource	Soil	Ferrous sulfate(FeSO4)	kg	0.000
14	INPUT	Resource	Soil	Fluorspar	kg	0.000
15	INPUT	Resource	Soil	Fluorspar(CaF2)	kg	0.000
16	INPUT	Resource	Soil	Granite	kg	0.000
17	INPUT	Resource	Soil	Gravel	kg	0.000
18	INPUT	Resource	Soil	Hard coal	kg	0.000
19	INPUT	Resource	Soil	Iron ore	kg	0.000
20	INPUT	Resource	Soil	Iron ore(46%)	kg	0.000
21	INPUT	Resource	Soil	Iron ore(65%)	kg	0.000
22	INPUT	Resource	Soil	Iron(Fe)	kg	0.000
23	INPUT	Resource	Soil	Kaolinite	kg	0.000
24	INPUT	Resource	Soil	Lead - zinc ore(4.6%-0.6%)	kg	0.000
25	INPUT	Resource	Soil	Lead ore	kg	0.000
26	INPUT	Resource	Soil	Lead(Pb)	kg	0.000
27	INPUT	Resource	Soil	Lignite	kg	0.022
28	INPUT	Resource	Soil	Limestone	kg	0.001
29	INPUT	Resource	Soil	Natural gas	kg	0.461
30	INPUT	Resource	Soil	Petroleum	kg	0.709

31	INPUT	Resource	Soil	Phosphate(PO43-)	kg	0.002
32	INPUT	Resource	Soil	Sodium chloride(NaCl)	kg	0.003
33	INPUT	Resource	Soil	Soft coal	kg	0.005
34	INPUT	Resource	Soil	Sulfur(S)	kg	0.003
35	INPUT	Resource	Water	Water	kg	80.944
36	OUTPUT	Emission	Air	Air	kg	0.003
37	OUTPUT	Emission	Air	Carbon dioxide(CO2)	kg	2.841
38	OUTPUT	Emission	Air	Carbon monoxide(CO)	kg	0.057
39	OUTPUT	Emission	Air	Exhaust	kg	0.015
40	OUTPUT	Emission	Air	Hydrocarbons	kg	0.002
41	OUTPUT	Emission	Air	Methane	kg	0.005
42	OUTPUT	Emission	Air	Nitrogen dioxide(NO2)	kg	0.002
43	OUTPUT	Emission	Air	Nitrogen oxides(NOX)	kg	0.008
44	OUTPUT	Emission	Air	off gas	kg	0.039
45	OUTPUT	Emission	Air	Sulfur dioxide(SO2)	kg	0.001
46	OUTPUT	Emission	Air	Sulfur oxides(SOX)	kg	0.006
47	OUTPUT	Emission	Air	Vapor	kg	0.970
48	OUTPUT	Emission	Water	Dissolved solids	kg	0.003
49	OUTPUT	Emission	Water	SS	kg	0.001
50	OUTPUT	Emission	Water	Steam condensate liquid	kg	0.039
51	OUTPUT	Emission	Water	Waste water	kg	10.244
52	OUTPUT	Emission	Water	Water	kg	0.998
53	OUTPUT	Product	Technosphere	ABS	kg	1.000
54	OUTPUT	Waste	Technosphere	Hazardous wastes(domestic)	kg	0.013
55	OUTPUT	Waste	Technosphere	Industrial wastes(domestic)	kg	0.191
56	OUTPUT	Waste	Technosphere	Industrial wastes(foreign)	kg	0.014
57	OUTPUT	Waste	Technosphere	Unspecified wastes	kg	0.030

Table A.6 Life cycle inventory of Water

번호	방향	그룹	환경	명칭	양	
				명칭	단위	
					기호/명칭	값
1	INPUT	Resource	Soil	Coal	kg	0.040
2	INPUT	Resource	Soil	Crude oil	kg	0.005
3	INPUT	Resource	Soil	Natural gas	kg	0.005
4	INPUT	Resource	Water	Water	kg	1030.000
5	OUTPUT	Product	Technosphere	Water	kg	1000.000
6	OUTPUT	Emission	Air	Carbon dioxide(CO_2)	kg	0.112
7	OUTPUT	Emission	Water	Waste water	kg	30.000
8	OUTPUT	Waste	Technosphere	Industrial wastes(foreign)	kg	0.061
9	OUTPUT	Waste	Technosphere	Unspecified wastes	kg	0.010

Table A.7 Life cycle inventory of Brass

번호	방향	그룹	환경	명칭	양	
				명칭	단위	
					기호/명칭	값
1	INPUT	Resource	Soil	Brown coal	kg	0.001
2	INPUT	Resource	Soil	Crude oil	kg	0.183
3	INPUT	Resource	Soil	Hard coal	kg	0.507
4	INPUT	Resource	Soil	Iron ore	kg	0.001
5	INPUT	Resource	Soil	Lead(Pb)	kg	0.006
6	INPUT	Resource	Soil	Limestone	kg	0.001
7	INPUT	Resource	Soil	Natural gas	kg	0.086
8	INPUT	Resource	Soil	Zinc ore	kg	0.358
9	INPUT	Raw material	Technosphere	Unspecified materials	kg	0.819
10	OUTPUT	Emission	Air	Carbon dioxide(CO_2)	kg	1.768
11	OUTPUT	Emission	Air	Nitrogen oxides(NO_X)	kg	0.006
12	OUTPUT	Emission	Air	NMVOC	kg	0.001
13	OUTPUT	Emission	Water	Chloride(Cl^-)	kg	0.006
14	OUTPUT	Emission	Water	Dissolved solids	kg	0.009

15	OUTPUT	Emission	Water	Zinc(Zn)	kg	0.001
16	OUTPUT	Waste	Technosphere	Hazardous wastes(domestic)	kg	0.019
17	OUTPUT	Waste	Technosphere	Industrial wastes(domestic)	kg	0.923
18	OUTPUT	Waste	Technosphere	Industrial wastes(foreign)	kg	0.007
19	OUTPUT	Waste	Technosphere	Unspecified wastes	kg	0.066
20	OUTPUT	Product	Technosphere	황동봉	kg	1.000

Table A.8 Life cycle inventory of Polyamide

번호	그룹	환경	명칭	양	
			명칭	단위 기호/명칭	값
1	Raw material	Technosphere	Acrylamide	kg	329.940
2	Resource	Air	Air	kg	121.450
3	Raw material	Technosphere	Ammonia(NH3)	kg	0.040
6	Resource	Soil	Baryte(BaSO4)	kg	2.186
7	Resource	Soil	Bauxite(Al2O3)	kg	3.934
8	Resource	Soil	Bentonite	kg	0.140
9	Resource	Soil	Caliche	kg	0.022
10	Resource	Soil	Carbon dioxide(CO2)	kg	26.415
11	Resource	Soil	Coal	kg	193.010
13	Resource	Soil	Crude oil	kg	350.361
14	Resource	Soil	Dolomite(CaMg(CO3))	kg	0.087
15	Resource	Soil	Hard coal	kg	644.570
18	Resource	Soil	Iron ore	kg	0.064
19	Resource	Soil	Iron ore(65%)	kg	0.127
22	Raw material	Technosphere	Kraft paper unbleached(t92)	kg	0.480
24	Resource	Soil	Limestone	kg	3.107
25	Resource	Soil	Natural gas	kg	117.654
26	Resource	Air	Nitrogen(N2)	kg	0.028
27	Raw material	Technosphere	Paper	kg	10.008
28	Resource	Soil	Phosphate	kg	5.337

29	Raw material	Technosphere	Phosphoric acid(H3PO4)	kg	0.013
30	Raw material	Technosphere	Polyethylene foil(PE)	kg	0.079
31	Raw material	Technosphere	Polymer	kg	0.010
34	Resource	Soil	Sand(SiO2)	kg	1.099
35	Raw material	Technosphere	Sodium carbonate(Na2CO3)	kg	0.005
36	Resource	Soil	Sodium chloride(NaCl)	kg	115.832
37	Raw material	Technosphere	Sodium hydroxide(NaOH,50%)	kg	0.046
38	Resource	Soil	Soft coal	kg	10.495
39	Resource	Soil	Soil	kg	0.181
40	Resource	Soil	Sulfur(S)	kg	3.108
43	Raw material	Technosphere	Unspecified chemicals	kg	0.021
44	Resource	Soil	Unspecified fuel	kg	0.054
45	Raw material	Technosphere	Unspecified materials	kg	312.135
46	Resource	Soil	Uranium ore	kg	28.452
47	Resource	Soil	Uranium(U)	kg	0.014
48	Resource	Soil	Urea(CO(NH2)2)	kg	21.350
49	Resource	Water	Water	kg	2413911.078
51	Product	Technosphere	Polyacrylamide(PAA.powder)	kg	1000.000
52	Emission	Air	Ammonia(NH3)	kg	15.715
54	Emission	Air	Carbon dioxide(CO2)	kg	1818.200
55	Emission	Air	Carbon monoxide(CO)	kg	0.462
56	Emission	Air	Dust	kg	0.698
57	Emission	Air	Ethane	kg	0.013
58	Emission	Air	Exhaust	kg	112.880
59	Emission	Air	Flare gas	kg	0.071
60	Emission	Air	Hydrocarbons	kg	3.450
61	Emission	Air	Helium(He)	kg	0.008
66	Emission	Air	Methane	kg	3.300
67	Emission	Air	Nitrogen oxides(NOx)	kg	5.191
68	Emission	Air	Nitrous oxide(N2O)	kg	0.008
69	Emission	Air	NMVOC	kg	1.968
70	Emission	Air	Sulfur oxides(SOx)	kg	5.560

71	Emission	Air	Vapor	kg	159.754
72	Emission	Air	Sulfur dioxide(SO2)	kg	0.771
73	Emission	Air	Air	kg	3.379
74	Emission	Air	VOC	kg	0.077
75	Emission	Water	Aluminium(Al)	kg	0.017
79	Emission	Water	BOD	kg	18.210
80	Emission	Water	Limestone	kg	0.099
81	Emission	Water	Calcium(Ca)	kg	0.010
82	Emission	Water	COD	kg	8.930
83	Emission	Water	Chloride(Cl-)	kg	13.507
84	Emission	Water	Dissolved inorganic matter	kg	0.013
85	Emission	Water	Dissolved solids	kg	10.754
86	Emission	Water	Fluoride(F-)	kg	0.016
88	Emission	Water	Iron(Fe)	kg	0.017
94	Emission	Water	Oil	kg	0.103
99	Emission	Water	Sodium(Na)	kg	1.187
100	Emission	Water	SS	kg	12.521
101	Emission	Water	Strontium(Sr)	kg	0.076
102	Emission	Water	Sulfate(SO42-)	kg	1.211
103	Emission	Water	TOC	kg	0.120
105	Emission	Water	Warmed sea water	kg	4324.400
106	Emission	Water	Waste water	kg	72682.427
108	Waste	Technosphere	Hazardous wastes(domestic)	kg	84.314
109	Waste	Technosphere	Industrial wastes(domestic)	kg	1032.643
111	Waste	Technosphere	Industrial wastes(foreign)	kg	291.790
112	Waste	Technosphere	Unspecified wastes	kg	177.353

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"But seek first the kingdom of God and His righteousness, and all these things shall be added to you. Matthew 6:33"

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