POLITECNICO DI MILANO

DEPARTMENT OF MANAGEMENT, ECONOMICS AND INDUSTRIAL ENGINEERING

Total Performance Analysis of a Product

Supervisor: Prof. Marco TAISCH
Assistant supervisor: Endris Temam KERGA

Submitted by: Doruk CENKCI 734752

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Abstract

During the last century, increasing consumption of natural resources and material goods has been monitored by the help of growing rate of industrialization. However, in recent decades, at the same time expanding economic activity has been accompanied to those affects by help of growing concerns about climate change, energy security and scarcity of natural resources.

Therefore, scientist, academicians and also company owners have been trying to measure their performances. This study uses a total performance analysis (TPA) method that evaluates a product from environmental and economic viewpoints simultaneously, considering the change in product values over time, so that a designer can easily find improvement targets in a product’s composition and life cycle.

In addition to that, to be able to understand what TPA is, there are some important topics should be discussed in order to understand in what contents TPA can help a company. These topics are mostly related to both environmental and economic concerned issues which are sustainability, life cycle thinking inside LCA and eco-efficient product design towards sustainability. This study will cover and give knowledge about these related topics.

As a result this study is based on TPA method and its framework and beside this all the step of framework will be explained by using a real product example (Multi-stage centrifugal pump)and the final results will show that how practical and improvable this TPA method is.

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1 Introduction

During the last century, increasing consumption of natural resources and material goods has been monitored by the help of growing rate of industrialization. This unavoidable hunger of human kind to the natural resource has had a tremendous effect on ecosystem and on environment [1].

However, in recent decades, expanding economic activity has been accompanied to those affects by help of growing concerns about climate change, energy security and scarcity of natural resources. While industries are showing greater interest in sustainable production, they are also undertaking a number of corporate social responsibility (CSR) initiatives [2]. Thus environmental consciousness has gained more and more interest in recent years, and the environmental performance of products and processes have become a key issue for both companies and their customers [3], which is why every year, many companies who span the entire spectrum of industries from energy producers to product manufacturers and service-oriented companies, want also to understand the environmental impacts that they cause to the environment, and they need to understand in order to control or better yet, avoid those impacts. They do so in a time of increasingly strict environmental regulations in an effort to stay within compliance and meet customer needs, all the while staying financially healthy which means for a company, is the main driving force to stay competitive in the marketplace. Corporate managers see the systematic reduction of environmental impacts as one way to help them accomplish this goal. There is also general growing desire by companies to simply do the “right thing” for the environment [4]. Therefore some companies are investigating ways to minimize their effects on the environment. While they have been trying to do that, they should have been considering product life cycle thinking that aims to maximize total performance while minimizing its environmental load and costs which should be implemented [3]. To evaluate a product’s life cycles and its environmental effects, Life cycle assessment method should be used.

Life Cycle Assessment (LCA) perspective which evaluates all stages of a product’s life from the perspective that they are interdependent, meaning that one operation leads to the next, should be taken into account. In addition, LCA enables the estimation of the cumulative environmental impacts resulting from all stages in the product life cycle, often including impacts not considered in more traditional analyses (e.g., raw material extraction, material transportation, ultimate product disposal, etc.). By including the impacts throughout the product life cycle, LCA provides a comprehensive view of the environmental aspects of the product or process and a more accurate picture of the true environmental trade-offs in product and process selection [5]. After evaluations, in each stage of product life cycle, performance of product should be measured, while doing that environmental concern and economic expectations from a product should be taken into account simultaneously, performance evaluation of a product should show a combined result about its performance. Products with primary or secondary components that specifically address environmental issues, as well as products whose usage, production, etc. may have a direct or indirect impact on the environment, need performance evaluation to see their impact on the environment while taking into account economical issues.. In order to achieve all that, this project proposes to use Total Performance Analysis (TPA) which consider all the approached mentioned before, is basically evaluates both environmental and economic performances of a product simultaneously for maximizing product performance throughout product life cycle with balancing its value, environmental load, and costs. In this study use phase results will be considered because of major impact among all life cycle stages. In addition to that TPA tries to estimate Optimal Lifetime of a product which is the optimal point between Product value which is decreasing and Environmental Impact which is increasing over time. And in the following sections entire specifications and method of TPA will be discussed [3].

Before to explain what TPA is, first of all, there are some important topics should be discussed in order to understand in what contents TPA can help a company. These topics are mostly related to both environmental and economic concerned issues which are sustainability, life cycle thinking inside LCA and eco-efficient product design towards sustainability. In addition to these, there are other topics which helps to TPA framework, will be discussed inside TPA perspective.

2 Overview

This thesis study will cover the TPA method and its related concepts. Therefore in the following sections today's trends and TPA method will be discussed accordingly to each other. Before to get in details; scope, objectives, assumptions, limitations and framework of the study should be defined very well to be able to understand entire TPA methodology.

2.1 Scope

The scope of this study is to understand the performance of a product from environmental and economic point of views simultaneously, to be able to do that TPA method will be explained and this study will try to show how TPA helps companies in terms of today's environmental issues and their economic concerns. In this study, with the help of real example (multi stage centrifugal pump), the usage of TPA method will be shown.

2.2 Objectives

This study uses a total performance analysis method that evaluates a product from environmental and economic viewpoints simultaneously, considering the change in product values over time, so that a designer can easily find improvement targets in a product's composition and life cycle.

- The one of the objectives of this study is to use TPA method in order to analyze performance in terms of cost and environmental load simultaneously that derives an adequate solution for maximizing the value of a product while minimizing its resulting environmental load and cost throughout its life cycle considering various future uncertainties.
- Secondly, to use TPA results to be able to reach accurate results.
- And finding strategies for end of life treatment of a product.

In the first step of this method, the environmental and economic performance throughout the entire life cycle of a product is evaluated using the total performance indicator (TPI), which represents the balance of consumer UV and the resulting environmental load and cost.

2.3 Assumptions

Basic assumptions in this study will be used during TPA real case example in section 6. The aim of using these assumptions is for the sake of simplicity. There are many uncertainties which cannot be covered in limited time duration. Therefore there are some assumptions to cover these uncertainties. Beside the formulas inside TPA method are also based on some assumptions which will be explained in section 4 and 5.

2.4 Limitations

This study's limitations start with time, because of the time constriction, limited sources has been used. This type of studies consider more detail about products, therefore the name of the companies and their products specifications are not used under a real name. To cover entire TPA method, detailed LCA and LCC research should be done, in this study already prepared LCA and LCC researches were taken into account because of that only limited data have been reached.

2.5 Framework

This study consist two main parts; one considers the literature review about today's environmental trends, topics that helped total performance analyze (TPA) method to be created. And second part is TPA method review. As a framework TPA method will be evaluated more detailed as shown in figure.

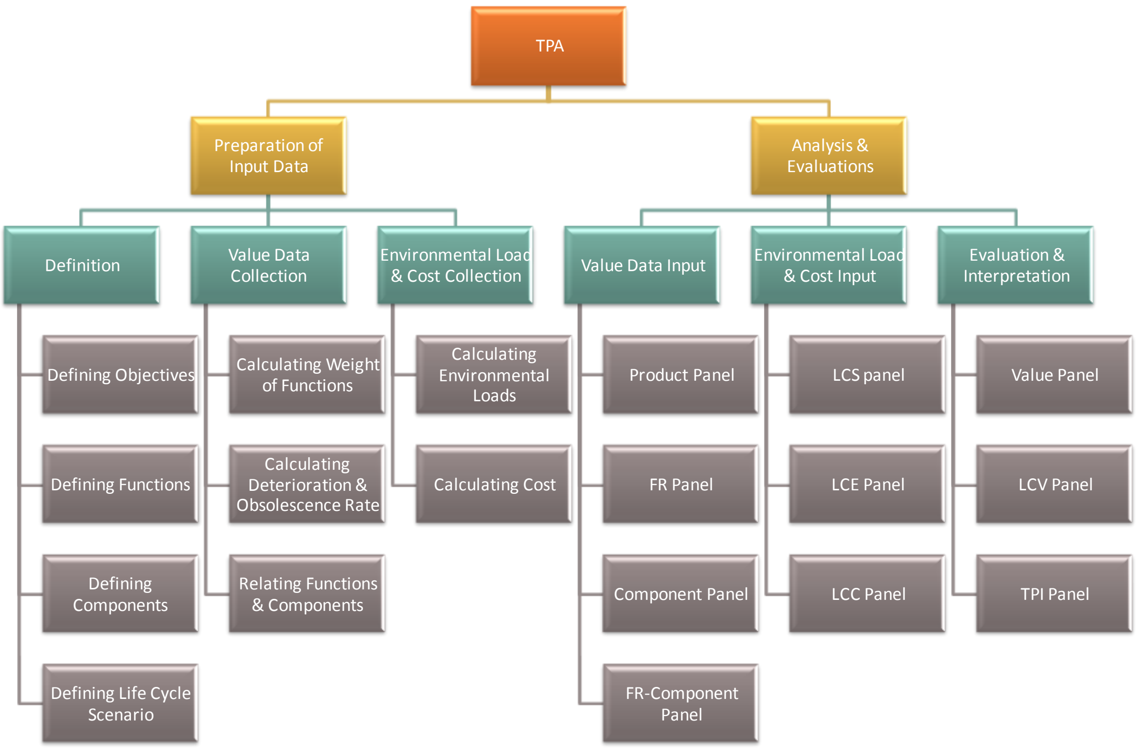


Figure 2-1 TPA Framework

3 TPA Concepts

For decades most of the newly created methods in academic world were created by combination of older concepts and methods, in other words, when new methods were being created, academicians had taken into consideration other concepts. Sometime they had used couple of methods to define new methods, sometimes they were inspired by older methods or concepts to create new methods.

For last decades Global warming effects are getting bigger and bigger, to be able to prevent this all of the scientists and producers are working on it. Therefore they are taking care about environmental issues more than before. However just thinking environmental issues are not the only considered subject by producers, the more important subject than this is being sustainable with taking into account entire life cycle of their products. In addition to that when a firm has a goal, it needs to evaluate its performance. TPA is concept that covers everything mention in this paragraph.

Thus, TPA is a new method and was born based on sustainability concept and Life cycle think concept. In this chapter these concepts will be explained to make better understanding of TPA method.

3.1 Sustainability Concept

During the last 25 years the world has become aware of the environmental problems. Significantly, some of these problems are now affecting the entire Earth. Air pollution from energy production, transportation and the consumption of natural resources and production of waste are reducing air quality in many areas, and causing acid rain, global warming and ozone depletion [6]. To prevent environmental problems and to protect environment new perspectives had been developed, such as sustainability.

The concept of sustainable development described in a 1981 White House Council on Environmental Quality report: “The key concept here is sustainable development” [7] and the concept of sustainability was first formulated in the 1987 with the Brundtland Report stating that the goal of sustainability is to “meet the needs of the present generation without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development (WCED), 1987) [8].

In 1987 the Brundtland Report recognized that economic development taking place today could no longer compromise the development needs of future generations. This concept of sustainable development aimed to encourage people to reflect on the harm economic development was having on both the environment and on society. According to that, the report highlighted three fundamental components to sustainable development: environmental protection, economic growth and social equity. It is so-called triple bottom line [9].

In detailed each perspectives of sustainability consist different focuses as shown in the figure;

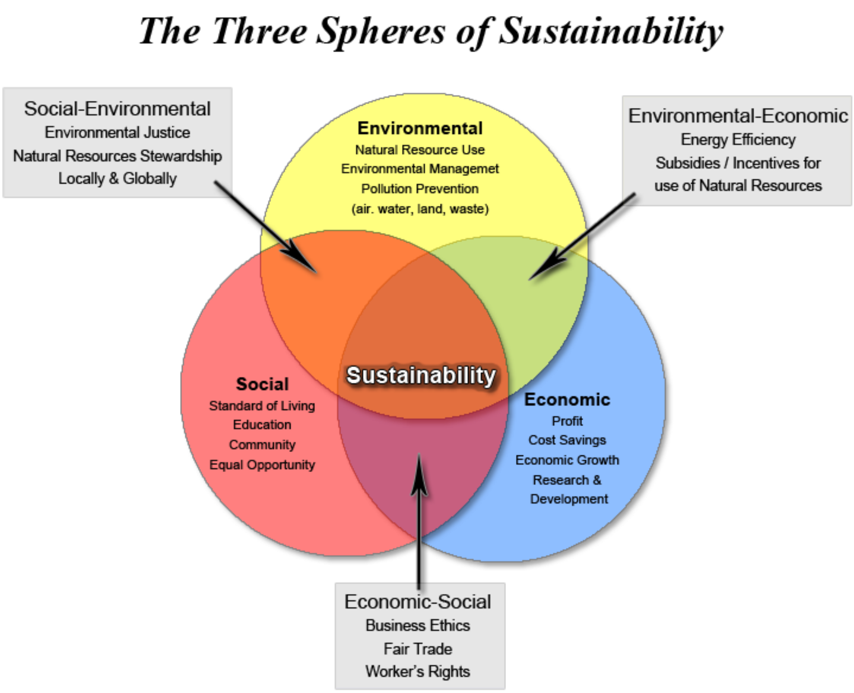


Figure 3-1 Triple Bottom Line of Sustainability **[9]**

The environment should be conserved and our resource base enhanced, by gradually changing the ways in which we develop and use technologies [6]. In addition to sustainability definition mentioned above, there is one more definition for sustainability among more than 100 definitions in the literature and it is:

"...using, conserving and enhancing the community's resources so that ecological processes on which life depends, are maintained and total quality of life, now and in the future, can be maintained". Australia's national strategy for ecologically Sustainable development (1992)[10].

Over the past 30 years, the concept of sustainability has evolved to reflect perspectives of both the public and private sectors. A public policy perspective would define sustainability as the satisfaction of basic economic, social, and security needs now and in the future without undermining the natural resource base and environmental quality on which life depends. From a business perspective, the goal of sustainability is to increase long-term shareholder and social value, while decreasing industry's use of materials and reducing negative impacts on the environment [7]. At present, a wide range of stakeholders including consumers, regulators, shareholders and public bodies are demanding that companies address sustainability in a more comprehensive way.

3.1.1 Sustainable Product

The things that were mentioned above were related to sustainability concepts and when this concept is tried to match with a product, sustainable products is created, which means a product respects each perspectives of sustainability concept. Products and services are fundamental in creating both economic development and quality of life, but at the same time they are the source of global environmental impacts [11].

3.1.2 Eco-Efficiency

In this study according to sustainability and sustainable products concepts, eco efficiency concept will be discussed; moreover focus will be on environmental and economical perspectives. Through improvements introduced over the product's life, businesses can potentially find further economic benefits, both in the product (e.g., less material waste, substituted hazardous materials) and in the market (e.g. improved image and competitive advantage). Already in 1992, before the World Summit in Rio, the World Business Council for Sustainable Development (WBCSD) introduced the concept "eco-efficiency" to highlight the link between environmental improvements and economic benefits, in short, "creating more value with less impact". [12]

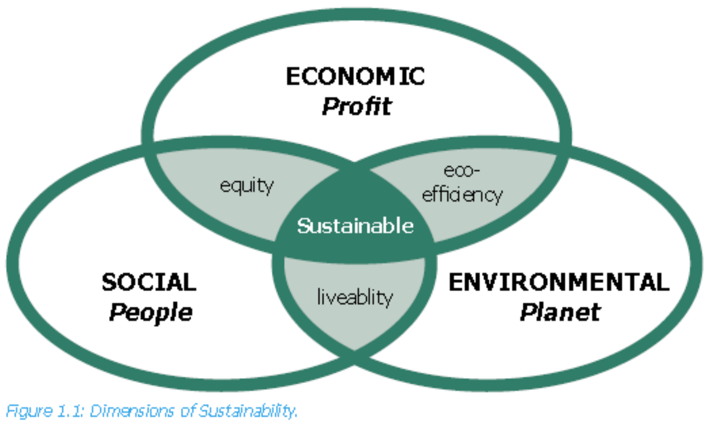


Figure 3-2 Intersection of Sustainability Dimensions**[12]**

"Eco-efficiency is achieved by the delivery of competitively-priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the earth's estimated carrying capacity." If simply defines as "creating more economic value with less environmental impact".[13] A recent major study by DEFRA (Department for Environment, Food and Rural Affairs) has emphasized the importance of product sustainability as the way forward, driven by environmental targets and increased demand and prices of energy and resources. Businesses that use resources more efficiently throughout the supply chain will benefit from cost savings and opportunities for growth, as customers increasingly demand products that save them money and reduce environmental impact. The sustainability agenda has strong linkages to energy-related issues, such as carbon dioxide emissions and climate change [14]. That also points out the eco-efficiency. According to these definitions of eco-efficiency, TPA is the most suitable method to evaluate a product's performance from eco-efficiency perspective.

3.1.3 Eco-Efficient Product through Eco-design perspectives

In the past, products have been designed and developed without considering its adverse impacts on the environment. Typical factors considered in product design included function, quality, cost, ergonomics and safety. However, no consideration was given specifically to the environmental aspects of a product throughout its entire life cycle. Often times, adverse impacts on the environment occurred from other life cycle stages such as use, end-of-life, distribution, and raw material acquisition. Without addressing the environmental impacts from the entire life cycle of a product, one cannot resolve all the environmental problems accruing from both the production and consumption of the product. This concept refers to Eco-design. There are several different ways to define eco-design. ISO/TR 14062 defined eco-design as an activity that integrates environmental aspects into product design and development. The integrated activities lead to continual improvement of the environmental performance of the product through technological innovation [15] [16].

In other words, "design has to be responsible in terms of the ecology and the society. And also has to be revolutionary and radical. It must be dedicated to the principle of the minimum effort of the nature, in other words: A minimum inventory guided to the maximum diversity. This means to consume less, to use the things more time, to recycle the materials and probably not to waste paper editing books like this one." [17] According to definitions mentioned above, the following question can be asked;

How eco-design can help the environment by making products smarter; while all products have an impact on the environment during their life-cycle spanning all phases from cradle to grave, such as the use of raw materials and natural resources, manufacturing, packaging, transport, disposal and recycling. [18] Therefore, to answer this question, eco-design aims at reducing the environmental impact of products, including the energy consumption throughout their entire life cycle. Also it aims to improve the environmental performance of products throughout the life-cycle by systematic integration of environmental aspects at a very early stage in the product design. [19]

On the other hand, the rebound effect should be beware of; eco-design requirements shall not lower the functionality of a product, its safety, or have a negative impact on its affordability or consumer's health. A medical device, for example, should not be designed to consume less energy at the cost of quality or patient safety. Eco-design requirements shall remain cost-effective. Excessive administrative burden for manufacturers has to be avoided, as well as negative impacts on affordability for consumers and on industry's competitiveness. Manufacturers can even have a competitive edge with the improved performance of their products [18].

Beside environmental progress can sometimes trigger a "rebound effect" that defeats the initial objectives. For example, the development of greener industrial processes might result in increased consumption of goods or services. Indeed, the lower cost price, made possible by these improved processes, generates additional disposable income that can be spent on more products and services [20] [21].

Stages	Cause	Solutions
1st stage Raw materials	Manufacturing a product means first exploiting raw materials. Extracting and processing these constituent parts consumes natural resources, uses energy and is a source of pollution.	Reduce quantities, choose the most appropriate materials, transform waste into raw materials, and prefer renewable materials and products that use only one type.
2nd stage Production	Manufacturing tends to consume large amounts of energy because of the complex processes it involves.	Optimize production processes; assemble products so they are easy to separate into their different

		components for repair or recycling.
3rd stage Packaging	Bottles, boxes, cans and other packaging currently account for over half the volume of household waste in developed countries.	Concentrate products; reduce the amount and volume of packaging to make savings along the chain, from manufacturing to waste disposal.
4th stage Transportation	Relocated production, cost-cutting and liberalized markets all add up to one thing: products travel thousands of kilometers before being used.	Choose manufacturing sites according to the products' final destination, use combined transport and alternative fuels, optimize loads
5th stage Use	Using products, operating appliances and maintaining them in working order require more or less energy, water, etc. Usually designed to be frequently replaced, goods today are increasingly fragile and hard to repair, which encourages wastefulness and generates waste.	Design functional, energy-saving or autonomous products that are lasting, safe and easy to maintain or repair.
6th stage Disposal & recycling	Worn-out or damaged products are more or less easy to recycle. The multiple components, alloys and other combinations of materials from which they are made render disassembling and processing a complex and costly procedure.	Develop reusable or recyclable products and components

Table 3-1 Some of the ways eco-design can minimize impacts [20] [21]

3.2 Life Cycle Thinking Concept

Life cycle thinking is essential to sustainable development. The main goals of life cycle thinking are to reduce a product's resource use and emissions to the environment as well as improve its socio-economic performance throughout its life cycle. This may facilitate links between the economic, social and environmental dimensions within an organization and throughout its entire value chain. In each life cycle stage there is the potential to reduce resource consumption and improve the performance of products [12]. Product life cycle, which also represents entire life time of product from purchasing materials to produce it until disposal of the product, is a sequence of activity phases, including the creation of a product concept, its development, launch, production, maintenance, maturity, reevaluation, and renewal in the form of a next generation product [22].

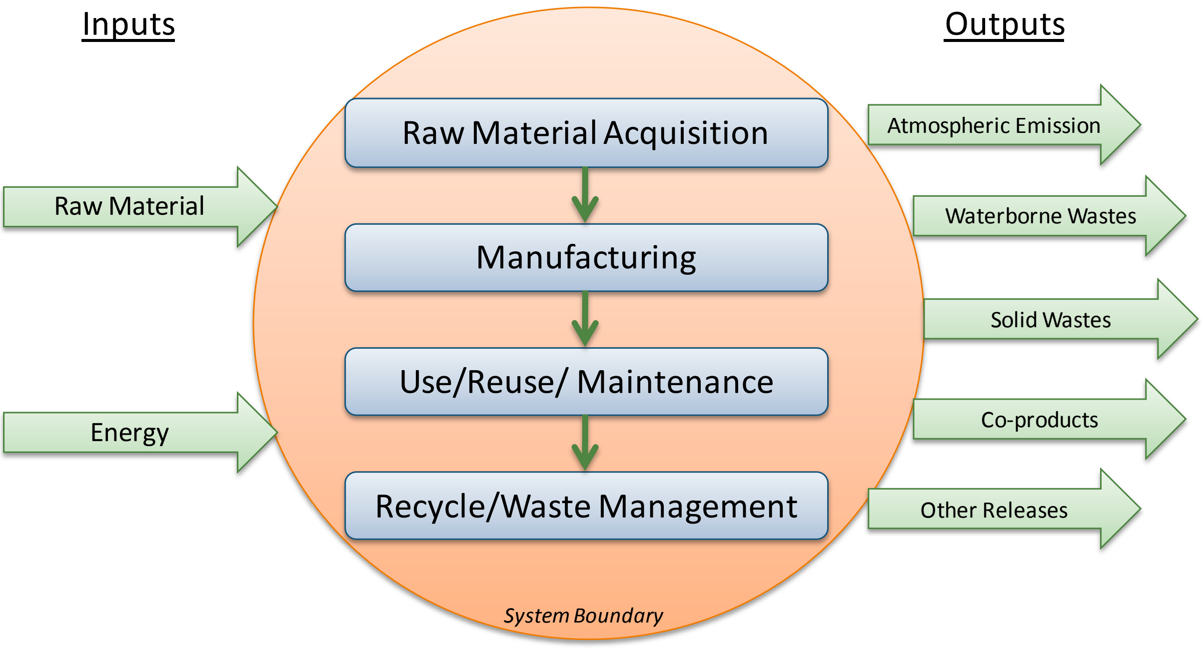


Figure 3-3 General Life Cycle Stages of A product [23]

3.2.1 Life Cycle Assessment

When considering the environmental implications of product and process design, think beyond the cost, technology and functional performance of the design and consider the broader consequences at each stage of the value chain. This fundamental principle, life cycle thinking, has motivated the development of life cycle assessment [22]. Therefore to be able better understanding what is going on during entire life cycle of a product, Life cycle assessment should be used. Life cycle assessment is a much more complex process than other techniques since it is “a cradle to the grave” analysis which reviews the environmental effects of all aspects of the product under investigation. It is concerned with the use of scare resources as well as with the release of hazardous substances, for example. It includes effects which contribute to the global problems, such as global warming, as well as to more local ones such as toxic emissions [23]. “Cradle-to- Grave” begins with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth.

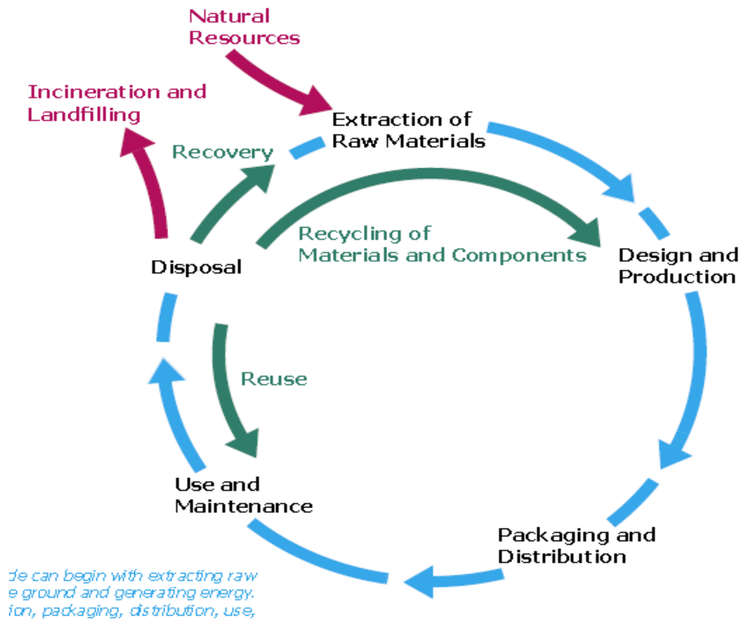


Figure 3-4 Product Life Cycle Concept [12]

LCA evaluates all stages of a product’s life from the perspective that they are interdependent, meaning that one operation leads to the next [5]. LCA is the most commonly used method to identify, quantify, evaluate and prioritize potential environmental impacts directly attributable to sustainability of products. In ISO 14040 standards, LCA is defined as the “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle”. When used in sustainable design, LCA is intended to incorporate environmental factors into early design phases to support the comparison of design options and the identification of improvement potentials, such as for material selections, manufacturing process methods, recycling strategies, and for revealing of environmental profiles [24].

LCA enables the estimation of the cumulative environmental impacts resulting from all stages in the product life cycle, often including impacts not considered in more traditional analyses (e.g., raw material extraction, material transportation, ultimate product disposal, etc.). By including the impacts throughout the product life cycle, LCA provides a comprehensive view of the environmental aspects of the product or process and a more accurate picture of the true environmental trade-offs in product and process selection. The aim of LCA is to suggest more sustainable forms of production and consumption. It uses a scientific approach in which the quantification of effects plays dominant roles [23]. The LCA process is also a systematic, phased approach and consists of four components: Stages of LCA under ISO 14040 are goal definition and scoping, inventory analysis, impact assessment, and interpretation.

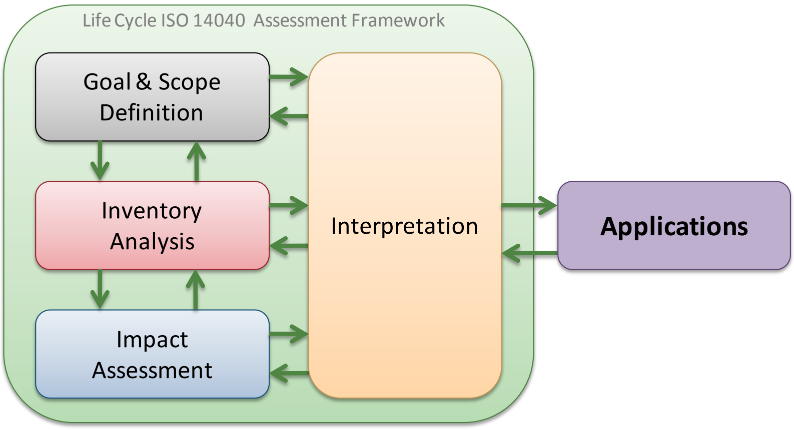


Figure 3-5 Life Cycle ISO Assessment Framework **[25]**

1. Goal Definition and Scoping - State intended application, reasons for doing LCA and to whom the LCA results are communicated; and define system boundary, assessment method, data requirement, functional units, assumptions, limitations, etc. [25]. Define and describe the product, process or activity. Establish the context in which the assessment is to be made and identify the boundaries and environmental effects to be reviewed for the assessment [5].
2. Inventory Analysis - Identify and quantify energy, water and materials usage and environmental releases (e.g., air emissions, solid waste disposal, waste water discharges)[22]. Collect the economic flows and environmental intervention data for each unit process within the system boundary [25].
3. Impact Assessment - Assess the potential human and ecological effects of energy, water, and material usage and the environmental releases identified in the inventory analysis [22]. And also includes,
   a. Section of impact categories and indicator;
   b. Classification of inventory data into impact categories;
   c. Characterization of inventory data within each category, and optionally;
   d. Normalization;
   e. Grouping; and
   f. Weighting the characterized results [25].

4. Interpretation - Evaluate the results of the inventory analysis and impact assessment to select the preferred product, process or service with a clear understanding of the uncertainty and the assumptions used to generate the results [5].

LCA will not determine which product or process is the most cost effective or works the best. Therefore, the information developed in an LCA study should be used as one component of a more comprehensive decision process assessing the trade-offs with cost and performance, e.g., Life Cycle Management which is an integrated framework of concepts and techniques to address environmental, economic, technological, and social aspects of products, services, and organizations, as any other management pattern, is applied on a voluntary basis and can be adapted to the specific needs and characteristics of individual organizations [5].

Life Cycle Management (LCM) is a product management system aiming to minimize environmental and socioeconomic burdens associated with an organization's product or product portfolio during its entire life cycle and value chain. LCM is making life cycle thinking and product sustainability operational for businesses through the continuous improvements of product systems, and LCM supports the business assimilation of policies such as integrated product policies [12].

When a product should be considered only, Product lifecycle management aspects should be used in order to manage a product through its entire lifecycle, from the conception to the disposal or recycle of the product. PLM helps a business reduce the use of time, materials, and energy by using a shared information core. In addition, it is difficult to achieve efficient green initiatives by optimizing individual parts of a product. It is essential to design the product as a whole from planning, through design and manufacturing, to usage, maintenance and reuse/recycling/disposal [26].

3.2.2 Life Cycle Cost LCC

Life cycle costs (LCC) are cradle to grave costs summarized as an economics model of evaluating alternatives for equipment and projects. The LCC economic model provides better assessment of long-term cost effectiveness of projects than can be obtained with only first costs decisions.

LCC are summations of cost estimates from inception to disposal for both equipment and projects as determined by an analytical study and estimate of total costs experienced in annual time increments during the project life with consideration for the time value of money. LCC is an economic model over the project life span.

Businesses must summarize LCC results in net present value (NPV) format considering depreciation, taxes and the time value of money. Government organizations do not require inclusion of depreciation or taxes for LCC decisions but they must consider the time value of money. [27]

3.2.3 Why use LCC?

LCC helps change provincial perspectives for business issues with emphasis on enhancing economic competitiveness by working for the lowest long term cost of ownership which is not an easy answer to obtain. Consider these typical problems and conflicts observed in most companies:

- Project Engineering wants to minimize capital costs as the only criteria,
- Maintenance Engineering wants to minimize repair hours as the only criteria,
- Production wants to maximize uptime hours as the only criteria,
- Reliability Engineering wants to avoid failures as the only criteria,
- Accounting wants to maximize project net present value as the only criteria, and
- Shareholders want to increase stockholder wealth as the only criteria.

In general, consider a typical discount value of 12% which is neither very low nor very high for calculations [27]

4 Total Performance Analysis of a Product with Life Cycle Consideration

Environmental consciousness has been growing in recent years and product life cycle design that aims to maximize utility value (UV) while minimizing environmental load and cost simultaneously. Therefore to evaluate eco-efficiency of products, the academicians and authors have proposed a new evaluation method named 'Total Performance Analysis' [28].

This study propose a total performance analysis method that evaluates a product from environmental and economic viewpoints simultaneously, considering the change in product values over time, so that a designer can easily find improvement targets in a product's composition and life cycle [29] [30] [31].

In general, there exist significant uncertainties in the product life cycle. Product preference and operation conditions differ from user to user, causing significant uncertainties in product conditions, lifetime and the amount of available resources for component reuse and recycling, which are important factors for a designer in determining adequate life cycle options (LCOPs) (e.g., reuse, recycling, landfill, etc.) for products and their components. Therefore, the design method for the product life cycle should be robust and tolerant against these uncertainties [30] [31].

The objective of this study is to use a practical design method that derives an adequate solution for maximizing the value of a product while minimizing its resulting environmental load and cost throughout its life cycle considering various future uncertainties. In the first step of this method, the environmental and economic performance throughout the entire life cycle of a product is evaluated using the total performance indicator (TPI), which represents the balance of consumer UV and the resulting environmental load and cost. [29] [30] [32]

This TPA method will be explained based on researchers' academic papers which they have been published in recent years. All the formulas and assumptions which are created and will be used in this study are also mentioned in every academic paper that those researchers have already done. Those are the references for academic papers [28][29][30][31][32][33], and more detailed information and examples about TPA methodology and its mathematical logic behind it can be found inside those papers. Following sections will be discussed with taking into account these academic papers, because there no broad literature about TPA methodology and it is a new invented practical method which is used to be helpful companies or other researchers to understand the effects of the product that they are working on.

4.1 Formulation of TPI for product

Since all products are produced to satisfy consumer needs, total performance throughout the product life cycle is evaluated as the balance of consumer UV and its resulting environmental load and cost throughout the entire life cycle. TPI is defined as follows:

$$TPI = \frac{UV}{\sqrt{LCE.LCC}} \quad (1)$$

Where LCE and LCC denote;

LCE: Environmental load throughout entire life cycle,

LCC: Life cycle cost, throughout the entire life cycle, respectively.

4.1.1 Formulation of UV

The UV of a product rises as the product’s functional performance increases and the longer it is used. Thus, UV is defined as the time integral of product value, assuming that the product value is strongly correlated with its functional performance.

$$UV = \int_{st}^{st+lt} V(t)dt \quad (2)$$

Where st, tt and V(t) denote,

st: beginning of the product use

lt: lifetime of a product

V(t): product value at time t, respectively.

According to previous researches about product value, product value at time t can be allocated to its dominant functional requirements (FR) given as follows: Before to calculation, functional requirements from product and components of product are defined then calculation is performed.

$$V(t) = \sum_i V_i(t) \quad (3)$$

$$V_i(t) = \sum_t w_t(t)FR_i(t) \quad (4)$$

where i, $V_i(t)$, $w_i(t)$ and $FR_i(t)$ denote the index of FRs, product value allocated to FR_i, weighted factor for FR_i and functional performance of FR_i at time t, respectively. Weighted factor for each FR represents its consumer importance. Those with high importance have great potential for improving product value. In this study, it is assumed that product value is measured by market price.

In addition to that, previous research on TPA assumed that the product value is strongly correlated with its functional performance. The cost and environmental load of a product are correlated with its components. Therefore, to evaluate the total performance of each component and FR, the relationships between FRs and components must be determined so that a designer can convert these values between them. To this end, the Quality Function Deployment (QFD) technique is employed. Based on the relationships between FRs and components, partial values, costs, and environmental loads of each FR and component are calculated so as to calculate their total performance [29].

QFD is a systematic method widely used for translating true customer needs of product/service into technical requirements for design, development, and delivery of a product, by correlating these items with each other. Following figure 4-1 represents the relationship between FRs and components as the relational matrix $m_{i,j}$. The relational matrix m_{ij} of a laptop computer represents the strength of the relationship between the FRs and components. The degree of the strength is expressed as the digit numbers 0, 1, 3 and 9, which represents no relationship, weak relationship, intermediate relationship, and strong relationship, respectively.

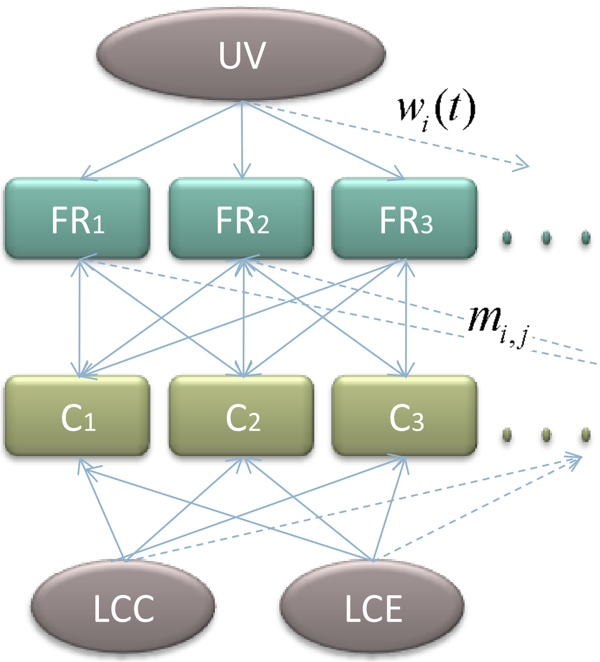


Figure 4-1 Relationships among Product Values, Costs and Environmental Load [29**]**

To be able to give visual example; in the following example, it can be seen that performance of ‘FR1, FR2 are strongly related with com1 and com2, respectively. in the following table FR1 and Com1 relation is shown as 9 and it represents as $m_{i,j}$.

			Components						**Total**
			Com1	Com2	Com3	Com4	Com5	Com6	
FRS	FR1	.	**9**	**3**	**1**		**1**	**1**	**15**
	FR2	.	**3**	**9**	**1**				**13**
	FR3	.		**3**	**9**	**3**			**15**
	FR4	.				**1**	**3**	**9**	**13**
	FR5	.				**9**			**9**
Total			**12**	**15**	**11**	**13**	**4**	**10**	

Table 4-1 Components & FRs Relation Matrix

The transformation matrix $m'_{i,j}$ and $m''_{i,j}$ which map LCC and LCE of components to those of FRs and LCV of FRs to those of components, respectively, are calculated in the following equations:

$$m'_{i,j} = \frac{m_{i,j}}{\sum_i m_{i,j}} \quad (5)$$

$$m''_{i,j} = \frac{m_{i,j}}{\sum_j m_{i,j}} \quad (6)$$

where $m'_{i,j}$ represents the ratio responsibility of FRi for component j and $m''_{i,j}$ represents the ratio of component j contributions to FRi..

After each ratio has been defined, value of components; LCC and LCE of FRs are calculated according to following formula;

$$UV_{k,j} = \sum_i m''_{i,j} UV_{k,i} \quad (7)$$

$$LCC_{k,i} = \sum_j m'_{i,j} LCC_{k,j} \quad (8)$$

$$LCE_{k,i} = \sum_j m'_{i,j} LCE_{k,j} \quad (9)$$

Where $LCV_{k,j}$, $LCC_{k,i}$, $LCC_{k,j}$, $LCE_{k,i}$ and $LCE_{k,j}$ denote LCV of components j at life-cycle stage k, LCC of components j and FR_i, LCE of components and FR_i, respectively.

Since UV is defined as the time integral of product value, time variation of product value should be estimated. During time almost every product loss its value and these value deteriorates due to the following causes:

- Physical causes

- Value causes

Physical causes include product failure and degradation due to aging and wear. Value causes include obsolescence of product FRs (including aesthetic quality). The value of products such as computers or mobile phones deteriorates too fast due to very rapid technological innovations. Therefore, both types of causes should be estimated at the same time. Since the value of a product is given as the weighed sum of its functional performance, value deterioration over time is given by decreases in functional performance and importance.

4.1.1.1 Deterioration due to physical causes

Here, deterioration due to physical causes is represented as a decrease in functional performance $FR_i(t)$. $FR_i(t)$ is estimated using empirical data on the deterioration of similar products at their use stage by applying reliability theory. For the sake of simplicity, deterioration of $FR_i(t)$ is expressed as the following linear equation:

$$FR_i(t) = c_i(t - st) + d_i \quad (10)$$

Where c_i and d_i denote;

c_i: Deterioration rate

d_i: Initial performance of FR_i

Functional Requirements		**Functional Parameters**	***Decrease rate (c_i)**	**Specifications in Life cycle (d_i)**	**Marginal Lifetime**
FR1	.	·		[kg]	[month]
FR2	.				
FR3	.				
FR4					
FR5					
.					

Table 4-2 Specifications of FRs

This table is filled at the beginning of Total performance analyze.

4.1.1.2 Deterioration due to value causes

Another cause of product value deterioration is obsolescence of FRs. Assuming that a set of dominant product FRs does not change, the obsolescence of each FR is expressed by the decrease in importance of each FR given as follows:

$$w_i(t) = a_i t + b_i \quad (11)$$

Where a_i and b_i denote;

a_i: Obsolescence rate

b_i: Initial importance of FR_i

These values can be estimated by regression analysis on $w_i(t)$ at various times t. In addition to be able to understand the obsolescence rate, the value of the each component is taken in two different years and the change rate between these years is found and it shows the obsolescence rate.

Weighting Factors for FRs	**W1**	**W2**	**W3**	**W4**	**W5**
Unit					
Initial importance					
Month-2006					
Month-2009					

Table 4-3 Differences between Weighting Factors for FRs

With equations mentioned above, the deterioration of each FR value is estimated as shown in Figure 4-2. The change in product value over time is calculated as the sum of partial values allocated to its FRs as given by equations and UV of a product is calculated as the time integral of product value over all product use stages [29].

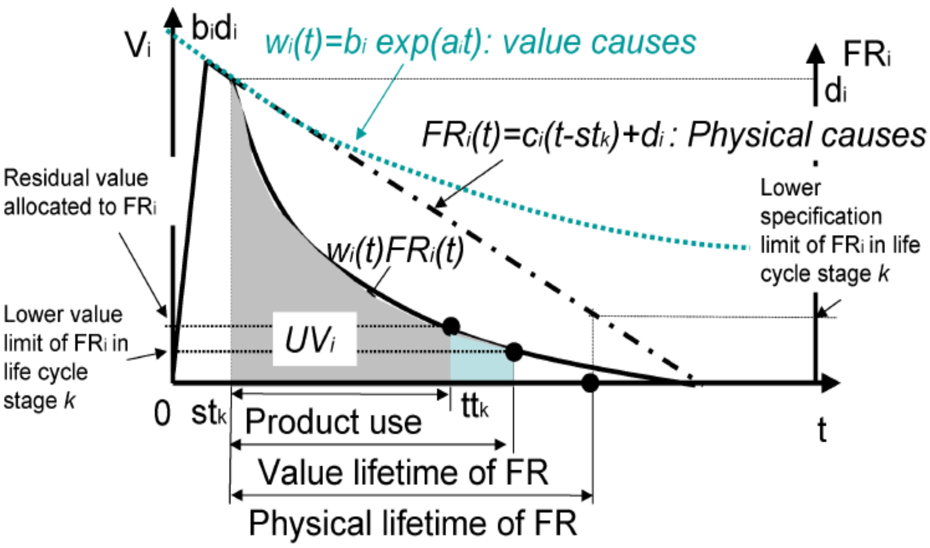


Figure 4-2 Deterioration of Partial Values allocated to FR

4.1.2 Formulation of LCE and LCC

In general, different performance levels imply different sets of components with different environmental load and cost. Thus, LCE and LCC of a product should be allocated to their corresponding components in order to calculate those of products with different performance levels. Focusing on energy-using products, the longer a product is used, the higher its LCE and LCC become. Thus, the simplest representation of LCE and LCC of a product is given as follows:

$$LCE = \sum_j LCE_j \tag{12}$$

$$LCC = \sum_j LCC_j \tag{13}$$

$$LCE_j = e_j.lt \tag{14}$$

$$LCC_j = g_j.lt \tag{15}$$

where j and lt denote the index for component and product lifetime, respectively. e_j and g_j denote partial environmental load and cost allocated to each component per unit time during the product use stage.

LCE and LCC of a product can be calculated by conventional life cycle assessment (LCA) and life cycle costing (LCC) tools, respectively. These values are allocated to each component by referring to the material and energy consumption of each component at each life cycle stage to calculate the above parameter values.

Components		**Estimated Use Time**	**LCE [kgCO$_2$] / unit time**	**LCC [euro]**
Com1				
Com2				
Com3				
Com4				
Com5				
Com6				

Table 4-4 LCE & LCC of Components

Since the product value decreases as given in equations (5) and (6) while the product LCE and LCC increase as product lifetime increases, there exists an optimal lifetime (olt) that maximizes the total performance of a product, as shown in **Figure 4-3**. Therefore, from the viewpoint of TPI, a product is ideally utilized when it is continued to be used for its optimal lifetime.

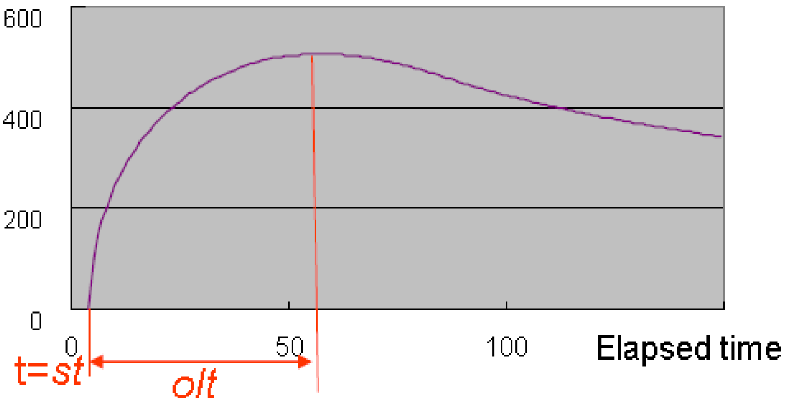


Figure 4-3 Time variation in TPI

4.2 Formulation of TPI for process and manufacturing system

1. TPI for process: To evaluate the efficiencies of manufacturing processes or systems, the same idea can be applied. Because the design engineers and manufacturers have long histories of serious effort to reduce cost of manufacturing, they might not accept an index which does not evaluate cost and functionality. The equation expresses the balance of the product value created by the manufacturing process and cost and environmental impact necessary to fabricate "one" product [30][31][32][33].

   $$\text{Process TPI} = \frac{UV}{\sqrt{\sum_{i=1}^{i=n} PE_i \sum_{i=1}^{i=n} PC_i}} \qquad (16)$$

   PC_i= cost of individual process

   PE_i= environmental impact of the individual process

   n: number or process

2. TPI for manufacturing system: The final extension shown is to evaluate system efficiency by the same idea. The equation means that the efficiency of the system is defined by sum total of product values fabricated by the manufacturing system within a certain period of time. Cost and environmental impact during the corresponding period are also considered. Cost and environmental impact to build the manufacturing system itself (so-called initial cost and initial environmental impact) should be divided by lifetime duration of the manufacturing system, and assigned to PC and PE in the equation. However, it is not easy to quantitatively calculate, because when the system is for "variety-and-variant production" or "one-off production", and produces some

different products, it is necessary to quantify all the value of the different products. But, fortunately, when the product of the manufacturing system is always the same, the system TPI equation can be simplified to. [30][31][32][33]

$$\text{System TPI} = \frac{\int_{to}^{to+T} \sum_{i=l}^{i=m} \Delta UV_i\, dt}{\sqrt{\int_{to}^{to+T} \sum_{i=k}^{i=l} PE_i\, dt \cdot \int_{to}^{to+T} \sum_{i=k}^{i=l} PC_i\, dt}} \tag{17}$$

T: period of estimation

m: kinds of product,

k: number of the first process of in the system

l: number of the first process of in the system

Or

$$\text{System TPI} = \frac{Tp}{\sqrt{\frac{(\frac{C_m}{L} + C_L)}{1600} \cdot \sqrt{E_e + \frac{E_m}{L \times 1600}}}} \tag{18}$$

Tp: throughput of the system (number of the product produced in an hour),

C_m: initial total cost of the machines (money)

C_L: labour cost (money/year)

L: life of the system (year)

E_e: environmental impact caused by electricity

E_m: environmental impact caused by the machines

The hours operated per year is assumed to 1600. Instead of the utility value of a product defined in the original index, throughput of the manufacturing system; "Tp" is introduced. By defining the throughput by number of products fabricated within an hour, the total performance indicator of the manufacturing system can be calculated. "C" can be calculated by using a sum total of machine costs, labor costs and other costs during the corresponding time. [30][31][32][33]

4.3 Business strategy and related control factors

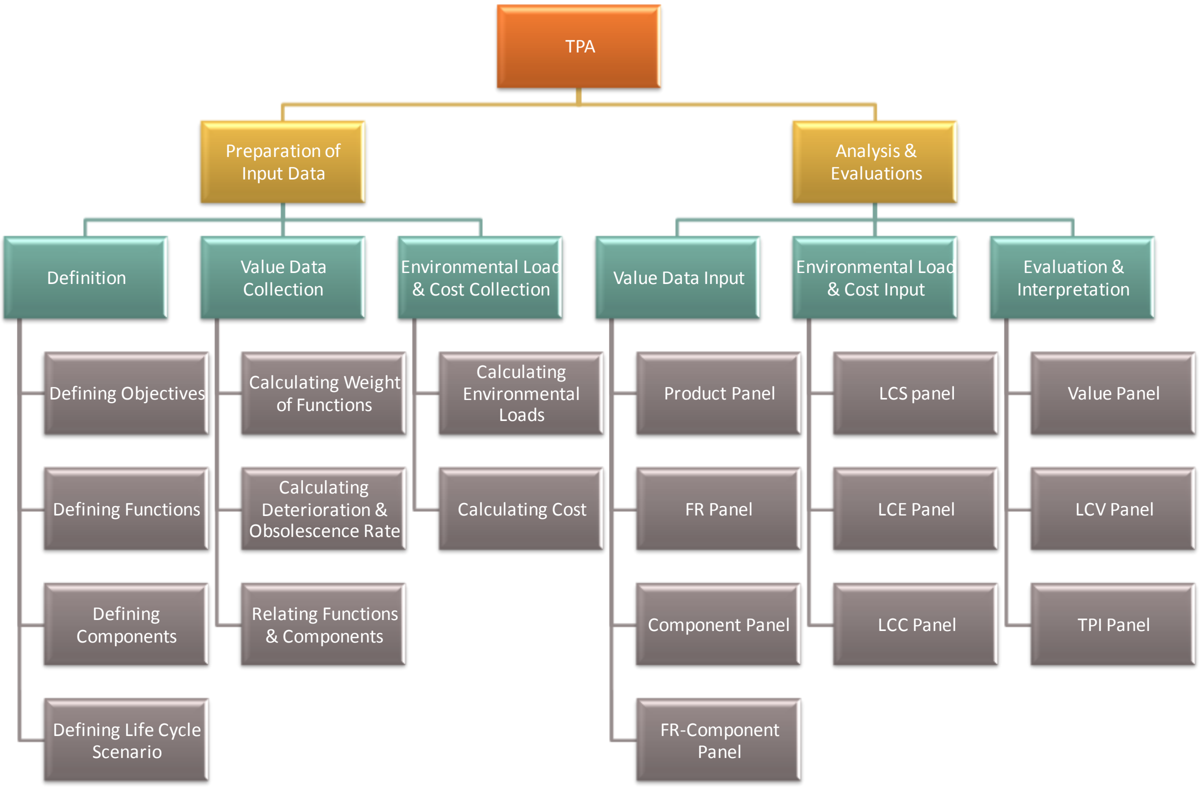
In optimization of TPI, the control factors and dominant noise factors change when a designer employs different business strategies. In this study, three types of business strategies are identified as follows:

1. **Product sales strategy:** The first type of business strategy is conventional product sales, where a manufacturer only sells its products and is not concerned about the products after they are sold. In this strategy, a manufacturer can only control the initial specifications (di) and the resulting environmental load and cost at the production stage.

2. **Lease and rental strategy:** The second type of business strategy is lease and rental. In this strategy, a manufacturer lends its products to consumers instead of selling them. The manufacturer can control the lifetime of a product (lt), in addition to the control factors in the product sales strategy. Examples of this strategy include some manufacturers of photocopiers, etc.
3. **Closed-loop manufacturing strategy:** The third type of business strategy is closed-loop manufacturing, where products are completely collected at the end of the product use stage and sent back to the manufacturer so as to promote product reuse and recycling. Manufacturers of one-time-use cameras employ this strategy to enhance their environmental and economic performance simultaneously. Because the designer can control LCOPs for each component in this strategy, LCE and LCC at production and EOL treatment stages should be modified by considering the potential reduction by reuse and recycling as shown in equations. [28][29]

5 TPA working Flow

5.1 TPA framework



5.2 Flow of Total Performance Design

Flow of the optimisation of the product TPI is summarised as follows: these steps are created to show main points of TPA methodology, however to complete the analyse each section of TPA framework should be covered.

Step 1: Product definitions: Prior to optimisation, dominant FRs and their corresponding components should be identified.

Step 2: Selection of business strategy and determining control factors: The first step of optimisation is selection of business strategy which determines the possible set of control factors which are important parameters inside TPA formulation When the number of control factors is too large for determining their optimal values at the same time, the designer should screen out the most influential factors among them.

Step 3: Estimation of UV, LCE and LCC UV, LCE and LCC of a product are estimated by conjoint analysis, LCA and LCC methods. From these results, original estimate parameters a_i, b_i, c_i, d_i, e_i, f_i, g_i and hi are determined.

Step 4: Incorporation of noise factors: Considering the uncertainties in the product life cycle, the levels of noise factors are determined and incorporated into the original estimate calculated in Step 3. Product lifetime (lt), collection ratio (rc) and yield ratio (reuse rg j and) rec rg j are also estimated in this step, if their values are not determined in Step 2.

Step 5: Optimization by control factors: Based on the number of control factors and their alternative levels determined in Step 2, an adequate orthogonal array (OA) is selected for reducing the number of calculation configurations. The average S/N ratio and the TPI for each level of each control factor are calculated from the results of calculations to separate out its effect on TPI variation and mean TPI. Based on these values, the designer selects adequate levels of control factors that minimize the variation of TPI while maximizing the mean TPI. Basically, signal-to-noise (S/N) ratio, which is the ratio of the mean (signal) to the standard deviation (noise), is used as a design metric for the optimization. In this study, the output value is TPI of a product. Considering tow noise parameters arrangements S/N ratio n in each design parameter setting is given as follows;

$$n = 10\log\left(\frac{\mu}{\sigma}\right)^2 \tag{19}$$

$$\mu = \frac{TPI_{max,1} + TPI_{min,2}}{2} \tag{20}$$

$$\sigma^2 = (TPI_{max,1} - \mu)^2 + (TPI_{min,2} - \mu)^2 \tag{21}$$

Where, μ, σ, TPImax,1 and TPImin,1 denote the mean and standard deviation of TPI over conditions 1 and 2. [28][29][33]

5.3 Application of total performance to the life-cycle design of a product

Based on the total performance of a product, components, and FRs, a designer can find out the improvement potentials of the total performance of a product in two aspects:

- the reduction of cost and environmental load
- The enhancement of product value.

Following Table 5-1 summarizes effective design options for each FR and component to enhance total performance of a product. Improvement targets and design options.

	Reduction of cost & E.L		Enhancement of Value		
Design Options	Components with low use-phase perf.	Components with low production perf.	FRs with high TPI	FRs with high obsolescence rate	FRs with high deterioration rate
Reuse	X				
Recycling		X			
Reduce		X			
Prolongment of physical life					X
Upgrading				X	
Enhancement of Functionality			X		

Table 5-1 Design & EOL Options

5.3.1 Reduction of cost and environmental load

From the viewpoint of reducing costs and environmental load, the components with low total performance should be focused on first. Reusing components with low use phase performance can effectively improve their total performance because they have large residual value at the end of product use stages that should be minimized. To improve the total performance of components with low production performance, reduction of material and energy consumption through the entire life cycle should be addressed. Recycling these components may improve their total performance through a reduction in materials and energy usage for their production.

5.3.2 Enhancement of product life-cycle values

To enhance product life-cycle value, FRs with high total performance values should be improved because they have a great potential to enhance product values under the assumption that the value of each FR increases proportionally to its resulting cost and environmental load through the entire life cycle in its location. Proper upgrading of FRs with high obsolescence rates and the extension of the physical lifetimes of those with high deterioration rates are also effective for enhancement of product life-cycle values. [29]

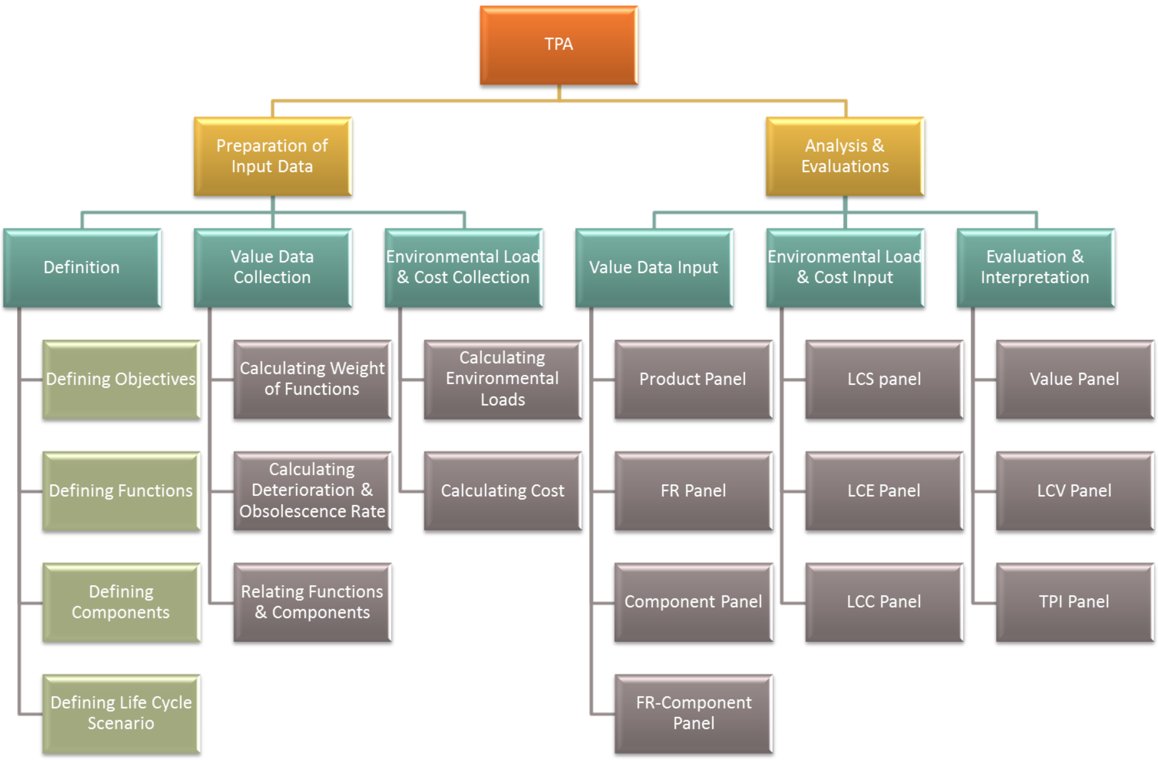
6 TPA Example

6.1 Product: Multi Stage Centrifugal Pump

The objective of this study is to propose a practical design method that derives an adequate solution for maximizing the value of a Multi Stage Centrifugal Pump while minimizing its resulting environmental load and cost throughout its life cycle considering various future uncertainties. The reference for assumptions is Investigation on Normalization of Environmentally Conscious Design, (Environmentally Conscious Design Normalization Report 2003), The Japan Machinery Federation. And the reference for the data is Advanced Manufacturing Research Institute Japan.

It is better to remind that product preference and operation conditions differ from user to user, causing significant uncertainties in product conditions, lifetime and the amount of available resources for component reuse and recycling, which are important factors for a designer in determining adequate life cycle options (LCOPs) (e.g., reuse, recycling, landfill, etc.) for products and their components. Under these circumstances different factors create different results and the improvement ideas might be different than other one.

6.1.1 Preparation of Input Data Section Part 1: Definition



Product definitions:

Centrifugal pumps are commonly used to move liquids through a piping system. Centrifugal pumps are used for large discharge through smaller heads. A centrifugal pump contains two or more impellers are called a multistage centrifugal pump. The impellers may be mounted on the same shaft or on different shafts. If we need higher pressure at the outlet we can connect impellers in series. If we need a higher flow output we can connect impellers in parallel.

Defining Functions:

Its main function is delivering water therefore in this study two main functional requirements are taken into consideration On the other hand there are other functional requirements like “using small space” however the result of regression analysis suggested that most of price explained by “delivering water”. Functional requirements are;

- Deliver large quantity of water (FR0)   0.1 [m^3/min]
  - When it becomes lower than 0.05 [m^3/min] by deterioration, this function losses its functionality. (this is an assumption for the sake of simplicity)
- Deliver water in high pressure (FR1)   43.5 [m]
  - When it becomes lower than 27.5 [m] by deterioration this function losses its functionality (this is an assumption for the sake of simplicity)

Defining Components:

Components are **casing, turbine, rotary shaft, bearing, shaft seal, base, and motor**. These components have strong relations with functional requirements of the product. But the relations are not the same, the relations between components and functional requirements will be explained in following context.

Co	Component Specifications				
ID		Weight	Volume	Lifetime	EoL Treatment
0	**Casing**	12	12	100	Landfill
1	**Turbine**	12	21	120	Landfill
2	**Rotary Shaft**	21	21	120	Landfill
3	**Bearing**	32	32	120	Landfill
4	**Shaft Sheel**	32	23	100	Landfill
5	**Base**	43	43	343	Landfill
6	**Motor**	32	32	100	Landfill

Table 6-1 Components Specification of Pump Example

Defining Life Cycle Scenarios:

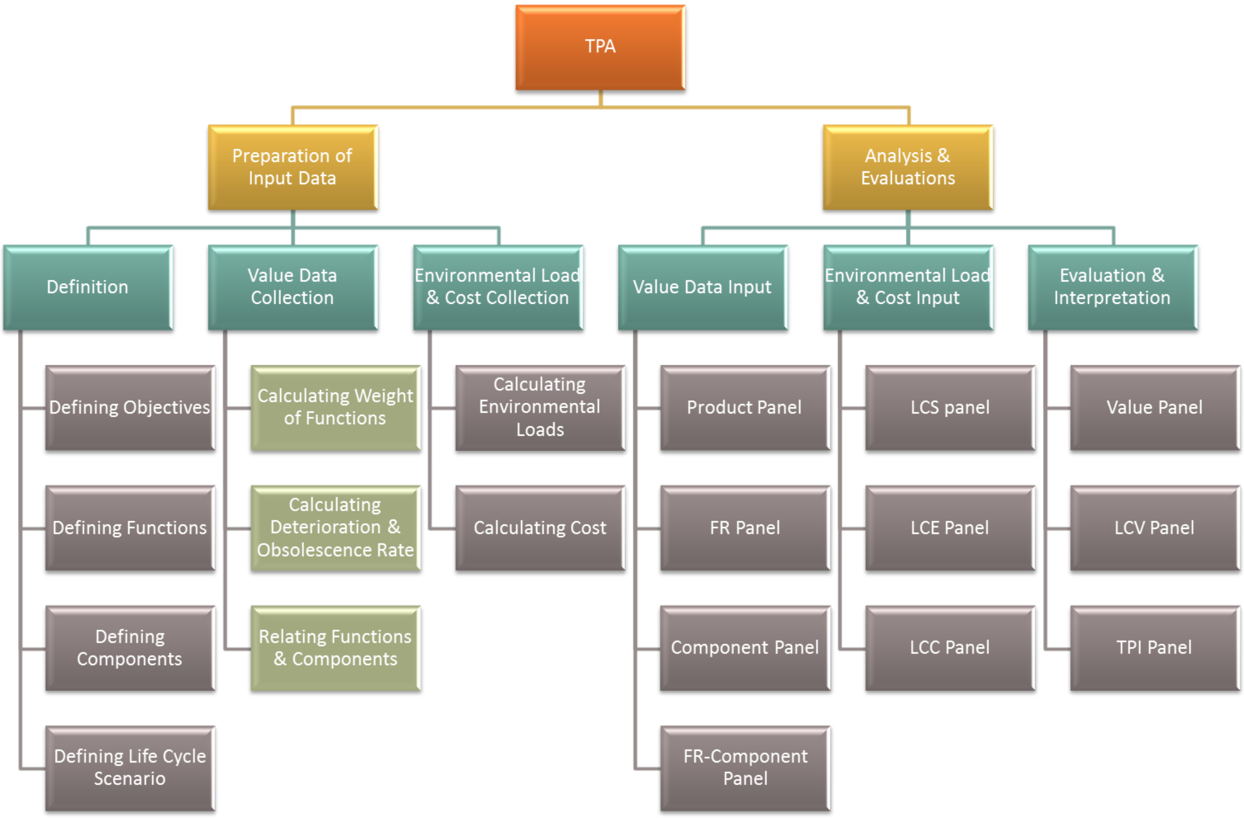
To be able to make better TPA analyze, the life cycle scenarios should be determined and most of the case the components of a product are used for determining the product life cycle scenarios and in this case, the life cycle of multistage centrifugal pump is defined as in table.

LCS				
ID	Name	**LCS Type**	**Starting Time**	**Length**
0	LCS 0 Production	Production	0	1
1	LCS 1 Distribution	Distribution	1	1
2	LCS 2 Use	Use	2	90
3	LCS 3 Collection	Collection	92	1
4	LCS 4 EOL	EOL	93	1

Table 6-2 Life Cycle Stage of Pump Example

6.1.2 Preparation of Input Data Section Part 2: Value Data Collection

In this part of this method, the value data collection throughout the entire life cycle of a product is done. The aim of this part is to understand how functions are changing overtime and its reasons. The time intervals effects directly to final outcomes because all the rates and values are correlated to time and companies product usage and disposal strategy.



Calculating Weight of Function

To be able to start calculating weight of each functional requirement, an analyze should be done, in this example, to find initial importance of "Quantity of Delivery" and "Pump Head" multiple regression analysis between retail prices and performances was used. It is better to mention that there is strong correlation between retail prices and performances.

The outcome is;

$$V(0) = 362.555{,}62 \times FR_0(0) + 2.799{,}23 \times FR_1(0) + 23.719{,}28$$

- **362.555,62** is importance of Quantity of Delivery
- **2.799,23** is importance of Pump Head
- **23.719,28** is the sum of **v**alues of other functions and are neglected (10-20%)

Type	Retail Price [JPY]	Estimate Value by Regression [JPY]	Value of Quantity of Delivery [JPY]	Value of Pump Head [JPY]	Quantity of Delivery [m3/min]	Head [m]
65MS365.5	271.986	259.690	90.639	145.332	0,25	51,9
80MS267.5	287.103	295.872	145.022	127.130	0,40	45,4
50MS363.7	205.375	217.819	58.009	136.091	0,16	48,6
65MS263.7	214.590	211.246	90.639	96.888	0,25	34,6
50MS262.2	171.467	166.295	58.009	84.567	0,16	30,2
40MS362.2	164.782	181.785	36.256	121.810	0,10	43,5
65MS367.5	284.453	287.412	90.639	173.054	0,25	61,8
65MS265.5	227.840	229.728	90.639	115.370	0,25	41,2
40MS563.7	258.736	262.992	36.256	203.017	0,10	72,5
50MS263.7	179.778	172.456	58.009	90.727	0,16	32,4
40MS261,5	143.341	141.182	36.256	81.207	0,10	29,0
50MS465.5	279.997	263.183	58.009	181.455	0,16	64,8
40MS463.7	222.600	222.388	36.256	162.413	0,10	58,0

Table 6-3 Price of Different Pump Products in Market

Calculating Value of Pump

When trying to calculate the value of a product, the assumption is needed and in this case, the relationship between price and specification of a product is considered as it does not change so much in several years. According to this assumption the values are shown as in Table. To calculate obsolescence and deterioration rate, there is another consideration which takes into account different years, however in this case, the values don't change in several years.

FR	Functional Requirement								
ID	**Name**	**Obs. Rate**	**Init.Imp.**	**Det. Rate**	**Init.Spec.1**	**Init. Spec 2**	**Max. Lifetime**	**Low Spec Lim**	**Low Value Lim**
0	**Pump Dischare**	-1000	362555	-0,0001	0,1	0,1	500	0,05	0,05
1	**Pump Head**	-1	2800	-0,18	43,5	80	90	27,5	0

Table 6-4 Specifications of FRs of Pump Example

Defining Relations between Functional Requirements and Components

After determining the obsolescence and deterioration rates, the relations between FRs and Components should be analyzed. The relation matrix was filled by the people who are expert in their field, on the other hand this kind of matrix consist inconsistency because of human error. The values should be given in a range; in recommendation part it will be explained. Correlation matrix is used to convert the data from FRs to components or vice versa. The relation matrix is;

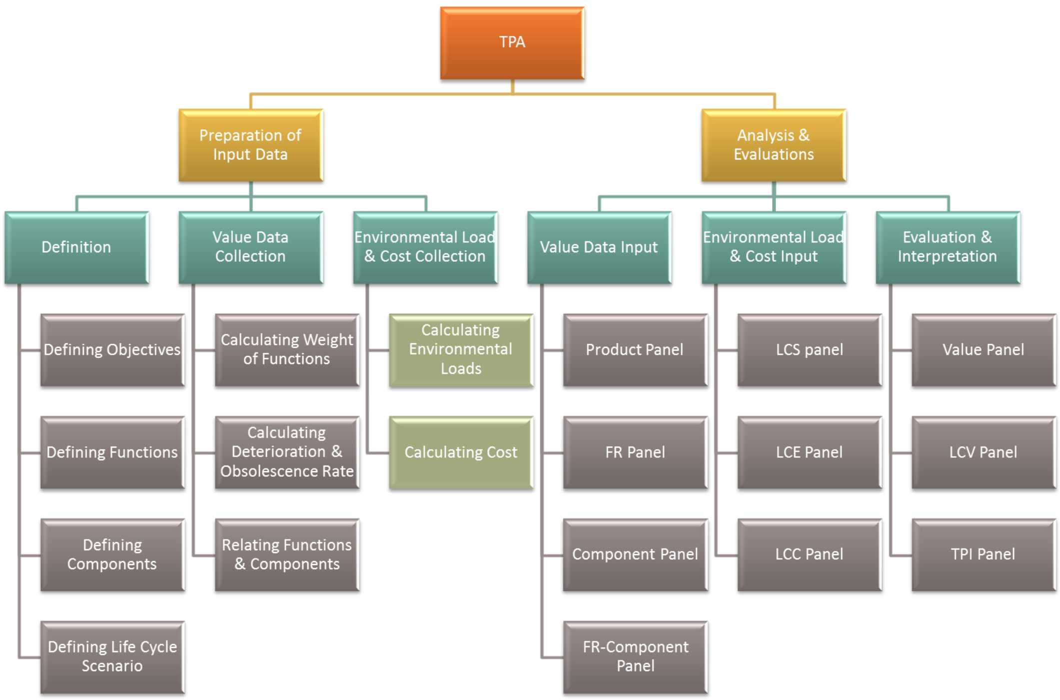
	Mi,j	FR-Co Relation								Components							
		Co 0 Casing	Co 1 Turbine	Co 2 Rotary Shaft	Co 3 Bearing	Co 4 Shaft Sheel	Co 5 Base	Co 6 Motor	Total	Co 0	Co 1	Co 2	Co 3	Co 4	Co 5	Co 6	Total
FR	Quantity of Delivery	1	9	1	1	0	1	9	22	0,05	0,41	0,05	0,05	0,00	0,05	0,41	1
FR	Pump Head	9	3	1	0	3	0	1	17	0,53	0,18	0,06	0,00	0,18	0,00	0,06	1
	Total	**10**	**12**	**2**	**1**	**3**	**1**	**10**									

		Co 0 Casing	Co 1 Turbine	Co 2 Rotary Shaft	Co 3 Bearing	Co 4 Shaft Sheel	Co 5 Base	Co 6 Motor
FR	Quantity of Delivery	0,1	0,75	0,5	1	0	1	0,9
FR	Pump Head	0,9	0,25	0,5	0	1	0	0,1
	Total	**1**	**1**	**1**	**1**	**1**	**1**	**1**

Table 6-5 Relation Matrix of Pump Example

6.1.3 Preparation of Input Data Section Part 3: Environmental Load and Cost Collection

In this part of this method, the environmental and economic performance throughout the entire life cycle of a product are collected to be evaluated through the total performance indicator (TPI), which represents the balance of consumer UV and the resulting environmental load and cost.



Environmental Load of each Component:

The data for environmental load were calculated by AIST in LCA study of pumps.

Environmental Load [kg-CO2]									
LCS Type	Starting Time	Co 0 Casing	Co 1 Turbine	Co 2 Rotary Shaft	Co 3 Bearing	Co 4 Shaft Sheel	Co 5 Base	Co 6 Motor	Total
Production	0	88	24,2	4,4	13,2	0	41,8	48,4	220
Distribution	1	8	0,6	0,6	1,2	0,2	4,8	4,6	20
Use	2	0	0	0	700	0	0	12000	12700
Collection	92	16	1,2	1,2	2,4	0,4	9,6	9,2	40
EOL	93	0	0	0	0	0	0	0	0

Table 6-6 Environmental Load of Components of Pump Example

The highlights of the LCA study are;

- Environmental load of the production stage is allocated proportionately to energy cost.
- Motor is responsible for most environmental load in the use stage.
- Environmental load of distribution and collection is allocated proportionately to weight of each component
- No CO2 is emitted in the End-of-life stage because treatment of this product is assumed to be landfill.

The following table shows the converted environmental load of FRs from LCE of components

Environmental Load [kg-CO2]					
ID	LCS Type	Starting Time	FR 0 Pump Discharge	FR 1 Pump Head	Total
0	Production	0	127,71	92,29	220
1	Distribution	1	11,69	8,31	20
2	Use	2	11500	1200	12700
3	Collection	92	23,38	16,62	40
4	EOL	93	0	0	0

Table 6-7 Environmental Load of FRs of Pump Example

Cost of each Component:

Production cost is estimated from the price of each component and distribution, collection and disposal costs are allocated proportionately to weight.

LCC [kJPY]										
ID	LCS Type	Co 0 Casing	Co 1 Turbine	Co 2 Rotary Shaft	Co 3 Bearing	Co 4 Shaft Sheel	Co 5 Base	Co 6 Motor	Total	Total
0	Production	0	30	10	10	5	5	20	40	120
1	Distribution	1	4,4	0,33	0,33	0,66	0,11	2,64	2,53	11
2	Use	2	0	0	0	80	0	0	440	520
3	Collection	92	8,92	0,67	0,67	1,34	0,22	5,35	5,129	22,299
4	EOL	93	0,35	0,028	0,028	0,028	0,014	0,091	0,154	0,693

Table 6-8 LCC of Components of Pump Example

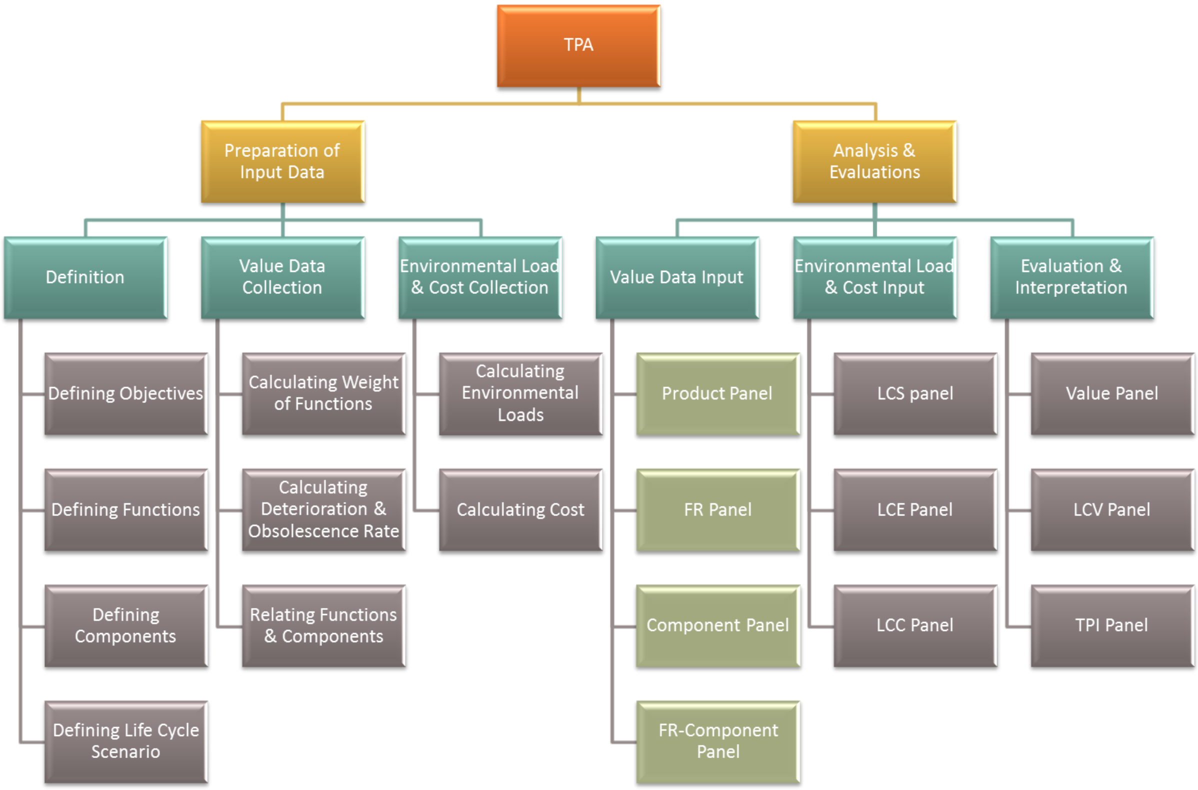
The following table shows the converted environmental load of FRs from LCE of components

LCC [kJPY]					
ID	**LCS Type**	**Starting Time**	**FR 0 Pump Dischare**	**FR 1 Pump Head**	**Total**
0	**Production**	0	76,50	43,50	120
1	**Distribution**	1	6,43	4,57	11
2	**Use**	2	476,00	44,00	520
3	**Collection**	92	13,04	9,26	22,3
4	**EOL**	93	0,33	0,37	0,7

Table 6-9 LCC of FRs of Pump Example

6.1.4 Analysis and Evaluation Section Part 1 Value Data Input:

After all the data are collected and prepared to be inserted into TPA software, the second section of the TPA analysis can be done. This section will be explained by using TPA software.



- <u>Product Panel:</u> Project and Product name, number of functional requirements and number of components have to be inserted into this panel. Obsolescent model has to be chosen from one of linear or exponential distributions.

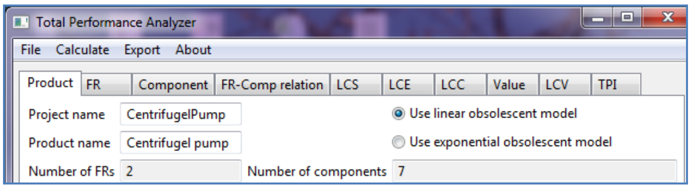


Figure 6-1 Product Panel (TPA Software)

- <u>FR Panel:</u> the necessary and main functional requirements of the product can be inserted into this panel; all the related fields have to be filled to perform the entire analysis. And when all the information is inserted for a FR, "add button should be pressed and then next FR can be created. These entries all can be changed and can be updated.

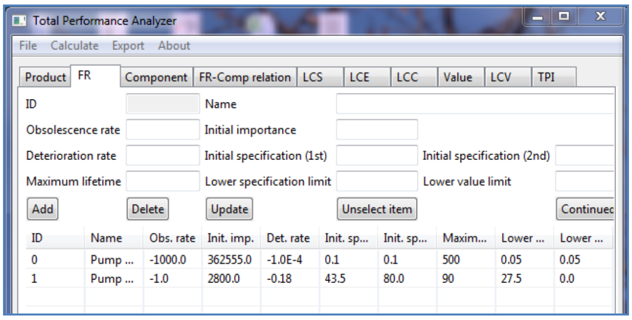


Figure 6-2 FRs Panel (TPA Software)

- <u>FR Components:</u> for this panel, lifetime of each components and end of life treatment fields are more important than components name. According the end of life treatment and maximum life time of each component are directly affecting TPI results. Any changes in this field can help to reach better solutions. The final recommendations will be related to these fields.

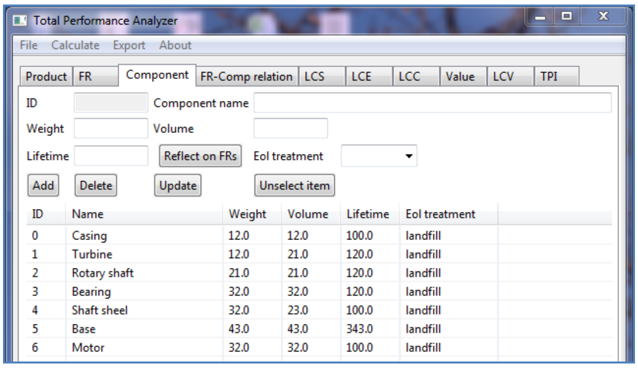


Figure 6-3 Components Panel (TPA Software)

- <u>FR-Component Relation Panel:</u> this panel is important to convert the LCE and LCC data from FRs to components or vice versa. The relation matrix has to be created according to experts' viewpoints. To fill this kind of relations there are several academic methods which will be mentioned in recommendation chapter.

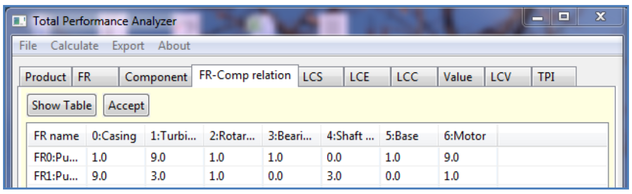
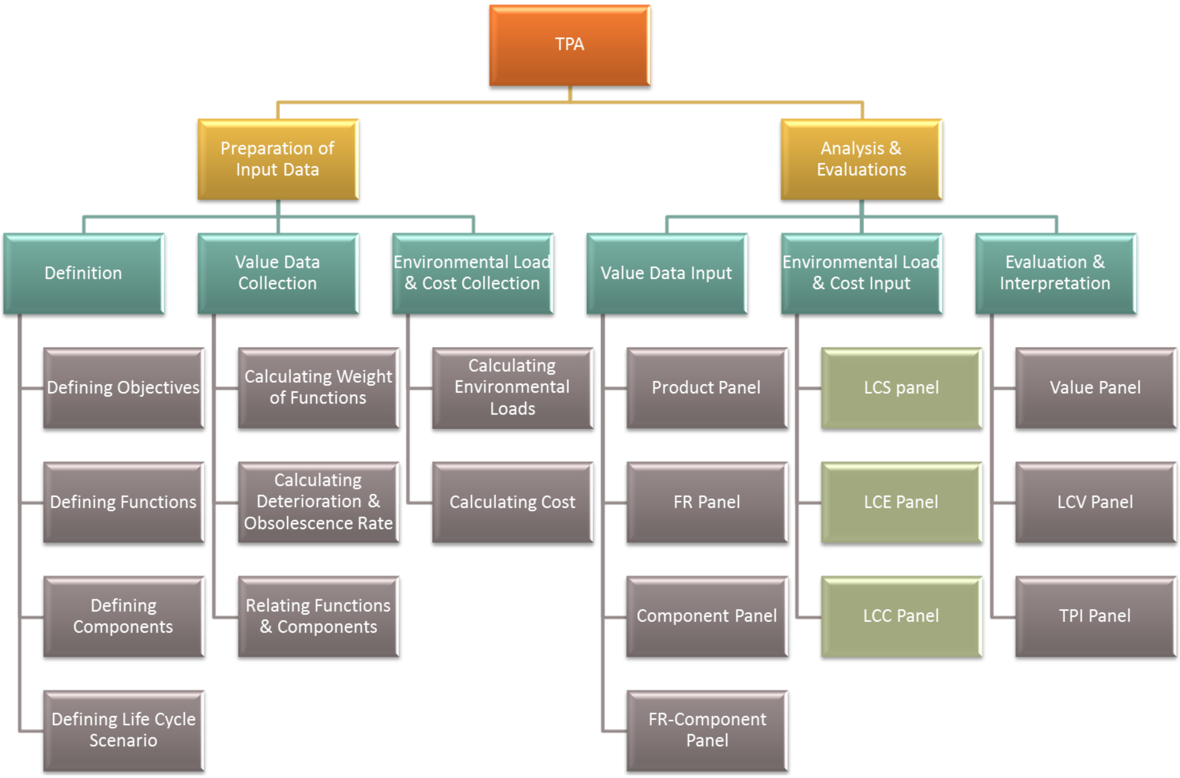


Figure 6-4 FR-Components Relation Panel (TPA Software)

6.1.5 Analysis and Evaluation Section Part 2 LCS-LCE-LCC inputs:



- <u>LCS Panel:</u> All the values, environmental loads and costs will be allocated into product according the data which are inserted into this panel. Therefore the starting time of each life cycle stage and their length are important. According to remaining value of product after use stage, product can be used longer or components can be used in a different way.

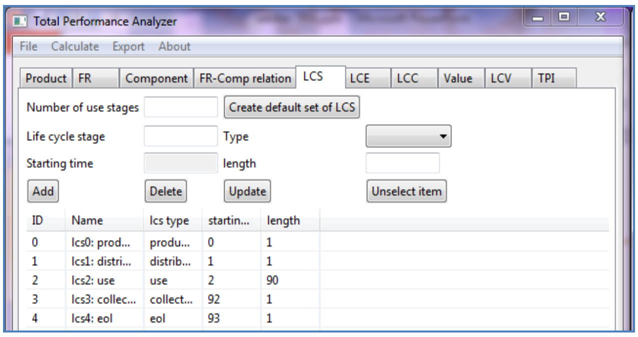


Figure 6-5 LCS Panel (TPA Software)

In part 1 and 2 all the data should be consistent to each other. TPA software doesn't allow inserting inconsistent data into system. However when TPA is calculated manually, a consistency analysis should be done and there should be check point to understand and to find where is an inconsistency

- LCE Panel: the values of environmental loads are inserted through this panel these values are calculated by unitary based; in this case unitary unit is month. To reach final outcome all unitary values have to be multiplied with related life cycle stage length. When all the unitary values are entered, software calculated the new values for entire cycles and converts the data into functional requirement based.

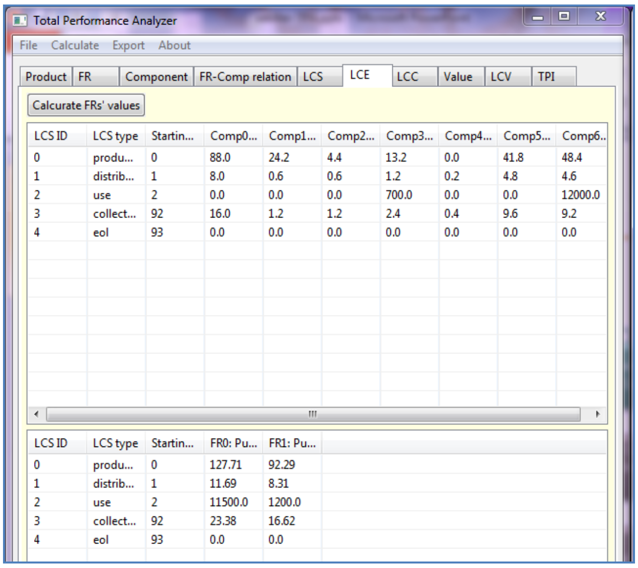


Figure 6-6 LCE Panel (TPA Software)

- LCC Panel: the values of cost are inserted through this panel these values are calculated by unitary based; in this case unitary unit is related unit for each component. And also Production cost of each component is estimated from the price of each component, and distribution, collection and disposal costs of components are allocated proportionately to their weight. The TPA software converts the data for component into functional requirement based data.

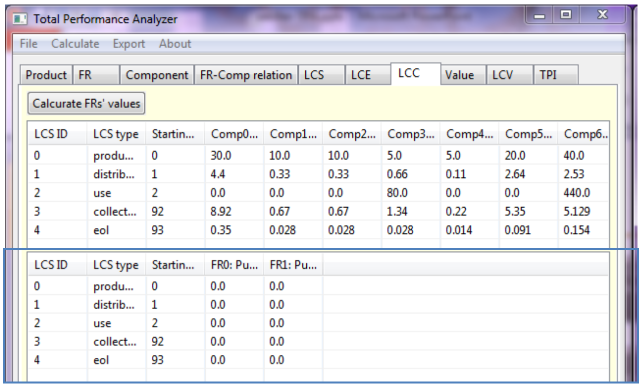
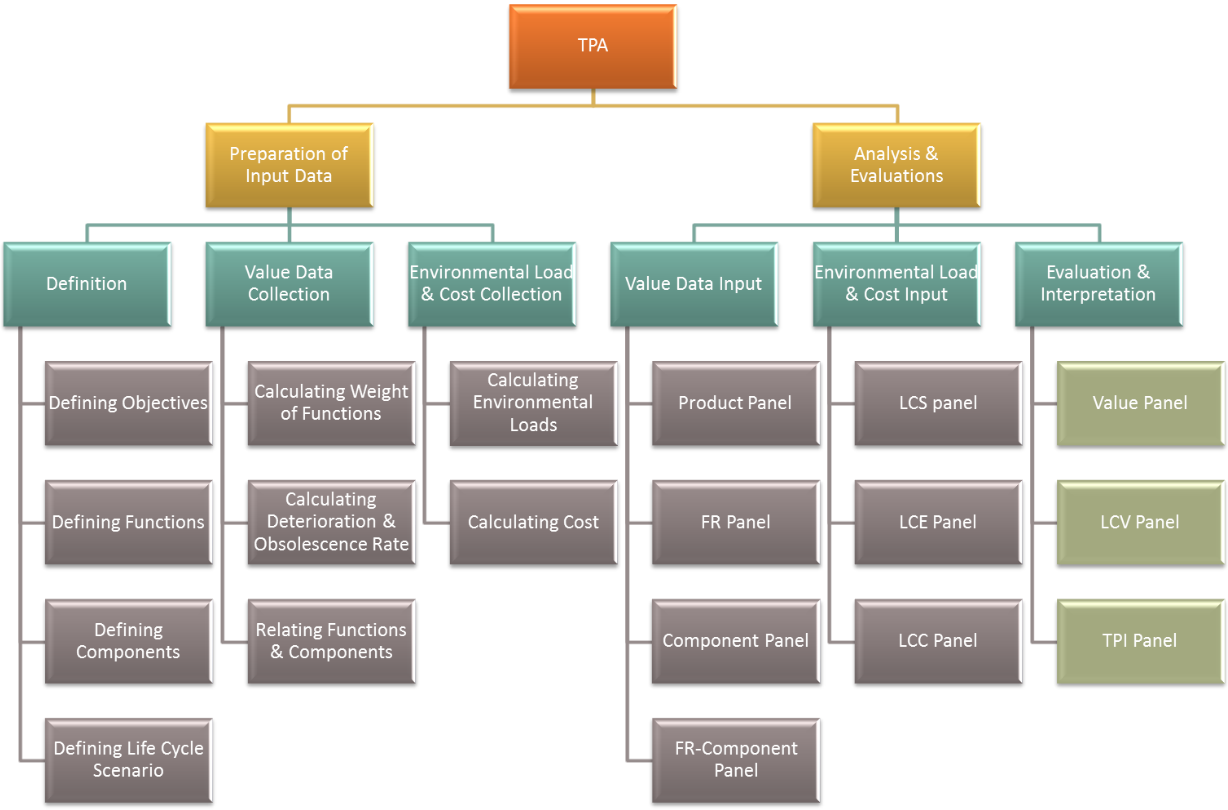


Figure 6-7 LCC Panel (TPA Software)

6.1.6 Analysis and Evaluation Section Part 3 Evaluation & Interpretation:

This part is prepared by using all the data inserted into previous panels. And this part represents final outcomes which are needed to be analyzed to find better solution for product.



Value Panel: the value panel shows the changes of components and functional requirements values over time. It this case time is limited with life cycle scenario which is defined at the beginning of the project. When "calculate value deterioration" button is pushed, all the values for each time interval are created by TPA software;

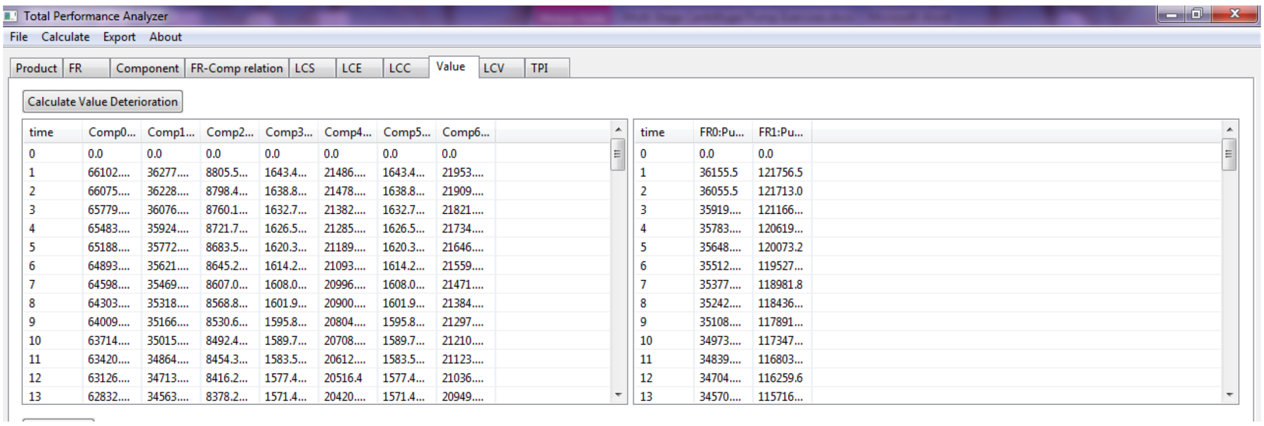


Figure 6-8 Value Panel (TPA Software)

And also the changes can be monitored as a graph and it is easy to be seen where values decrease dramatically.

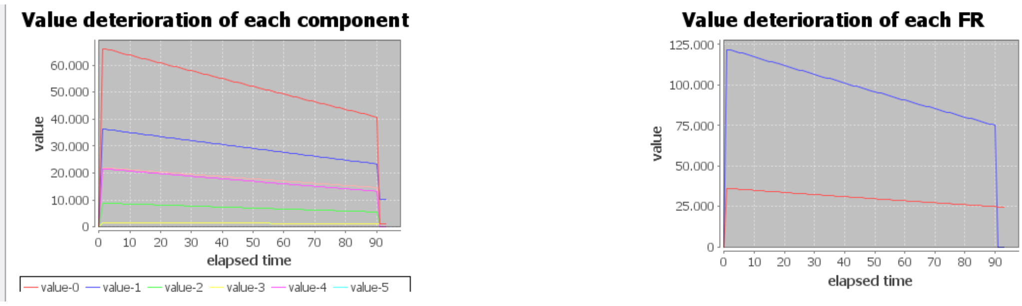


Figure 6-9 Graphs of Value Deterioration

- LCV Panel: in this panel, according to previous data, the cumulative value of each component and functional requirement are calculated. Much more than this, this panel also shows the remaining value of each component in each cycle (RLCV) and shows potentially obtainable value (MLCV).

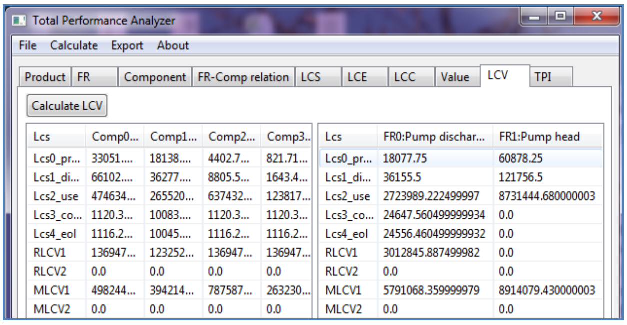


Figure 6-10 LCV Panel (TPA Software)

When the time is come to disposal phase, there is a failure of FR1 (the cause is lower than specification limit) and there is still remaining value for FR0.

- TPI Panel: this is the final panel which the final outcome of the project can be seen here. All the inserted data are evaluated and total performance analyze is performed for each components and functional requirements. According to results recommendation can be said after this final analyze. In this panel PP represents production performance, CP represents consumption performance and TPI represents total performance index.

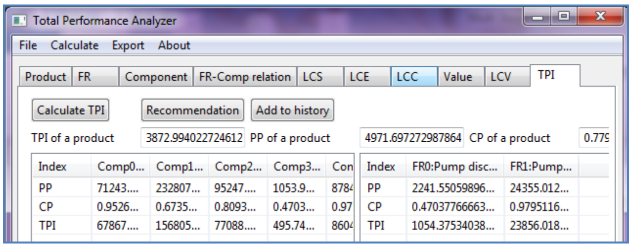


Figure 6-11 TPI Panel (TPA Software)

In the TPI panel graphs can be seen and they help to the final results to be seen easier. Now recommendation of improvements based on PP, CP and TPI can be said.

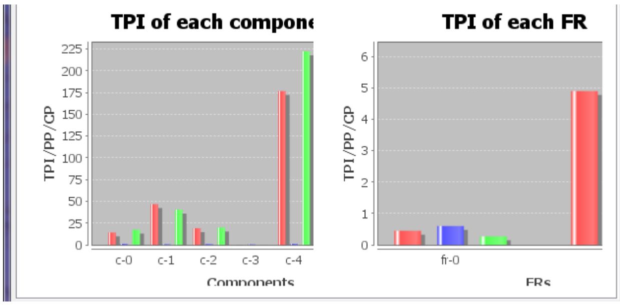


Figure 6-12 Graphs of TPI

7 Recommendation & Conclusion

7.1 Recommendation

Based on the total performance of a product, components, and FRs, a designer can find out the improvement potentials of the total performance of a product in two aspects:

- the reduction of cost and environmental load
- The enhancement of product value.

In this case according to results there are three main things to do by company to enrichment their products value. And there are bottleneck components therefor these improvements are needed and they are;

	Reduction of cost & E.L		**Enhancement of Value**		
Design Options	Components with low use-phase perf.	Components with low production perf.	FRs with high TPI	FRs with high obsolescence rate	FRs with high deterioration rate
Reuse	Turbine, Bearing Base & Motor				
Recycling		Bearing & Motor			
Reduce		X			
Enhancement of Functionality			Pump Head		

Table 7-1 Design & EOL Options for Pump Example

- Bearing and Motor component should be reused or recycled because of low PP. during production phase their environmental load and their cost are higher therefore their production performances come low. When company reuse or recycled these components they can reduce the environmental load and cost of components. As a design option these components should be designed according to easy recycling or reusable concept.

- Base component should be reused because of low CP. This component shows low performance during consumption phase in terms of environmental load and cost. To decrease the cost this components should be reused and therefore it is going to be used for longer period.
- Enhance functionality: pump head functional requirement should be enhanced. Because TPI of FR1 is higher, it is better to enhance FR1. Company should focus on highest functional requirements because the price of the product has a strong correlation with functional requirements also customers evaluate the performance according to the time period that they can use their product. In this case if the functionality of product is enhanced, the value of the product will be enhanced.
- These are the only end of life solutions for a product there are other options that a company may use it. And these solutions may be more efficient. This TPA software takes into account only these options.
- Other possible solutions will be mentioned in conclusion part.

7.2 Conclusion

This TPA method is a practical method for all types of businesses. And the results are easy to understand and improvable. Most of the companies are not aware that their products' performances can be improved in terms of money and environmental load. Therefor this study is tried to show how TPA method is practical and helpful to companies to satisfy their customer.

Beside this example considered various uncertainties in the product life cycle, discussed their influence on product TPI and proposed a design method to maximize the average TPI while minimizing its variation resulting from these uncertainties. The feasibility and effectiveness of the method were demonstrated by a case study of a Multi stage centrifugal pump, where an adequate design solution maximizes the mean TPI while minimizing its variation. By using the method, it is possible to derive an adequate solution that maximizes the UV of a product while minimizing its resulting environmental load and cost throughout its entire life cycle considering various future uncertainties.

The improvement was limited. One reason for this is that the TPI of a product changes as its lifetime changes. And a possible limitation of the method is the evaluation model for the product value throughout the entire life cycle. In the method, product value is correlated with its functional performance although there may be other features that contribute to product value.

Also because of the lack of data and time limitation for this study control factors are not considered. One of the key benefits of the proposed method is that it can be a viable design tool for the realization of sustainable society by the infusion of sustainable products into society. As the method considers the balance of the product value, environmental load and cost throughout the entire life cycle, the sustainable product not only encompasses the features of an eco-product but also contributes to sustainable consumption into society.

For the following studies it is better to expend TPA concept from a single product to modular products. Most of the companies are producing more than one product and most of the products have a family which means that the end of life treatments can be variable and can be more efficient.

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