Sustainable Design Approach underpinned with Life Cycle Impact Assessment(LCIA) and Ontology

Zhongming Ren

A thesis submitted in partial fulfilment of the

requirements of Nottingham Trent University

for the degree of Doctor of Philosophy

This research programme was carried out at

Advanced Design and Manufacturing Engineering Centre,

School of Architecture, Design and the Built Environment

Nottingham Trent University

Burton Street, Nottingham

NG1 4BU, UK

September 2013

Abstract

Sustainable development has been a subject of global interest when people shift the focus from the economy and productivity only to the economy with consideration of the environment and resources on the earth. Manufacturing industry is one of the most crucial sectors that people focused on to make it more sustainable. However, the sustainability for current existing products are not enough to satisfy the requirement of sustainable development within the modern society. Therefore, an approach to design and to optimise product considering ecological impact is to be developed by this research. After review and comparison of popular LCIA methods and tools, the three-tier sustainable design approach considering human labour ecological impact is developed. Design optimisation with eco-constraints using genetic algorithm is followed. Moreover, from a product life cycle point of view, production may not be the least sustainable section. Use and disposal also play important roles in the whole product life cycle. In this case, Ontology is proposed in the research. It is a powerful tool to collect and exchange data of products and manage the relationships among different parts, properties of products, and suppliers in one specific area such as a factory or an industrial estate. Afterwards, The approach is validated by case study. Finally, the sustainable design approach underpinned with life cycle impact assessment (LCIA) and ontology is developed.

Acknowledgment

I would like to express the deepest appreciation to my director of study, Professor Su, for his continuous guidance, support, and encouragement. Without his supervision and constant help this thesis would not have been possible.

I would like to thank my second supervisor, Leslie Arthur, for his endless enthusiastic help and inspiration.

Also, I am grateful for the support received from myEcoCost project (Grant No. 308530) sponsored by the European Commission through the FP7 Environment programme. In particular, I would like to thank Dr Giuseppe Salvia and Jonathan Smith for their help on conducting the project and the work related to my PhD study.

In addition, thank you to my school mates, Wenjie Peng and Yongjun Zheng, for your selfless assistance.

At last but not least, thank my father and mother, for loving and inspiring me immensely.

Zhongming Ren

30/09/2013

List of publications resulted from this research

Ren, Z. & Su, D., (2013) Comparison of Different Life Cycle Impact Assessment Software Tools, Key Engineering Materials Vol. 572 (2014) pp 44-49.

Su, D. & Ren, Z., (2011) Ecological Impact Assessment and Eco-design of Industrial Gearboxes, Key Engineering Materials Vol. 486 (2011) pp 197-200.

Zheng, Y., Ren, Z., Su, D., Arthur, L., (2010) Semantic Similarity Based on Ontology Technology and Its Application in Mobile Information Retrieval for Product Design, Key Engineering Materials Vol. 419-420 (2010) pp 741-744.

Nomenclature

AHP	Analytic hierarchy process
ANP	Analytical Network Process
BEES	Building for Environmental and Economic Sustainability
CDM	Clean Development Mechanism
CES	Cambridge Engineering Selector
CFC	Chlorofluorocarbon
CML	Institute of Environmental Sciences
CO2	Carbon dioxide
DDT	Dichloro-Diphenyl-Trichloroethane
DKH	Design Knowledge Hierarchy
EDIP	Environmental Design of Industrial Products
EI 99	Eco-Indicator 99
ELCD	European reference Life Cycle Database
EPA	US Environmental Protection Agency
EPD	Environmental Product Declaration
EPS	Environmental Priority Strategies in product design
FAHP	Fuzzy Analytic Hierarchy Process
GA	Genetic Algorithm
GHG	Green House Gas
GWEE	Global Warming Eco-Efficiency
IPCC	Intergovernmental Panel on Climate Change:
IPP	The Green Paper on Integrated Product Policy
JESS	Java Expert System Shell
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
MET	Material, Energy and Toxicity

NIST	US National Institute for Standards and Technology
PAH	Polycyclic Aromatic Hydrocarbon
PBEMS	Product-Based Environmental Management System
PIT	Product Ideas Tree
PV	PhotoVoltaic
RIVM	Dutch national institute for public health and the environment
SM	Sustainable Minds
SPCS	Sustainable Product Conceptualisation System
SPI	Sustainable Production Indicators
SPSD	Sustainable Product and Service Development
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
TRIZ	The theory of inventive problem solving design method
VOS	Voluntary Observing Ship program
UNFCCC	United Nations Framework Convention on Climate Change
WCED	World Commission on Environment and Development

Table of Contents

List of Figures

List of Tables

Chapter 1 Introduction

An increasing number of environmental issues, such as global warming and climate abnormality, have arisen recently. Sustainable development has been a subject of global interest when people shift the focus from the economy and productivity to the economy with consideration of the environment and resources on the earth. Mechanical production plays an important role in manufacturing industry which is one of the most crucial sectors. However, the sustainability for current existing products is not enough to satisfy the requirement of sustainable development within the modern society. Therefore, an approach to design and to optimise products considering ecological impact is to be developed by this research.

1.1 Aim and objectives

The aim of the project is to develop a sustainable design approach of mechanical products such as gearboxes. Within the approach, design optimisation will be conducted, considering the product's ecological cost and impact as design constraints; and to reduce inputs (material, energy, and human labour) and outputs (emission and waste) of the whole product life cycle, reduce loss from the whole product life cycle to environment, and, hence, make the mechanical product more sustainable. The approach is to be used by designers. And follow-up work may transfer the complex approach into a software package with a user friendly interface based on SimaPro, a LCIA software tool, for design application. It also enables the consumers to assess of the product's ecological impact based on the approach developed, so that the consumer can purchase more sustainable mechanical products.

To achieve the aim, the following major work has been conducted and presented in this thesis.

Literature review in relevant areas including ecological indicators, product life cycle assessment, renewable energy and material selection, responsibilities of roles, application of ontology technique into data management for sustainability, sustainable design and a clean development mechanism and others.

1) Review of ecological impact methods such as ReCiPe, EI 99, etc. and suggestion for their utilisation in this research.
2) Comparison of five popular LCIA tools including CES EduPack 2010 Eco audit tool, Solidworks 2010 Sustainability tool, Sustainable Minds, SimaPro 7.2, and Gabi 4 education, in six evaluation criteria, product definition, LCIA method, database, database modification, presentation, and details.
3) Research of a three-tier framework to assess product’s ecological impact.
4) Development of a method to calculate human labour ecological impact which is little considered by previous research in sustainable scope.
5) Development of a method to calculate the ecological impact of mechanical product based on three-tier framework.
6) Design optimisation with eco-constraints using genetic algorithm.
7) Modelling of ontology for life cycle of an industrial gearbox.
8) Integration of the optimisation, ontology and the pre-processing data, using COM interface of SimaPro, for designer to apply the developed approach.
9) A case study using industrial gearbox to illustrate the application process of the developed method for mechanical product.
10) A case study using farm food to propose the possibility of application of developed method in more area.

1.2 Research methods

1.2.1 Significance of research methodology

In Oxford dictionary, the meaning of research is defined as ‘the systematic investigation into and study of materials and sources in order to establish facts and reach new conclusions’ (Oxford dictionaries, 2013). Generally speaking, that means the aim of the research is to establish facts and reach new conclusions. The method and process of the research are to systematic investigate and study materials and sources. In Cambridge dictionary, the definition of research is ‘a detailed study of a subject, especially in order to discover (new) information or reach a (new) understanding’ (Cambridge dictionaries online, 2013). It is similar as that in Oxford dictionary. Research is a study process in a specific subject to find new information and approach a new comprehension. In conclusion, research is to explore new knowledge from materials and sources in a specific issue using systematic, scientific method.

As a PhD student, research is the main task during the study. So, the significance of the research must be identified before conducting the research. Furthermore, the aim of PhD study is not only to research an issue to get the academic degree of Doctor of Philosophy, but also to master methods to do research and apply them in future research works to benefit future life. Therefore, to probe deep into research methodology is indispensable for PhD study.

1.2.2 Research process and main architecture

Before conducting the research, the whole picture or architecture of the research should be drawn out or constructed to get a bird’s eye view of the research and make sure the research process is on the correct track. Based on the guideline of the research process form Kothari (2004), the research process can be divided into 11 stages including:

1. Definition of research issue
2. Literature review
3. Proposal of hypothesis
4. Research design
5. Sample design
6. Data collection
7. Project execution
8. Data analysis
9. Test of the hypothesis
10. Generalisation and interpretation
11. Report writing up

According to the guideline, the architecture of the research is constructed into the follow stages:

1) The research issue is the ecological impacts of existing products are not enough to satisfy the requirement of sustainable development within the modern society.

2) Massive literature review is conducted.

3) The hypothesis is proposed as the aim of the research is to develop a sustainable design approach of products such as gearboxes.

4) Comparison of popular LCIA tools and methods. Development of the three-tier framework to assess product's ecological impact, a method to calculate human labour ecological impact, a method to calculate the ecological impact of mechanical product based on three-tier framework. Design optimisation with eco-constraints using genetic algorithm.

5) 6) 7) 8) These four steps are integrated together and cannot be separated. Because there are several feedback and feed forward among them. These

stages are listed below. The industrial gearbox is taken as the sample in the research. Modelling of ecological impact in SimaPro, modelling of ontology in Protégé for life cycle of an industrial gearbox. Design optimisation of gearbox life cycle.

9) The comparison and data analysis of LCIA of the original and the optimised design test the hypothesis.
10) Generalisation and interpretation is stated in the conclusion of thesis.
11) Thesis writing up

1.2.3 Research methods

There are numbers of research methods in different type of research. For example in library research, there are analysis of historical records, and analysis of documents. In field research, there are Mass observation, mail questionnaire, personal interview, telephone survey, and case study. In laboratory research, there are small group study of random behaviour and play and role analysis. (Kothari, 2004)

Base on the research process and the main architecture, the following research methods are applied in the research.

a. To establish the aim and objectives of the research.
b. Literature review in relative areas.
c. Case study to prove the research hypothesis.
d. Data collection and modelling to simulate the working situation and life cycle of the gearbox and the ecological impact of human labour.
e. Theorem proof during the testing of the hypothesis.
f. Validation and optimisation of research design.

1.3 Structure of the thesis

On the basis of research architecture mentioned above, the thesis is comprised by 11 chapters in total.

Chapter 1 Introduction

A brief opening of the thesis states the aim and objectives of the research. Research methodology and architecture of thesis are also presented.

Chapter 2 Literature review

Literature review in possible relating areas are conducted in this chapter. The purpose is to illustrate the shape of current research and reveal some emerging technologies and information in relative areas to the research to seek the gap of existing researches. The foundation of the research is established.

Chapter 3 Comparison of different LCA tools

After the literature review, a comparison of different LCA tools is followed to illustrate advantages and disadvantages of these LCA tools in six evaluation criteria, product definition, LCIA method, database, database modification, presentation, and details. These LCA tools include CES EduPack 2010 Eco audit tool, Solidworks 2010 Sustainability tool, Sustainable Minds, SimaPro 7.2, and Gabi 4 education. This is a preparation of the research in tools and methods.

Chapter 4 A life cycle impact assessment method for sustainable design

This chapter is the main part of the research to develop a novel approach for sustainable design. Sustainable product life cycle assessment is introduced at the beginning. Secondly, the development of the Three-tier approach to assess product's ecological impact is described. The calculation method of human labour's ecological impact is presented after that.

After preparation mentioned above, method of product life cycle assessment using SimaPro and ReCiPe is developed. And a representation layout called EI-COST is proposed. It is a spider net chart applied to present and evaluate the product specification or illustrate product properties including ecological impact and manufacture cost.

Chapter 5 Sustainable design optimisation using genetic algorithm

Optimisation design using genetic algorithm is applied as a stage of the approach to optimise the original design to decrease the ecological impact. The optimisation design considers the product's ecological impact and manufacture cost as design constraints. The objective is to reduce inputs (material, energy, human labour) and outputs (emission, waste) of the whole product life cycle, reduce loss from the whole product life cycle to environment, and make the mechanical product more sustainable.

Chapter 6 The ontology of a product life cycle

In this chapter, modelling approach of ontology for mechanical product is presented after a brief introduction of ontology and modelling tools, Protégé. Finally, the scope of system integration which integrates users, method, and software used together in the whole life cycle of product is prospected.

Chapter 7 Life cycle impact assessment of industrial gearboxes

A case study of gearbox is illustrated in this chapter to test and verify the approach developed in chapter 4. After analysis of structure, the gearbox is modelled in SimaPro in a parametric method. Accordingly, the gearbox life cycle is also modelled in SimaPro. Then, the LCIA of gearbox life cycle is conducted to show the current results. Within the optimisation, a spread sheet for data exchange between software is written.

Chapter 8 Design Optimisation of gearbox life cycle

After analysis of results and optimisation proposal, three optimisation including extending the services life, increasing the recycle rate, and optimisation design using GA, are executed successively. A comparison of LCIA results between the original design and the optimisation design is followed to show the improvement of the optimisation using GA.

Chapter 9 Ontology modelling of life cycle of the gearbox

Ontology of life cycle of the gearbox is modelled in Protégé. The modelling includes class modelling, property modelling, and instance modelling. The function of the ontology is a database in the research to store the data of the whole life cycle.

Chapter 10 Sustainable design of farm food

In this chapter, the approach will be applied in a case study of farm food to prospect the application possibility of the approach in wider range of product. Based on the farmer's knowledge and experience, the results of LCIA are showed. After analysis of results, optimisation plans are proposed. Finally, ontology of farm food is modelled.

Chapter 11 Conclusion and future work

Conclusion of the research is given in this chapter. Novelty of the research and contribution to knowledge are also described. Finally, an outlook of future work is presented.

Chapter 2 Literature review

In 1987, the World Commission on Environment and Development (WCED) proposed a widely accepted concept of sustainable development. It is a proposal to meet present requirements without damaging future generations' ability to meet their requirement for living (WCED, 1987). As a crucial industrial subject area, production often consumes considerable energy and material, while it produces much emission and waste, because main physical or chemical change in product life cycle is occurred during production. A study (Burall, 1996) revealed that production could be much more sustainable. Almost twice the quantity of materials is thrown away during manufacturing as ends up in the product and 2314kWh of electricity is consumed to manufacture a computer workstation. This section reviews the methods, tools and technologies relevant to sustainable production, i.e., how to make the production more sustainable. These issues include ecological indicators, product life cycle assessment, renewable energy, material selection, roles of responsibilities, application of ontology techniques into data management for sustainability, sustainable design, clean development mechanisms, and other methods, tools and policies.

2.1 Ecological indicators

A number of methods have been developed to calculate a products' ecological indicator in numbers of areas. For instance, Eco-Indicator 99 (Goedkoop and Spriensma, 1999) is a standard published by the Ministry of Housing, Spatial Planning and the Environment in the Netherlands. This standard includes the following indicators: production of different materials, processing of different materials energy consumption (such as electricity, solar energy and heat), transport, recycling of waste, waste treatment, landfill (Harry Baayen, 2000). Aoe (2006) proposed eco-efficiency indicators and has actually used them since 2001 in companies, and has conducted many case studies of eco-efficiency using these indicators. The Global Warming Eco-Efficiency (GWEE) indicator is based on global warming influence in order to measure the eco-efficiency of a product (Cha et al, 2007). Tseng et al (2009) evaluated the performance of synthetic sustainable production indicators (SPI) by adopting fuzzy measure and an analytical network process (ANP) method. Recently, more updated methods, such as ReCiPe and Okala 2007, are developed.

ReCiPe is an impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. This method is an improvement on CML 2001 method (Guinée et al, 2001) and Eco-indicator 99 method (Harry Baayen, 2000). The main contributors to this project are PRé Consultants, Centre of Environmental Science, Leiden University (CML) and the Dutch national institute for public health and the environment (RIVM), Radboud University. Figure 2.1 below shows overall structure of the method. The method calculates eighteen midpoint indicators and sum up these midpoint indicators into three endpoint indicators. Because the eighteen midpoint indicators are not easy to interpret, the three endpoint indicators are more understandable. User can choose at which level it wants to have the result:

- Eighteen relatively midpoints, but not easy to interpret.
- Three easy to understand, but more uncertain endpoints:
    - Damage to Human health
    - Damage to ecosystems
    - Damage to resource availability (PRé, 2011)

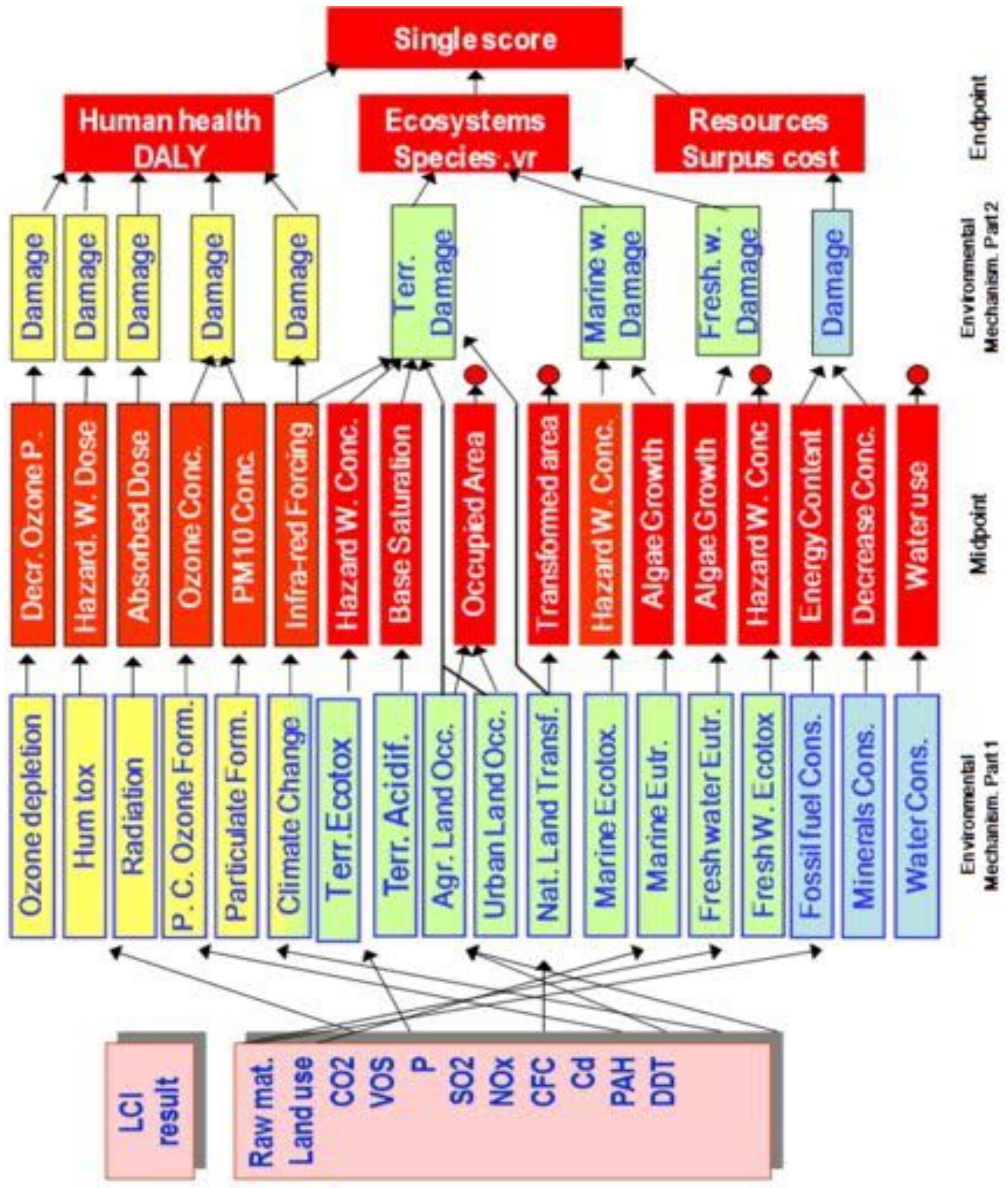


Figure 2.1 Overall structure of the ReCiPe method (ReCiPe Mid/Endpoint method, 2011)

Some of the advantages of the ReCiPe framework relative to other approaches include:

- The broadest set of midpoint impact categories.

- Where possible, it uses impact mechanisms that have global scope.

Unlike other approaches, Eco-Indicator 99, EPS Method (Steen, 1992), and Impact 2002+ (Jolliet et al. 2003), It does not include potential impacts from future extractions in the impact assessment, but assumes such impacts have been included in the inventory analysis.

Eco-indicator 99 (Goedkoop and Spriensma, 1999) is one of the most widely used impact assessment methods in LCA (Life Cycle Assessment). It is the successor of Eco-indicator 95, the first endpoint impact assessment method, which allowed the environmental load of a product to be expressed in a single score. It is an LCA weighing method specially developed for product design. This method has proved to be a powerful tool for designers to aggregate LCA results into easily understandable and user-friendly numbers or units, the so-called Eco-indicators.

The EI99 for production of material are based on 1 kilo of material. The unit of the Eco-indicator 99 uses the Eco-indicator point (Pt.). In the Eco-indicator 99 lists there often show milli-point (mPt) as the unit of the Eco-indicator. The larger the indicator, the greater the environmental impact is. The value is not an absolute value but it is a relative value which can compare differences between items. All the productions of material are considered included from the extraction of the raw material to last production stage. Data have been collected in advance for the most common materials. As an example, Table 2.1 shows the Ecological impact factors of production of Ferro metals. Analogously, there are factors of processing of metals in EI 99. Most of processing methods has been listed. But some more special processing methods are not included, such as hobbing, gear shaping, gear shaving, gear honing, grinding, forging, casting etc. Also, there are Ecological impact factor of other elements listed in EI99 such as distribution, usage, retirement, recycle, reuse, disposal, landfill, etc.

Table 2.1 Ecological impact factor of production of Ferro metals (Goedkoop and Spriensma, 1999)

Production of ferro metals (in millipoints per kg)		
	Indicator	Description
Cast iron	240	Casting iron with > 2% carbon compound
Converter steel	94	Block material containing only primary steel
Electro steel	24	Block material containing only secondary scrap
Steel	86	Block material containing 80% primary iron, 20% scrap
Steel high alloy	910	Block material containing 71% primary iron, 16% Cr, 13% Ni
Steel low alloy	110	Block material containing 93% primary iron, 5% scrap, 1% alloy metals

ReCiPe and EI99 has three cultural perspectives as listed below. These perspectives represent a set of choices on issues like time or expectations that proper management or future technology development can avoid future damages. Three cultural perspectives:

- *Individualist*: short term, optimism that technology can avoid many problems in future.
- *Hierarchist*: consensus model, as often encountered in scientific models, this is often considered to be the default model.
- *Egalitarian*: long term based on precautionary principle thinking. (PRé, 2011)

Sustainable Minds (SM) 2011 Impact Assessment Methodology is updated method from the **Okala Impact Factors 2007**, which is the impact factor which is proposed by Okala ecological design guide. It was developed from a North American perspective, yet it may be useful in many regions of our planet. The SM 2011 uses the Okala point as the score presenting in the LCIA result. Each Okala point contains impacts from the ten impact categories outlined by Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) (TRACI, 2007). The 2007 impact categories are specified by the TRACI impact assessment method, which was developed by the US Environmental Protection Agency (EPA). The SM 2011 also used the normalisation and weighting values specified by EPA and the US National Institute for Standards and Technology (NIST). And process inventory data from the most credible sources worldwide. SM 2011 evaluates 10 midpoint environmental impact categories and 3 endpoint environmental impact categories which are showed below, Currently, it is applied by Sustainable minds (Sustainable minds, 2012) on line.

Table 2.2 Sustainable Minds 2011

Methodology	Midpoint impact categories	Endpoint impact categories
SM 2011 (Okala)	● global warming/carbon emissions, ● acid rain, ● eco-toxicity, ● ozone depletion, ● water eutrophication ● photochemical smog, ● human respiratory, ● human toxicity, ● human carcinogens ● fossil fuel depletion	● Ecological damage ● Human health damage ● Resource depletion Turn into one Okala point only

The applications of eco-indicators to reduce products' negative impact on the environment can also be found in the literature. For example, Carlos Cerdan (2009) proposed a series of eco-design indicators and tests to measure the extent of the application of these simple indicators that provides a reliable indication of the reduction of environmental impact, as measured by employing Life Cycle Impact Assessment (LCIA) indicators. Two of the newly-developed indicators， reusable parts and reusable materials, were applied and compared to LCIA indicators, focusing on design for disassembly and for recycling. A good correlation was found, providing that these simple eco-design indicators can be used as a proxy to quickly and effectively gauge the environmental improvements introduced in a product system at the design stage.

2.2 Product life cycle assessment

Sustainable product design leads people to research the product life cycle assessment. Because the most important benefit of sustainable product design can be only obtained when the entire product life cycle is considered at the design stage (Fabio Giudice et al, 2006). Product life cycle assessment was developed as an analytical tool to help assess the environmental impacts from products or services (Hauschild, 2007).

Life cycle assessment as an effective tool of sustainable design has been used in a variety subject areas. Firstly in sustainable energy, life cycle assessment of solar PV-based electricity generation systems is reviewed by Sherwani et al (2009). Biofuels is also a more sustainable energy for industry, and Zah et al (2009) has proposed a standardised and simplified life cycle assessment for biofuels. Stoeglehner and Narodoslawsky (2009) concluded that biofuels could offer huge environmental benefits compared to fossil fuels by applying modified calculation methods of the ecological footprint. Matos and Hall (2007) conducted a case study of life cycle analysis in oil, gas and agricultural biotechnology and an attempt to integrate sustainable development in the supply chain.

In the construction industry, there are also some developments of life cycle assessment (Huang et al, 2008; Ortiz et al, 2008). Meester et al (2007) implements a resource consumption evaluation in the built environment based on an exegetic life cycle assessment (LCA).

Two research projects of emission using LCA are conducted. Huang et al (2009) conducted a comparative study of the emissions by road maintenance works and the disrupted traffic using life cycle assessment and micro-simulation. Braungart et al (2006) proposed to apply cradle-to-cradle design as a strategy for eco-effective product and system design. Hu and Bidanda (2009) developed a product life cycle evolution system based on stochastic dynamic programming.

Recovery and remanufacture are crucial stages in the product life cycle for sustainable development. Ferrer and Swaminathan (2009) conducted research for a company to manufacture new products using returned cores. The monopoly environment in a different period of the company was analysed. Dehghanian and Mansour (2009) designed a sustainable recovery network of end-of-life products using a genetic algorithm. For remanufacturing, Ostlin et al (2009) used a product life cycle perspective to foresee the supply and demand situations and possible strategies.

Transportation is an important stage of product life cycle. Although attention has been paid to this issue, more efforts should be made to reduce its negative impact on the environment. Eco-driving is an efficient method for transportation. Energy and emission impacts of a freeway-based, dynamic eco-driving system were analysed by Barth and Boriboonsomsin (2009). By applying this system to drivers, approximately 10–20% in fuel savings and lower CO_2 emissions are possible without a significant increase in travel time. Saboohi and Farzaneh (2008) developed a model of optimal driving strategy and it has been applied for the assessment of eco-driving rules. The model may be categorised as an optimal control and the objective function is the minimisation of fuel consumption in a given route. A transport project assessment methodology within the framework of sustainable development is conducted by Joumard and Nicolas (2009). A case study conducted by Hu et al (2009) shows that the potential energy saving capacity for sustainable road transportation in China is 60%.

Chamier-Gliszczynski (2011) has presented an investigation of a transport system in cities. The results show that the use of passenger cars should be limited.

2.3 Renewable energy and material selection

In production process, energy and material are the main consumption. Researchers have paid great attention to make them more sustainable. Multi-criteria decision analysis methods have become increasingly popular in decision-making for sustainable energy consumption. Wang et al (2009) reviewed the corresponding methods in different stages of multi-criteria decision-making for sustainable energy. Jin et al (2009) reported the situation of sustainable development of energy systems for western China. A multi-functional energy system is proposed by Kowalski et al (2008), which can achieve 10–14% in the energy conservation ratio, a 4–8% reduction of investment cost and a 10–37% decrease of the main pollutants. Wang et al (2010) present a design method of electromechanical products for saving energy based on energy flow analysis.

Scenarios and multi-criteria analysis have been applied in decision-making for energy. Giatrakos et al (2008) presented a sustainable power plan for the island of Crete. In Algeria, renewable energy such as solar, wind and biomass are being used (Himri, 2008). Hydropower is also a potential renewable energy. Turkey has a total gross hydropower potential of 433GWh/year, but only 125GWh/year of the total hydroelectric potential of Turkey can be economically used. Therefore, economic and environmental benefits of renewable energy for the future world are remarkable, particularly in the developing countries (Yuksel, 2009).

On the other hand, there are also examples of research on material selection for sustainability. For instance, the guidelines for sustainable product development were presented by Ljungberg (2005), which consisted of material selection with consideration of sustainability. The evaluation indicators of materials are presented by Zhou (2008), and an integration of artificial neural networks with genetic algorithms is proposed to optimise the multi-objectives of material selection. A research of composite materials to combine mechanical and environmental features for agricultural machines is also presented (Alves et al, 2009). Lauwers (2008) conducted research to justify the incorporation of the materials balance principle in frontier-based eco-efficiency models, facilitating more proactive eco-efficiency research.

2.4 Responsibilities of roles

Product services have been valued recently because a producer's responsibility for a product is extended to the post-consumer stage of the product's life cycle (Davis, 1997). In Europe, there are a number of applications already. The Green Paper on Integrated Product Policy (IPP), adopted by the European Commission in 2001, proposes 'the concept of producer responsibility relates to the integration of costs occurring on the product has been sold into the price of new products. This encourages prevention at the design stage and allows consumer to bring back end-of-life products free of charge' (EC-IPP, 2001). In addition, the standards of the ISO 14000 series focus on product life cycle (ISO14040, 1997) (ISO14062, 2002). Park and Tahara's (2006) research focuses on producer and consumer-based eco-efficiency, which is equal to the ratio of product of quality value and service life to the environment impact. In addition, Yao et al (2008) proposed the use of information and communication technology in developing countries.

The environmental performance of a product in its entire life cycle is influenced by interaction between all the roles involved. Effective approach to the environmental issue must be considered by the entire society, understood as a complex system of actors including government, manufacturers, consumers and recyclers (Sun et al, 2003).

Overall, the consumer plays a crucial role in the product life cycle. Marchand and Walker (2007) present the notion of 'responsible consumption'. Their study showed that people adopt more sustainable lifestyles not only because of an ecological consciousness, but also because of perceived personal factors or benefits. They suggested that product designers can support and encourage those already active or interested in orienting their consumption habits towards more sustainable solutions by envisioning appropriate ecologically and socially responsible product alternatives. Nes and Cramer (2005) discussed how and when product lifetime optimisation of consumer goods could be a challenging strategy towards more sustainable consumption.

2.5 Application of ontology technique into data management for sustainability

Tom Gruber originally proposed this concept in 1992. Ontology in computer science and information science is a formal representation of a set of concepts within a domain and the relationships between those concepts. (Gruber, 2001)Based on the concept and feature, it is a powerful tool to manage concepts and the relationships in one specific area.

As a result of advantages of ontology, many applications and research for ontology have been done. Blomqvist and Ohgren (2008) constructed enterprise ontology for an automotive supplier. Automatic and manual ontology construction method has been applied in this paper. Kwon and Shin (2008) constructed a location-aware cooperative query system for securely personalized services. Conceptual distance which can measure all data values had been introduced. And this system can switch to different role modes if users log-in in privy way. Qu et al (2008) built an ontology library on the strong convection in meteorology. This research describes a standard domain ontology construction process. Li et al (2007) did research on ontology-based description model of part information. And a description pattern of part features and its structure are also presented in this paper.

Also, there are some examples for the application of ontology related to sustainable development or management. Macris and Georgakellos (2006) present a prototype model for the design and development of environmental training materials. They built a prototype environmental pollution ontology and three self-contained sample educational scenarios. Edum-Fotwe and Price (2008) present an ontology that can be employed to provide a systematic articulation to the issues that impinge on the social dimension of sustainability appraisals. Tserng et al (2009) develop an ontology-based risk management framework of construction projects through project life cycle. This study integrated LCA into ontology management. In addition, Janssen et al (2009) proposed the integrated assessment and modelling using ontology to support decision-making in a project. Ontology to cope with problems in modelling is proposed by Shangguan et al (2009). The similar study is presented by Dori and Shpitalni (2007). Ontology can also support collaborative manufacturing. The economy is transforming from goods-based to services-based. Yan et al (2009) proposed an ontology of service-oriented collaborative manufacturing to organise the concepts and knowledge between service-oriented architecture and service-dominant logic. It provides an understanding of the collaborative manufacturing domain from a service orientation perspective. Furthermore, this ontology will increase the level of automation in service discovery, invocation, composition and interoperation. Ming-Piao Tsai (2010) developed a knowledge-based system for product design with modules which is applying Protégé and JESS (Java Expert System Shell) expert tool. Zeng et al (2010) has proposed an ontology-based workflow framework of multi-disciplinary collaborative design.

2.6 Sustainable design and a clean development mechanism

Sustainable design is proposed by many researchers, which is considered economically viable and environmentally friendly. Some research has been developed in this area. For example, a sustainable product conceptualisation system (SPCS) has been proposed. In this system, the product platform of a specific product is first generated by designers or domain experts using general sorting, a requirement acquisition technique, a design knowledge hierarchy (DKH) and a knowledge representation structure. In addition, the Hopfield network is used to narrow down initial design space based on initial design criteria solicited by domain experts (Wei Yan et al, 2008). Maxwell et al (2006) proposed the Sustainable Product and Service Development (SPSD) based on general industry testing results. This provides valuable information on how functional and systems-related considerations can be practically and effectively included in sustainable development.

The Clean Development Mechanism (CDM) is one of the ‘flexibility’ mechanisms defined in the Kyoto Protocol (IPCC, 2007). It is defined in

Article 12 and is intended to meet two objectives: (1) to assist parties not included in Annex I in achieving sustainable development and in contributing to the ultimate objective of the United Nations Framework Convention on Climate Change (UNFCCC), which is to prevent dangerous climate change; and (2) to assist parties included in Annex I in achieving compliance with their quantified emission limitation and reduction commitments (greenhouse gas (GHG) emission caps). Annex I parties are industrialised countries listed in the treaty. Non-Annex I parties are developing countries (Kyoto protocol, 1998). The Clean Development Mechanism should be practised to reduce pollution and waste during manufacture in developing countries (Karakosta and Psarras, 2009). Applications on machining technologies for sustainable production are proposed by Pusavec et al (2009). At the same time, sustainability evaluation of materials has been proposed, which can be a reference for material selection in design stage.

Re-manufacturing rate of engine has been proposed by Liu et al (2010), which has a potential for application into remanufacture of mechanical product. Iberahim et al (2011) proposed a remanufacturing index which can assist manufacturers in design for remanufacturing and application of recovery strategy.

Table 2.3 Sustainability evaluation of materials (Pusavec et al, 2009)

Sustainability evaluation of materials (1 - best sustainability score, 5 - worst sustainability score)						
Factor	Steel	Stainless steel	aluminum	Cast iron	Titanium	Copper alloys
Abundance of raw material	2	3	1	2	5	4
pollution during machining	3	4	1	3	3	3
Life of metal	4	2	3	4	1	3
Ease of recycling	2	3	4	3	5	1
Cost of finished product	2-3	4	2	1-2	5	4
Overall score	13.5	16	11	13.5	19	15

2.7 Other methods, tools and policies

A number of methods and tools have been developed recently. For example, the Product Ideas Tree (PIT) diagram, which is the output from chaotic idea generating sessions, is a structured method aiming to help eco-innovation. The further development of PIT diagram contributes several new approaches to sustainable product and sustainable processes design (Jones et al, 2001). A multidisciplinary approach to sustainable product and process design has been described by Carrano and Thorn (2005). A method for sustainable product development based on a modular system of guiding questions has also been presented by Byggeth et al (2006). Houe and Grabot (2009) have suggested a method aimed at providing support to the user when checking the compliance of a product with an eco-label. Donnelly et al (2006) have proposed a product-based environmental management system (PBEMS) to address formally the impacts of wireless hardware products on the environment throughout the entire product life cycle, regardless of where the products are developed. Li et al (2009) have proposed a fuzzy analytic hierarchy process (FAHP) approach to eco-environmental vulnerability assessment for the Danjiangkou reservoir area in China. Locating sustainable industrial areas is important to minimise the environmental impacts. Fernandez and Ruiz (2008) created a conceptual descriptive model to locate sustainable industrial areas. Knight and Jenkins (2008) presented three key eco-design techniques: checklists, guidelines and a material, energy and toxicity (MET) matrix. Li et al (2010) developed two algorithms about solving undetermined parameters based on evidence theory and fuzzy comprehensive decision-making methods. Teng et al (2010) has proposed an approach for module partition of product, which could be used in module design. And Teng et al (2011) also proposed an evaluation method for module partition schemes of complex product systems. TRIZ, the theory of inventive problem solving design method, has turned into a popular one to carry out a concept design. Using TRIZ methods, Hu et al (2011) design and improve a presenter mouse.

Policy is a crucial support from government for sustainable development. Technological innovation can be fostered and promoted by policy. A study conducted by Chang et al (2009) presents the official policy for sustainable transportation, and the research carried out by Li and Oberheitmann (2008) focus on the policies for sustainable energy use, environmental stewardship and social development in China.

2.8 Concluding remarks

Overall, sustainable production has attracted great attention from researchers, the public, and government in recent years. As mentioned above, many studies and implementations are emerging. As revealed by the review results, the ecological indicators and product life cycle assessment are powerful tools to evaluate products' ecological impact; and methods for eco-efficiency evaluation can also be used for ecological impact evaluation. In a product life cycle, energy and material selection for sustainable manufacture have been developed.

However, although efforts have been made, challenges still lay ahead for sustainable production, especially for mechanical design and manufacture which play crucial roles in production. For example, manufacturing process, which is the primary section of manufacture, has not been paid enough attention regarding its ecological impact. Sustainable transportation also needs to be implemented into sustainable product design. New energy and material which has more recycle rate should be used during manufacture. Consumers play the most important role for sustainable development because most products are finally consumed by them. Therefore, the consumers' responsibility and interest of consumption should be more sustainable. Government policy should be used effectively to coerce and guide the public and consumers. On the other side, producer can design the product that can be upgraded to enhance the lifetime of product, and producer and consumer must communicate well with each other to achieve the most efficient results. The producer should also notice the consumer when they should discard the product and how to recycle it. As mentioned, the lifetime of product should be limited in an optimal range. Ontology can be implemented for data management, decision-making, modelling, and communication among manufacturer, designer, and consumer.

This research is focusing on the area of mechanical design and manufacture process. Within the project, the ecological impact factors, ReCiPe, will be used to measure the ecological impact of products. As a framework of the research, a sustainable product life cycle will be presented and an assessment of sustainability will be conducted. The ecological impact of a product can be implemented with an eco-label, which shows the quantity of the ecological impact to customers directly. For example, spider net can presents multi-criteria clearly at the same time. The customer will be guided by the eco-label for purchasing and consumption. In addition, the implementation should be support by government policy. Module design, AHP, ANP, and remanufacturing rate may be applied to achieve the aim of the research. Ontology will be applied to improve communications and data management. Software communication will be set up to make the approach more effective for different users. Also, ecological impact of human labour is often ignored by previous research. This research developed a method to calculate it through SimaPro. The multi-objective function optimisation design approach underpinned with genetic algorithm (GA) for mechanical product will be implemented in mechanical production by designer and manufacturer to achieve sustainable design and production. For consumer, they will indicate the sustainability of each product rely on the eco-label.

Chapter 3 Comparison of different LCA tools

3.1 Introduction

Nowadays, sustainability has become an important consideration in product design. There have been number of commercial life cycle impact assessment (LCIA) software tools available in the market which provide valuable aids to conduct sustainable product design. There is a demand for a guide to help the designers to choose a suitable LCIA tool for them to effectively conduct their design. To meet such a demand, this study reviews five popular LCIA tools, including CES (Cambridge Engineering Selector) EduPack 2010 Eco audit tool (Granta Design, 2010), Solidworks 2010 Sustainability tool (Dassault Systèmes, 2010), Sustainable Minds (2010), SimaPro 7.2 (PRé Consultants, 2010), and Gabi 4 education (PE-international, 2010). In the review, the following six evaluation criteria are used:

- Function to define the product and its life cycle, i.e., how easy and accurate to specify the product/service to be assessed.
- LCIA methods employed in the software. And capability for the user to choose a suitable method to assess their product.
- Accuracy of assessment. And range and quantity of databases.
- Availability for the user to modify/update the databases, and flexibility for the user to use the databases.
- Presentation, especially the graphical layout, of ecological impact or results of sustainability assessment.

- Detail information of LCIA results.

3.2 Review of LCIA software tools

3.2.1 CES EDUPACK 2010

CES EduPack 2010 is a powerful tool for teaching materials and process, which has been widely used in higher education in engineering subject areas. CES EduPack provides a module called 'Eco-Audit tool' assessing ecological impact of products based on the powerful database built inside the package. After the user inputs materials, processes, transport and recycle information, the results of energy consumption and CO2 footprints are then presented.

The most attractive feature of this package is its large database of materials and process information. Sustainability for Eco-design is included in the package alongside others functions in a wide range of engineering subjects areas including general and mechanical engineering, manufacturing, materials science and engineering, industrial and product design, etc. This feature is particularly beneficial for material selection during design and conducting product LCIA.

Unfortunately, the database cannot be modified by the user, and the software package's function of eco-audit tool is limited. In product definition stage, only materials, primary process, and mass can be defined. There are only five selectable options which are landfill, down cycle, recycle, re-engineer, and reuse. Meanwhile, recycle content can be defined from 0% to 100%. Transport and use also can be defined based on the database. In the transport type, options are simple and not diversified. Figure 3.1 and 3.2 show the product definition and results of the CES eco-audit.

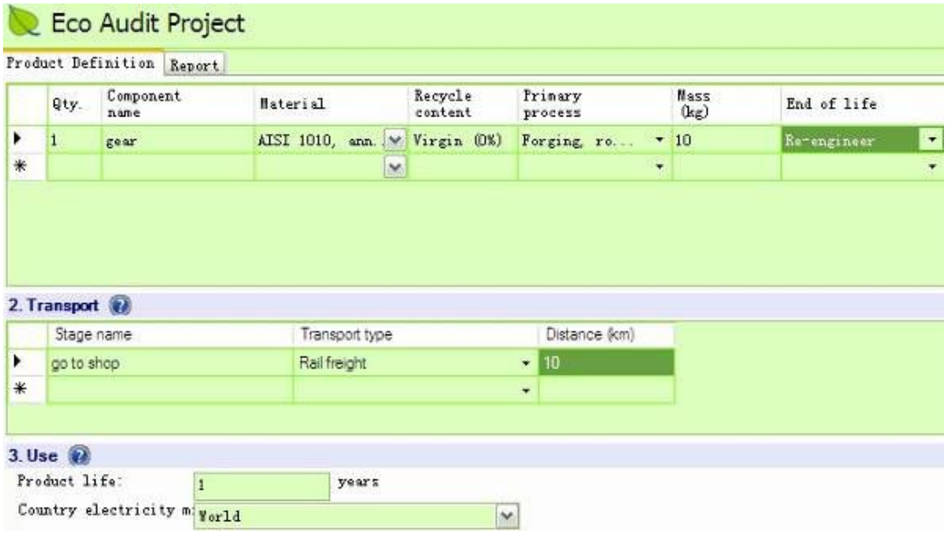
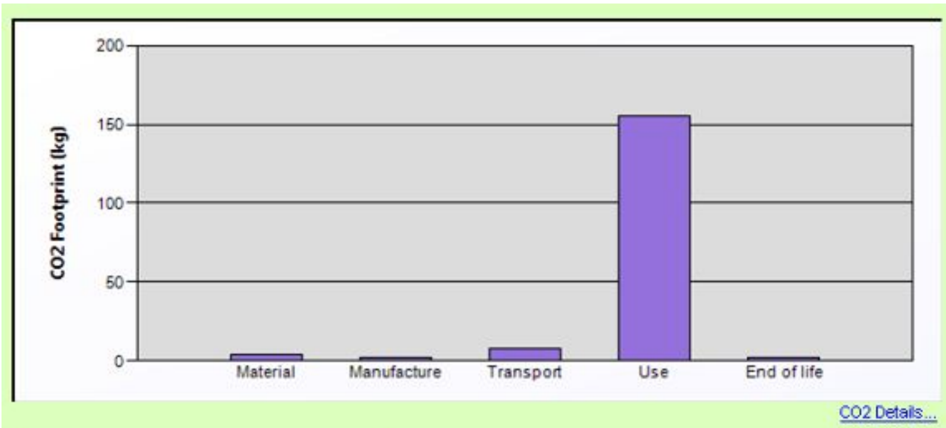


Figure 3.1 Product definition stage in CES



Phase	Energy (MJ)	Energy (%)	CO2 (kg)	CO2 (%)
Material	105.5413	3.77	3.9577	2.32
Manufacture	22.8341	0.82	1.8191	1.06
Transport	115.3901	4.12	7.7333	4.52
Use	2578.0680	92.02	154.9206	90.64

Figure 3.2 CES eco audit results of electric kettle

Also, the results of eco audit tool are not detailed enough. As shown in Figure 3.2, the results only reports two values, energy and CO2 footprint, which come from eco-audit methodology from Granta, and the database of CES itself. The results of these two ecological impact values of five stages in product life cycle are presented as a bar chart, and corresponding data are shown in a table below the bar chart.

3.2.2 Solidworks 2010

Solidworks is a well-known 3D modelling CAD tool. In its 2010 version, a sustainability module is integrated into the package which can assess the sustainability of modelled parts or assemblies. After modelling a part or an assembly of several parts, the sustainability module can calculate the environmental impact of the part(s). The environmental impact indicators considered in the software include carbon footprints, water eutrophication, air acidification and energy. The results of these indicators are displayed as pie and bar charts in the result report.

In the package, a product can be defined by designer through CAD modelling and material selection. The product volume will be calculated by the software based on the model created, and the mass of the part is then obtained. After determining the processing method, it considers transportation from the region where the product is manufactured to the region where the product is used, and energy consuming between different continents. The package uses the life cycle assessment method and database of Gabi 4 software, which is a widely-used LCA database in Europe. Solidworks employs the original database which cannot be modified by the user.

Figure 3.3 Example of Solidworks 2010 result presentation

The impact distribution proportion of components is available in the results of Solidworks 2010. It provides a comparison between several parts or assemblies and determines which component has the most or least environmental impact. Unfortunately, the results only shows carbon footprints, water eutrophication, air acidification and energy, which may be not detailed enough for application in further design optimisation. Besides, CAD modelling is requested before getting the sustainability report of a product. Sometimes the CAD modelling process is time consuming and a complex work. Design optimisation is not convenient and efficient if the results cannot be obtained immediately. Figure 3.3 shows an example of the user interface of the package.

3.2.3 Sustainable Minds

Sustainable Minds is a Web-based sustainability assessment tool. Its Web-based feature enables all the data used are stored in the server, so that the use can access his/her data all over the world through the Internet and an USB or mobile storage device are not necessary.

Before the evaluation process, the designer must input material and part's manufacturing process, use, end of life and transportation consumption. The progress is similar to that of CES. All the data is based on the database stored in the server and cannot be changed by the user. The results of Sustainable Minds are presented using Okala point which is one single score representing ecological impact of the product. The Okala life-cycle assessment methodology 2007, which is originally proposed in Okala ecological design guide, has been updated to SM 2011 Impact Assessment Methodology, which is a life cycle assessment methodology for evaluating potential ecological and human health impacts from products used in North America. SM 2011 calculates the ecological impacts from ten impact categories outlined by Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) (TRACI, 2007). It is designed for the user who is not a LCIA specialist, and the Okala points are presented in the way easy to understand.

Nevertheless, the results may be not detailed enough for further in-depth analysis, and the database cannot be modified. The data cannot be assessed if there is not an Internet connection. The Web-based features may make it run slowly in some cases and Internet access is required. It could be suitable for a sustainability demonstration purpose, but not for advanced applications. Figure 3.4 shows an example of the user interface of data input and results in Okala point of Sustainable Minds.

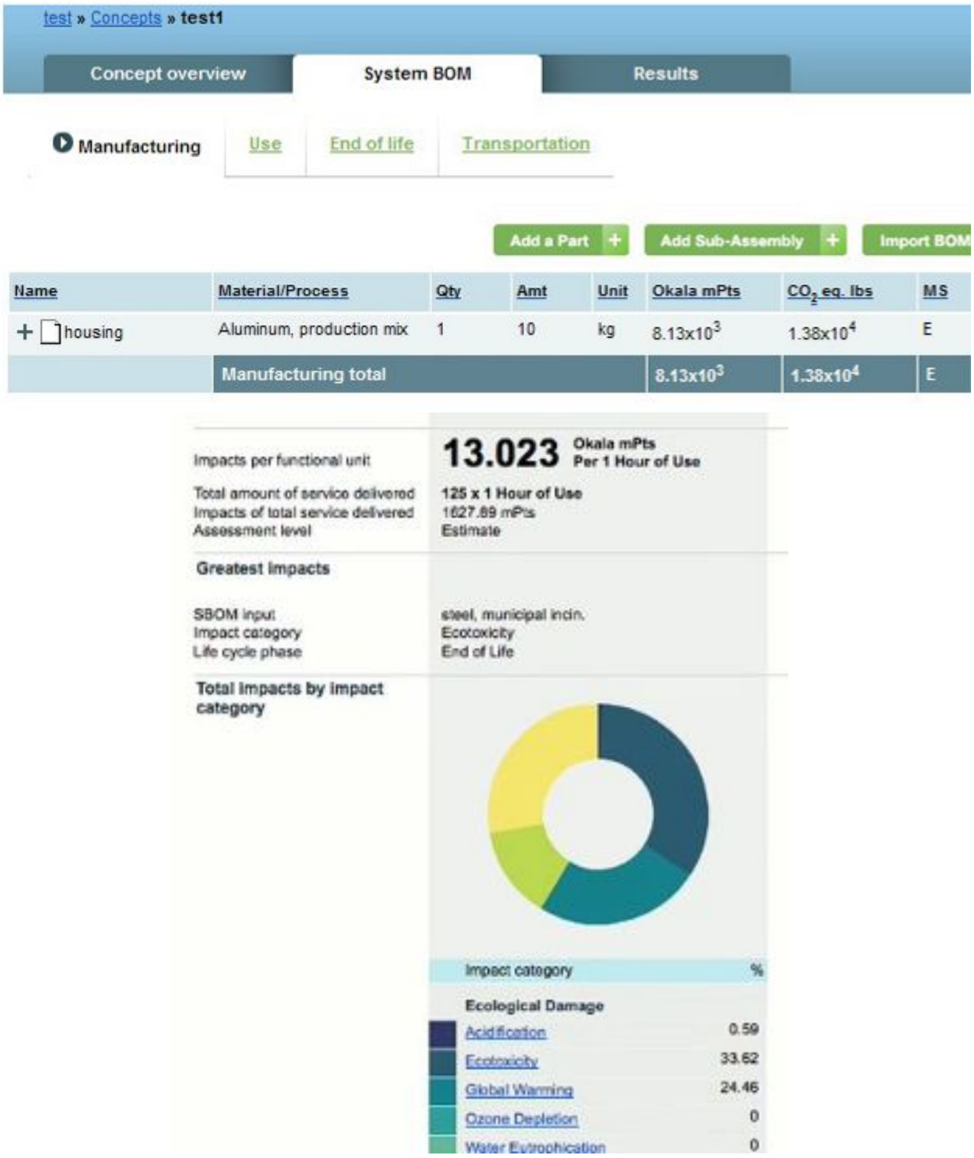


Figure 3.4 Sustainable minds input process and results in Okala point

3.2.4 SimaPro 7.2

SimaPro is a well know sustainable software package developed by PRé Consultants which focuses on the life cycle assessment and sustainable tools, and it has been in the market for more than twenty years. It provides a professional tool to collect, analyse and monitor the environmental impact of products and services. The user can model and analyse complex life cycles in a systematic and transparent way, following the ISO 14040 series recommendations (PRé Consultants, 2010). The package requires the user to build a product life cycle and fill details in each stage of product life cycle such as material, process, transport, recycle, reuse, and disposal; and then, the results of product life cycle network and ecological impact are presented.

In data collection stage, the user can input the amount of material, processes and relative data available in the huge databases built in the package, which are collected from a large number of sources, including ecoinvent v.2, US LCI, ELCD (European reference Life Cycle Database), US Input Output, EU and Danish Input Output, Swiss Input Output, LCA Food, Industry data v.2. It includes a mass of impact assessment methods including ReCiPe, Eco-indicator 99, USEtox, IPCC (Intergovernmental Panel on Climate Change) 2007, EPD (Environmental Product Declaration), Impact 2002+, CML-IA, Traci 2, BEES (Building for Environmental and Economic Sustainability), Ecological Footprint, EDIP (Environmental Design of Industrial Products) 2003, Ecological scarcity 2006, EPS (Environmental Priority Strategies in product design) 2000, Greenhouse Gas Protocol and others. Furthermore, the database can be modified and extended based on the user's requirements. The user can add new material or process into the database and use it in his/her application. Function equations are also supported by SimaPro when the user adds new parameters or elements.

These functions make the software efficient and flexible in a particular LCIA application.

SimaPro 7.2 also has the clear and precise presentation of results. The breakdown network of processes and materials is shown in Figure 3.5. At the right side of each element, ecological impact indicator is illustrated as a red colour bar. The size of the colour bar indicates the scale of the impact: the larger one represents larger ecological impact of this element. Figure 3.6 shows an example that the comparison between the initial design of gearbox (red colour) with its optimised eco-design (green colour). This function is helpful for the designer to compare the LCIA of different products, which is particular useful for eco-design optimisation.

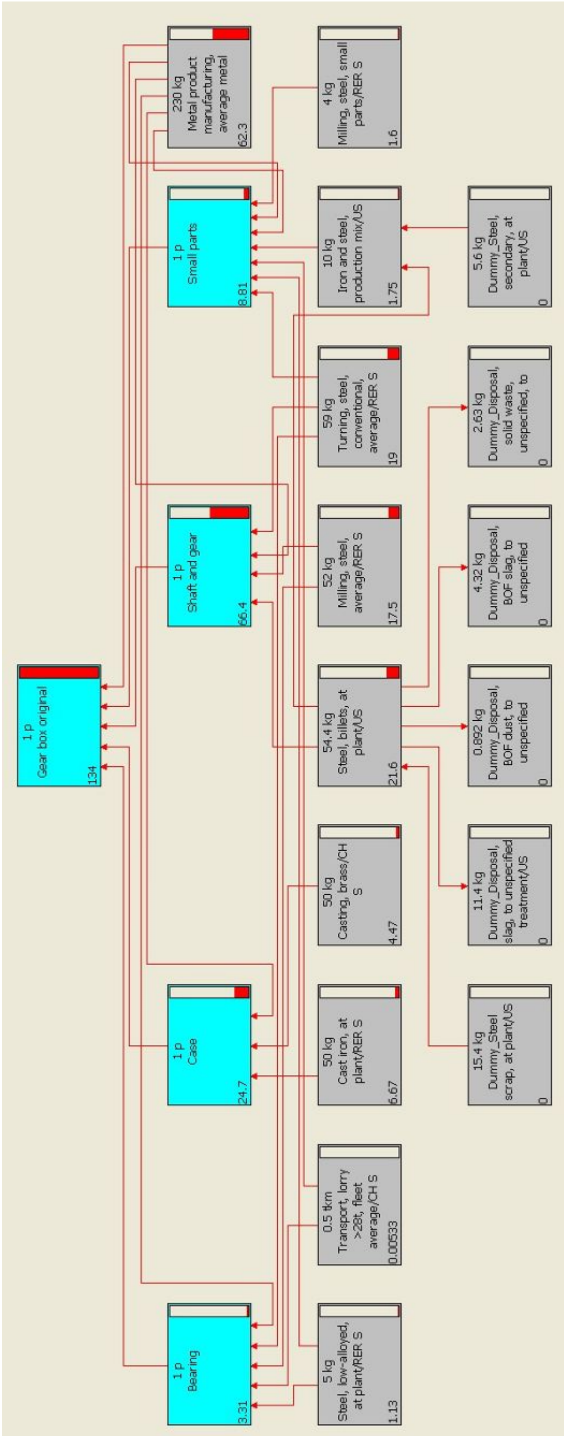


Figure 3.5 Breakdown network of processes and materials

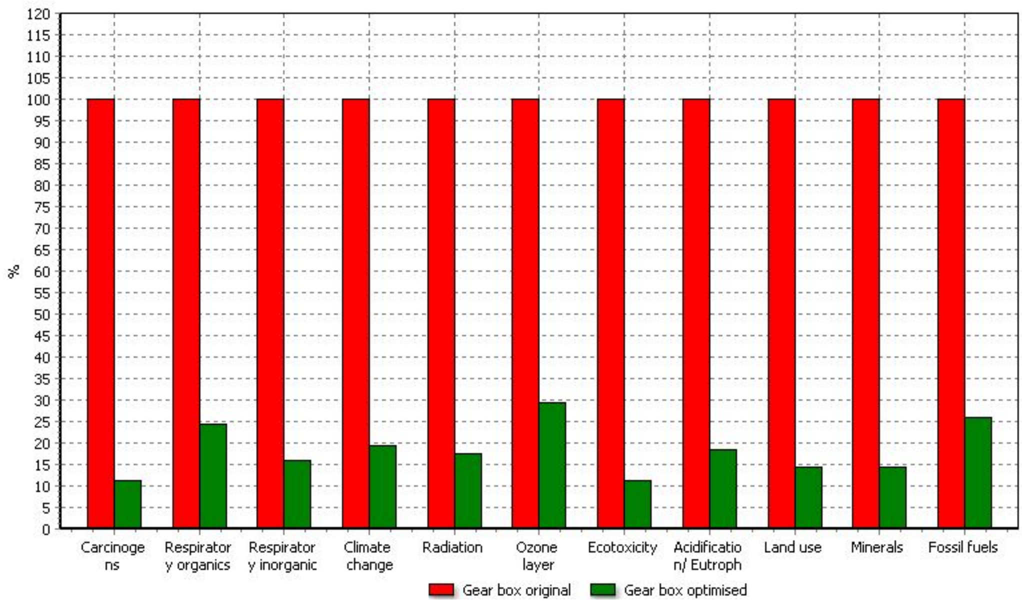


Figure 3.6 Comparison of the initial and optimised gearbox design

3.2.5 Gabi 4.

Gabi 4 is a well-recognised software tool for assessing products and systems from a life cycle perspective. Before LCIA process, the user should build a life cycle of the product as shown in Figure 3.7. Based on the life cycle, the user defines inputs and outputs of material and energy for each stage; and then a sustainability report including resources and emissions is generated. Graphical construction of the life cycle of a product is unique feature to others. The life cycle modelling in Gabi 4 is in a very clear way to illustrate and represent the whole life cycle of the product. It has a similar function to the life cycle framework and generating network used in SimaPro.

The Gabi database has been widely applied in various areas in Europe. It is created by PE International and includes over 4,500 life cycle inventory profiles. It contains all major impact assessment methodologies, such as: CML 2011, Eco-Indicator 99, EDIP 2003, Impact 2002+, ReCiPe, TRACI 2.0, and USEtox. Meanwhile, the user can modify and add elements into database and apply them when new life cycle is to be modelled. The results provide detail data chart and inventories similar to those in SimaPro.

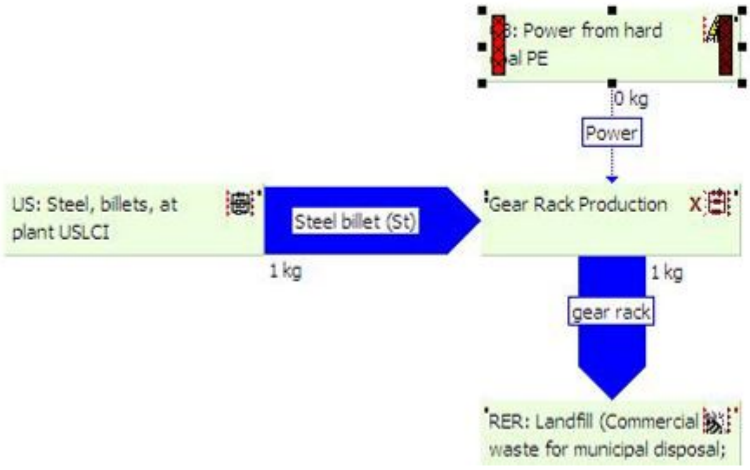


Figure 3.7 Graphical life cycle modelling using Gabi 4

However, the results chart and inventories is not easy to illustrate because so many data are listed and not visible in the table. Also, the graphic function is limited. In addition, the interface of Gabi is complicated to use and not user-friendly, which looks like an out of date version of Visual Basic programme's interface. Figure 3.8 shows an example of the LCIA result interface.

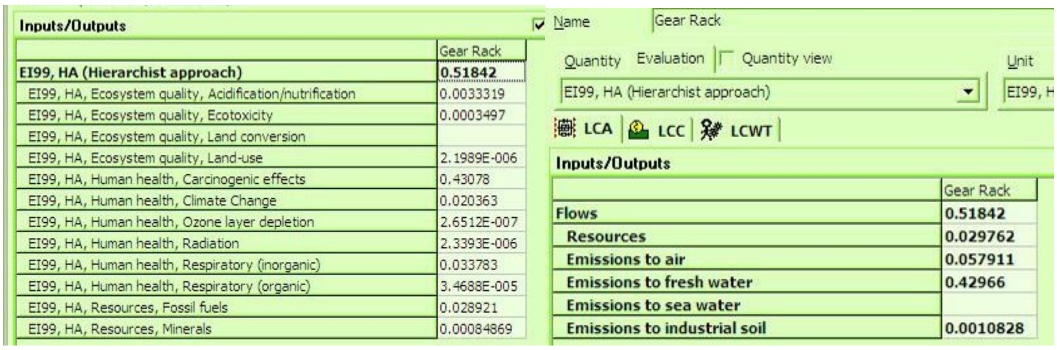


Figure 3.8 Gabi 4 LCIA results

3.3 Analysis of the LCIA Software Tools

According to their strength and weakness presented above, comparison of the LCIA software tools is summarised in Table 3.1, where the six comparison criteria mentioned in the introduction of this chapter are used and the number of stars indicates the rating results, the more star the better. The analysis is based on three issues: product life cycle definition and assessment results presentation, databases embedded in the software tools, and assessment categories and available LCIA methods.

Table 3.1 Comparison results

Considerations	CES	Solidworks	Sustainable Minds	SimaPro	Gabi
Product definition based on LCA	★★	★	★★	★★★	★★★★
LCIA Method	★	★★★	★★	★★★★	★★★
Database	★★★	★★★	★★	★★★★	★★★
Database Modification	★	★	★	★★★★	★★★
Presentation	★★	★★	★★★	★★★★	★★
Details	★	★★	★★	★★★★	★★★★

3.3.1 Product life cycle definition and assessment results presentation

Gabi provides the best product definition function because the life cycle can be built through the user interface of life cycle builder in a graphical way. SimaPro is rated second, due to its life cycle structured framework and the network based on the life cycle framework. CES and Sustainable minds both have similar rating for product definition function, which only defines limited amount of elements in product life cycle. Solidworks can only define product via CAD modelling which is time consuming and complex work requiring professional knowledge.

SimaPro uses graphic and inventory to simultaneously to present the results, which is better than Gabi which uses inventory and limited graphic presentation function. In addition, SimaPro has a comparison function between two products which is very useful for product design optimisation and presentation of comparison results. CES and Sustainable Minds both have similar report presentation which are bar and pie charts plus the data sheet. But Sustainable Minds has impact distribution of different parts, which is clearer than that in CES. Solidworks only has charts and simple data to present the results. Table 3.2 summarises comparison results.

Table 3.2 Product life cycle definition and assessment result presentation

Packages	Definition of product and life cycle	Presentation of results
CES EDUPACK 2010	Data input via tables	● Information with carbon and energy ● Results presented via bar and pie charts plus data sheets
Solidworks 2010	● Product is defined via 3D CAD models ● Life cycle data entered via tables and pull-down menu.	● Relatively detailed information available ● Results presented via pie charts, tables and the CAD model
Sustainable Minds	Data input via tables	● Relatively detailed information available ● Results presented using pie charts and data sheets ● Impact distribution of different parts
SimaPro	● Data input via tables ● Life cycle is defined via structured framework and the network based on the life cycle framework	● Detailed information available ● Results are presented via network framework, tables and bar charts ● Comparison function between two products
Gabi	Product is defined through a user-friendly life cycle builder in a graphical way	● Detailed information available ● Results are presented via lengthy tables with limited graphic presentation, not very user friendly.

Table 3.3 Databases of the LCIA software tools

Packages	Diversity of databases	Allow user to modify database
CES EDUPACK 2010	Rich engineering material databases, but limited sustainability data for energy consumption and carbon footprints only	No
Solidworks 2010	Gabi LCA Databases for five indicators only (see table 3.2)	No
Sustainable Minds	TRACI database (TRACI, 2007)	No
SimaPro	ecoinvent, US LCI, ELCD, US Input Output, EU and Danish Input Output, Swiss Input Output, LCA Food, Industry data v.2.	Yes
Gabi	Gabi LCA Databases, ecoinvent, US LCI	Yes

3.3.2 Databases

Availabilities to use reliable databases and to select the databases suitable for particular application highly affect the quality and accuracy of the assessment results. As shown in Table 3.3, SimaPro and Gabi have more potential for utilization of databases and, hence, enable their potentials for high quality and accuracy of the assessments. In some applications, the required data may not be available in the databases embedded the software tools, and, hence, the tool's flexibility to allow the user to modify the databases or to add new data to the database are helpful.

3.3.3 Assessment categories and available LCIA methods

Based on their powerful and large database, SimaPro (PRé Consultants, 2010) and Gabi (2013) have the most details results, while other software tools, such as CES, Solidworks, and Sustainable Minds do not have such details results of LCIA; both SimaPro and Gabi provide large number of assessment methods for the user to select, which enhanced their LCIA capacity, as summarized in Table 3.4.

Table 3.4 The LCIA tools' assessment result category and available assessment methods

Packages	Assessment categories	Available assessment methods
CES EDUPACK 2010	Energy consumption and carbon footprints	Granta Eco Audit methodology
Solidworks 2010	Carbon footprints, water eutrophication, air acidification and energy consumption	Eco-indicator calculation embedded in the package
Sustainable Minds	Okala points	SM 2011 Impact Assessment Methodology
SimaPro	Various results related to the LCIA methods applied	ReCiPe, Eco-indicator 99, USEtox, IPCC 2007, EPD, Impact 2002+, CML-IA, Traci 2, BEES, Ecological Footprint, EDIP 2003, Ecological scarcity 2006, EPS 2000, Greenhouse Gas Protocol
Gabi	Various results related to the LCIA methods applied	CML 2001, EDIP 2003, Impact 2002+, Description of the IMPACT 2002+ Method, ReCiPe, TRACI 2.1, UBP 2006

3.4 Guidelines for Selection of the LCIA Tools

Based on the comparison results, the following guidelines are proposed for selection of the LCIA software tools for conducting sustainable product design.

1. For an engineering project where the materials are clearly identified, and the assessment is limited to energy consumption and carbon footprints only, then CES EDUPACK 2010 could be a good choice. The assessment could be conducted much quicker and easier than using other tools.
2. If 3D CAD models have to be created for a design task, then the sustainability module of Solidworks is a suitable tool to conduct the LCIA. However, the assessment has to be limited to the five Eco-indicators: carbon footprints, water eutrophication, air acidification and energy consumption.
3. Sustainable Minds has been designed for the users, who are not

specialists of LCIA, in mind so the interface is easy to use and the analysis is also easy to be carried out. It suits 'what if' scenarios which requires the assessment to be carried out fast, and high accuracy of the assessment is not crucial. It is particularly useful for evaluation of concepts during conceptual design, where the product information is not as detail as that available in detail design. The assessment result of single Okala point makes the concept evaluation relatively simple, because each concept carries a single evaluation score (Okala point) and the concept with the highest Okala point is obviously the best concept for selection.

4. Both SimaPro and Gabi are comprehensive LCIA tools, which can be used to conduct full LCIA, for example, if ReCiPe method is used, 17 midpoints (such as Climate change, Ozone depletion, Terrestrial acidification, Freshwater eutrophication, etc.) and three end-points (eco-systems, human health and resource) impact can be assessed. The assessment requires a lot of high quality data which makes the assessment time-consuming. It requires the user to have experience in LCIA and specific knowledge of the product to be assessed. Assessment results are quite accurate and reliable. As discussed in the above section, Gabi has a user-friendly user interface for definition of the product, while SimaPro has better presentations for the assessment results.
5. The software tools can jointly utilised in conducting a LCIA task. For example, in the example of eco-lighting product design (Casamayor and Su, 2013), Sustainable Minds was used in conceptual design to evaluate the concepts' eco-features, while SimaPro was employed for detailed analysis of the ecological impact throughout the product life cycle at the detail design stage.

3.5 Concluding Remarks

In this section, five popular LCIA software tools are reviewed against criteria regarding the function to define the product and its life cycle, LCIA methods and databases employed in the software, presentation detail information of the assessment results. The comparison results determine that SimaPro is the most appropriate tool of the LCIA for this research.

Chapter 4 A life cycle impact assessment method for sustainable design

The aim of the project is to develop a novel approach for sustainable design. Within the approach, a life cycle impact assessment (LCIA) method for sustainable design is developed. In conjunction with the LCIA sustainable design, a design optimisation will be conducted, considering the minimal product's ecological impact and manufacture cost as optimisation objectives; and to reduce inputs (material, energy, human labour) and outputs (emission, waste) of the whole product life cycle, reduce loss from the whole product life cycle to environment, and make the mechanical product more sustainable. Therefore, the life cycle assessment should be processed at first to investigate the sustainability of product.

The development of the LCIA based sustainable design method is detailed in this chapter, while the sustainable design optimisation will be presented in the next chapter.

4.1 Sustainable product Life cycle impact Assessment

The Sustainable Product Life cycle should be defined before processing life cycle assessment. Throughout the whole life cycle of a product, there are three inputs: materials, energy and human labour; and two outputs: harmful emission and waste.

As an important objective of the product life cycle impact assessment (LCIA), both of the inputs and outputs should be reduced as much as possible. In the existing literature, human labour has not been considered as an input for LCIA. Existing research often ignores the effect of human activities in the calculation of ecological impact of mechanical products, and also, overhead in ecological cost, or so called eco-cost, is often in the same situation. These two are indirect input. In this research, human labour, and overhead will be considered. Human labour includes mental work and physical labour for design, production, use in product service life etc. Overhead includes using machine, office consumption, etc.

The outputs of this whole product life cycle are emission and waste. Emission includes CO_2, SO_2, etc. Waste represents any sort of unrecyclable waste.

In the centre of Figure 4.1, a sustainable product life cycle is shown. On the left side, there are inputs of the whole life cycle, including material, energy and human labour. And on the right side, there are outputs of this life cycle, including emission and waste. Indirect inputs including time and overhead costs are on the bottom.

The middle of Figure 4.1 shows the product life cycle, the product design is initiated by the clients' demands, based on the demands, the product design specification (PDS) has to be formulated. With the PDS, designer may propose several concepts, and after evaluation, the best concept is selected for detail design, and the final design is then completed in the production section, process planning, manufacturing, assembling and packaging are included. This is the most important part for calculation of the ecological impact factor, because this section transfers designs to products through manufacture. The manufacture makes the most ecological impact in the product life cycle. The accuracy of manufacture influences how sustainable the final product is and indirectly affects how sustainable it is. Distribution and usage stage also should be considered. After all, retirement makes the product end its service life. After disassembling, the retired products goes in three routes includes material for recycling, components for reuse and disposal. All of these are considered in the LCIA process. Material for recycling goes back to material input and components for reuse goes back to the assembling stage in production section. The disposal section makes up of landfill, physical, chemical, biological, and sustainable treatment and incineration. Incineration and treatments can produce energy for the whole life cycle to reuse. And some treatments can recycle some material for production.

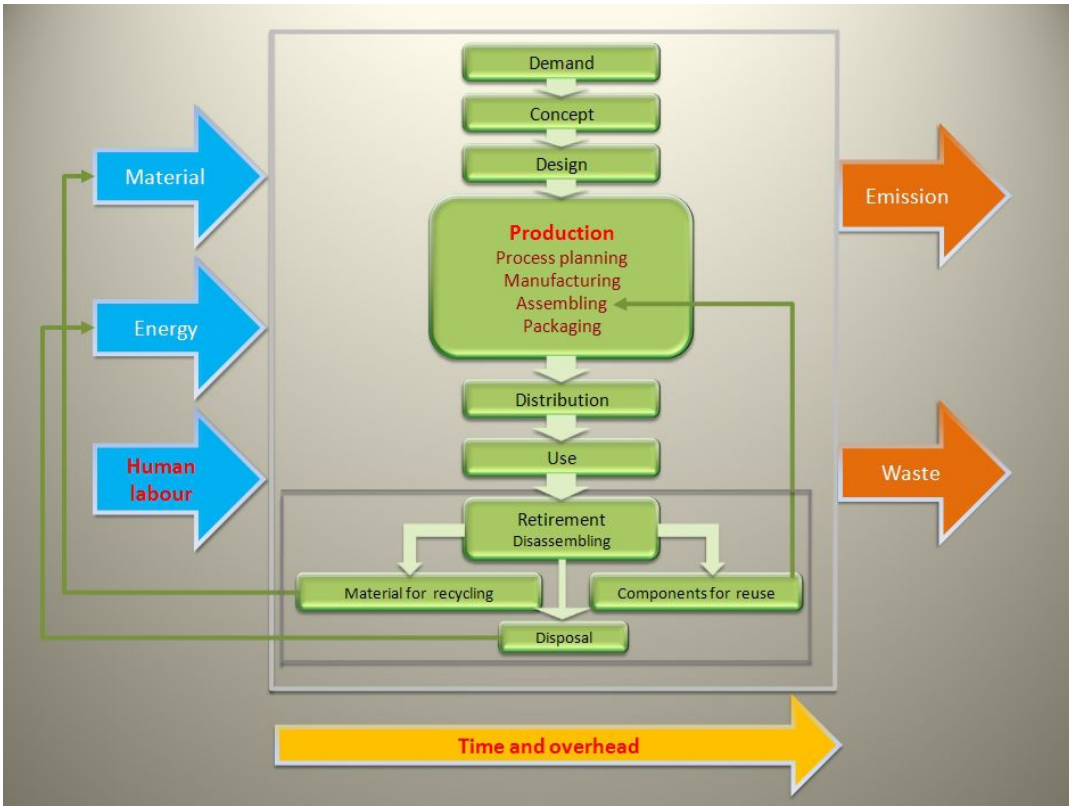


Figure 4.1 Sustainable product life cycle analysis assessment

4.2 Three-tier approach to assess product's ecological impact

In the approach, a product is broken into three tiers: component, subassembly, and assembly. Within the production process of a product, related components are assembled together to form a sub-assembly, and then all the sub-assemblies are assembled to form the final product (assembly). The ecological impact elements associated with the production process, including materials, processes, human labour, energy, are relevant to the component and sub-assembly tiers, including impacts of materials used, manufacturing process, packaging, and transportation, as well as human labour and overhead eco-cost. In the assembly tier, the ecological impact elements considered include transportation, packaging, product service life, design for disassembly, product re-use, recycling, and disposal.

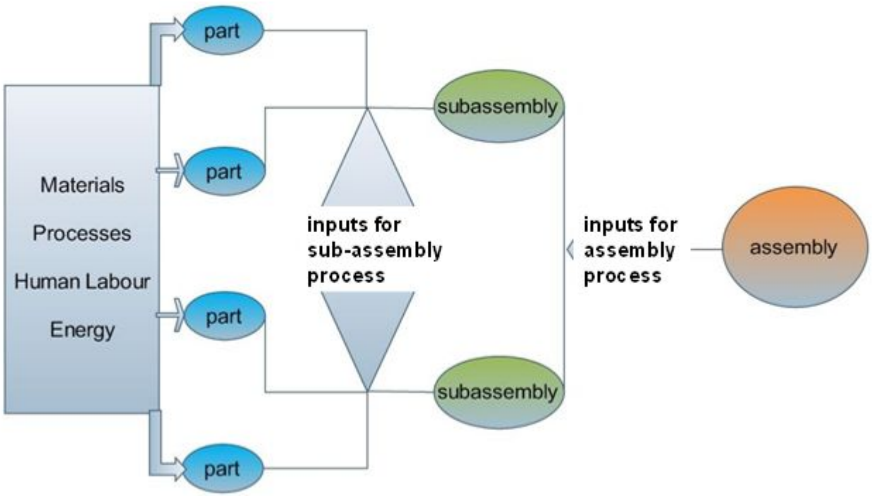


Figure 4.2 Three tier approach to assess product's ecological impact.

4.3 Human labour's ecological impact

Human labour is a crucial consideration in LCIA. However, little research has considered it as an ecological impact element. Therefore, the research has developed a human labour process in SimaPro which can be added into the gearbox life cycle and effect the results of LCIA. Development of process has two steps including input and output. The input elements are food, drink, and transport consumption between home and workplace in one normal day per person. The output is respiration or human metabolism and a set of emission belong to it. Further details are listed below.

Human labour input, food and drink. The food consumption of a person per day is calculated based on the Guideline of Daily Amount (GDA) which is a guide to represent how much energy and nutrients are required for a person's daily dietary needs (GDAs, 2011), as shown in Figure 4.3, It relies on nutrition recommendations from the Eurodiet project, a panel of scientific and policy experts established by the European Commission. And the UK Government advises that one person should drink at least 1.2 litres of water in one day to prevent dehydration. The food distribution is calculated from food database in SimaPro. Bread, sugar, potatoes, skimmed milk, port, cod fillet, chicken, beef and butter are existed in SimaPro food database already. As shown in Figure 4.5, the amount of each item is balanced to meet the standard nutrition recommendations. And the final deviation is ±20g from the standard values of GDA. Based on those data, the ecological impact of human input can be calculated.

Figure 4.3 Guideline daily amount values (Guideline Daily Amounts, 2011)
[Removed due to Copyright restrictions]

Human labour output, metabolism. The output is human metabolism includes urine, faeces and respiration, as shown in Figure 4.4. Based on the data from the official report of EU (Labour Force Survey, 2011), the ecological impact of person's output can be calculated.

Outputs	
Urine (CH_4ON_2)	27.4
Faeces (C_2H_4O)	13.7
Respiration: C in CO_2	71.2
Respiration: CH_4	0.083
Respiration: H_2O	89.9

Figure 4.4 Output of human metabolism for one person in one year (Schmidt, 2010)

Name	standard	Bread,	suger,	potatoes,	skimmed milk,	pork	cod fillet	chicken,	beef	butter,	calculation	differences
Typical values(g)(ml)		120	100	600	250	50	50	30	50	70	1320	
Calories	2250	288	400	474	92.5	105	40	33	80	513.8	2026.3	223.7
Protein	50	10.5		12.6	9	9.8	8.95	6.84	10.6	0.42	68.71	-18.71
Carbohydrate	265	53.4	100	103.2	12.25	0	0	0		0.63	269.48	-4.48
Sugars	105	4.2	100	3.6	12.25	0	0	0		0.42	120.47	-15.47
Fat	83	2.7		1.2	0.75	7.1	0.45	0.51	4.1	56.63	73.44	9.56
Saturates	25	0.9		0	0.25	3.4	0.1	0.15	1.65	37.8	44.25	-19.25
Fibre	24	3		7.8	0	0	0				10.8	13.2
Salt	6	1.26		0		0.15	0.15	0.09	0.15	1.19	2.99	3.01

Figure 4.5 Food distribution based on the guideline of daily amount

For investigating the extent of human labour in mechanical production in future works, an input parameter is defined as yes1_or_not0. The parameter decides the human labour ecological impact whether engages the LCIA process or not. The parameter is multiplied by each kind of food in Figure 4.6. When the value equal to 1 which means human labour is included and the value equal to 0 which means human labour is not included. Comparing work can be done between manufacture with human labour and without human labour. So, the importance of human labour ecological impact can be determined.

Input parameters		
Name	Value	Distribution
yes1_or_not0	1	Undefined

Figure 4.6 Human labour engaged parameter yes1_or_not0

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distr
Bread, wheat, fresh, in supermarket	120*yes1_or_not0 = 120	g	
Sugar, in supermarket	100*yes1_or_not0 = 100	g	
Potatoes, in supermarket	600*yes1_or_not0 = 600	g	
Skimmed milk, in supermarket	250*1.033*yes1_or_not0 = 258	g	
Pork minced meat (halssnitter), fresh, in superm.	50*yes1_or_not0 = 50	g	
Cod fillet, fresh, in supermarket (no quotas)	50*yes1_or_not0 = 50	g	
Chicken, fresh, in supermarket	30*yes1_or_not0 = 30	g	
Beef steak (oksetyndsteg), fresh, in supermarket	50*yes1_or_not0 = 50	g	
Butter, in supermarket	70*yes1_or_not0 = 70	g	
Tap water, at user/RER U	1.2*yes1_or_not0 = 1.2	kg	
Operation, passenger car, petrol, fleet average 2010/RER U	27/60*36*yes1_or_not0 = 16.2	mile	
(Insert line here)			

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*
(Insert line here)				

Outputs

Emissions to air

Name	Sub-compartment	Amount	Unit
Methane, biogenic		.083/365*yes1_or_not0 = 0.000227	kg
Carbon dioxide, biogenic		71.2/12*44/365*yes1_or_not0 = 0.715	kg
(Insert line here)			

Emissions to water

Name	Sub-compartment	Amount	Unit	D
Urea		27.4/365*yes1_or_not0 = 0.0751	kg	
Acetaldehyde		13.7/365*yes1_or_not0 = 0.0375	kg	
Waste water/m3		89.9*yes1_or_not0 = 89.9	cm3	

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity
Human labour	24*yes1_or_not0 = 24	hr	Time

Figure 4.7 Construction process of Human labour in SimaPro

Transport. The National Labour Force Survey states that the main method of travel to work is by car, van, mini bus, and works van, which represents 70% in England. The time taken to travel to work is 27 min (t) in average in the UK [3]. The Department of Transport statistics shows the average speed (v) on built-on roads is 36 mph (Road traffic and speeds statistics, 2010). Therefore, the distance between home and workplace (d) is: d =v*t=27min*36mph=16.2miles. With the above information, the ecological impact of transport for human labour's travel from home to work place can be calculated.

4.4 Product life cycle assessment using SimaPro and ReCiPe

Based on previous research, SimaPro is chosen to continue the project cause their advantages. ReCiPe also has been chosen as the LCA method, which is an improvement of EI 99 and CML 2000. This is a simple example to show that how the sustainability assessment works underpinned with SimaPro. An example how to connect SimaPro and mechanical product manufacture is shown below.

Ecological impact of machining a shaft. The manufacture of a shaft has two processing methods involved, including turning and milling. Also, human labour values half an hour for these processes. At first, the volume of blank (A) is calculated according to the drawing of the shaft as Figure 4.8 shows. Length and diameter of blank is defined and valued. Meanwhile, five length and five diameters are defined as L1 to L5 and d1 to d5. Each one represents a relative value on the drawing of the shaft. Then the volume of finished part (B) is calculated. Finally, the scrap produced during turning and milling is obtained by A-B. According to the density of the material, the mass of metal that be cut off by these processes is then calculated. Based on this geometry approach, the mass of each part of the gearbox can be calculated. In addition, the power consumed by the machines, and the pollution on the environment made by the coolants used during the machining process are also added with the processes.

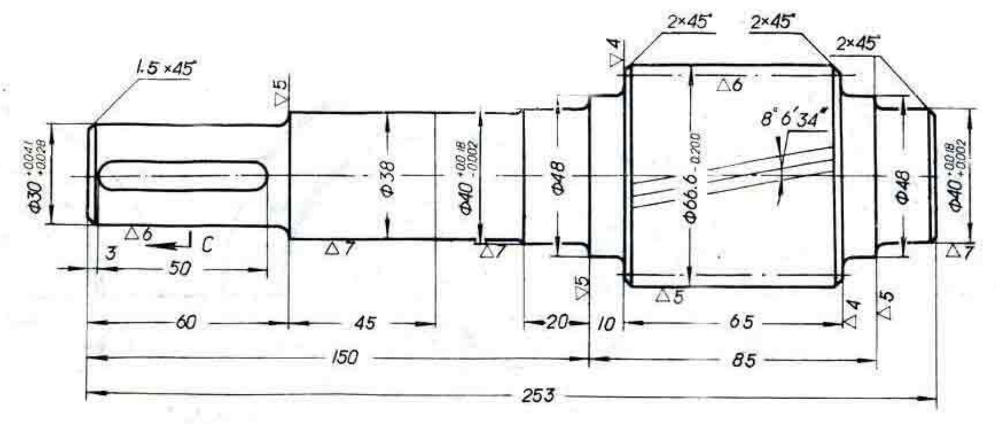


Figure 4.8 drawing of the shaft (Gong et al, 1981)

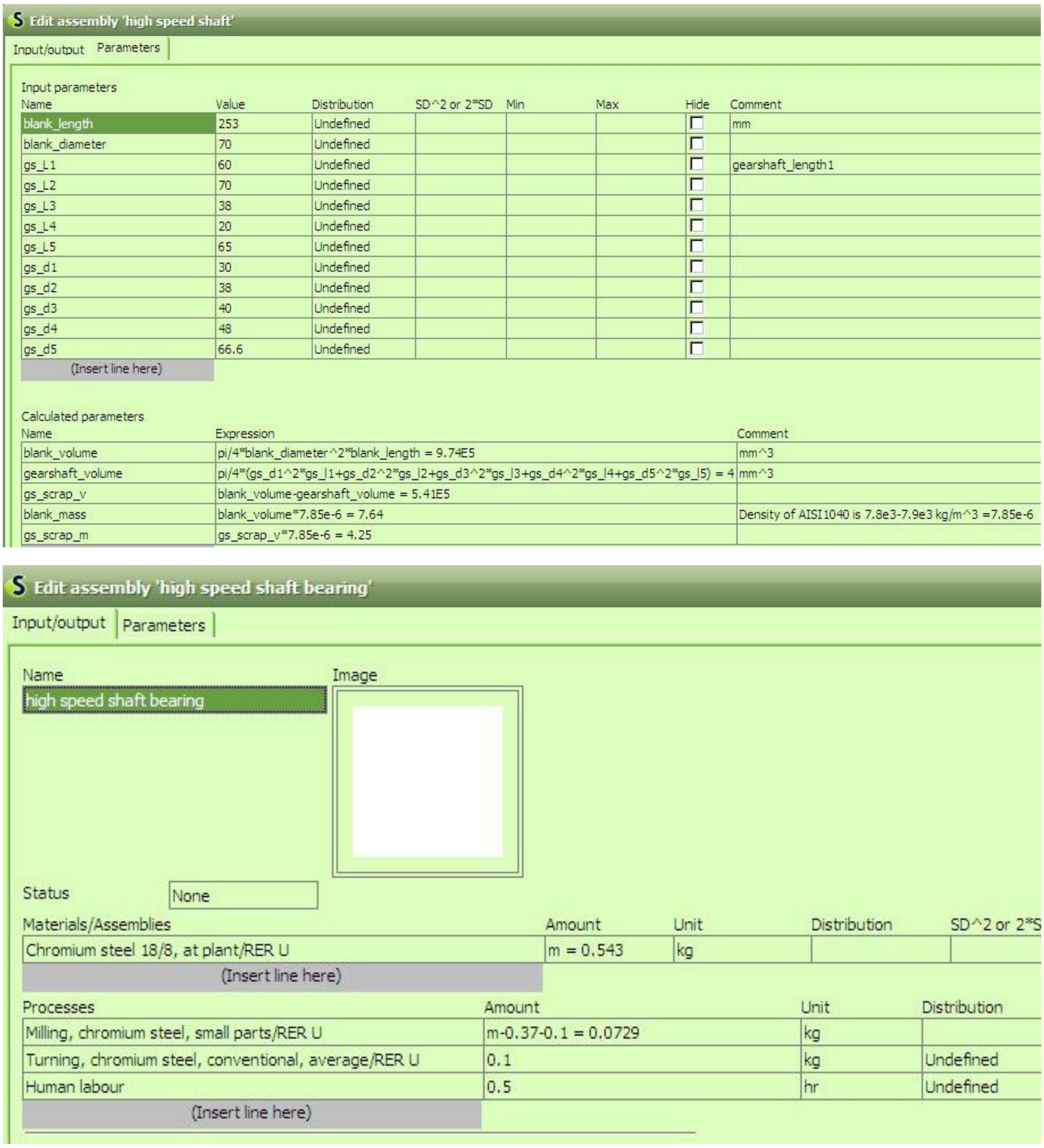


Figure 4.9 Calculations of the shaft

Parameter function built in SimaPro provides an approach to calculate the quantities after parameters and formation are defined. In this section, all geometric dimensions are defined in input parameters and other parameters which are calculated from a formation form by input parameters are listed in calculated parameters. Therefore, calculated parameters can be output as soon as user input all geometric dimensions of the part. The calculation process is executed by SimaPro.

4.5 EI-COST

EI-COST is a proposal of representation layout, which is a spider net chart applied to present and evaluate the product specification or illustrate product properties including ecological impact and manufacture cost.

The advantages of spider net chart to other charts are to illustrate plenty of characters in one chart at the same time and present the result very intuitive and clear. The spider net layout combines shape with quantity. It is very useful for designer. During design stage, there are a number of criteria in the product specification and evaluation. Other chart such as matrix is not very distinct when considerable amount of criteria should be evaluated by designer. But the spider net chart, EI-COST, can presents product characters including ecological impact, manufacture cost and other traditional factors to the designer in one chart only. For evaluation, it is also very effective to compare different design plans in few charts.

It is also very useful for consumer to compare product with similar function but different ecological impact. It will encourage and guide consumer to purchase more sustainable product in market. On the other hand, it will encourage manufacture to product more sustainable product to attract consumer and beat competitive product. It is a virtuous circle for sustainable development.

Two examples of EI-COST are presented in Figure 4.10. The first one has six criteria including EI, manufacture cost, performance, price, efficiency, and service life. This presentation is for common market. The second one is for specific market which considers sustainability of product more. There are eight criteria including energy consumption, material use, production or manufacture cost, function or performance, efficiency, service life, recovery or recycle rate, emission or waste.

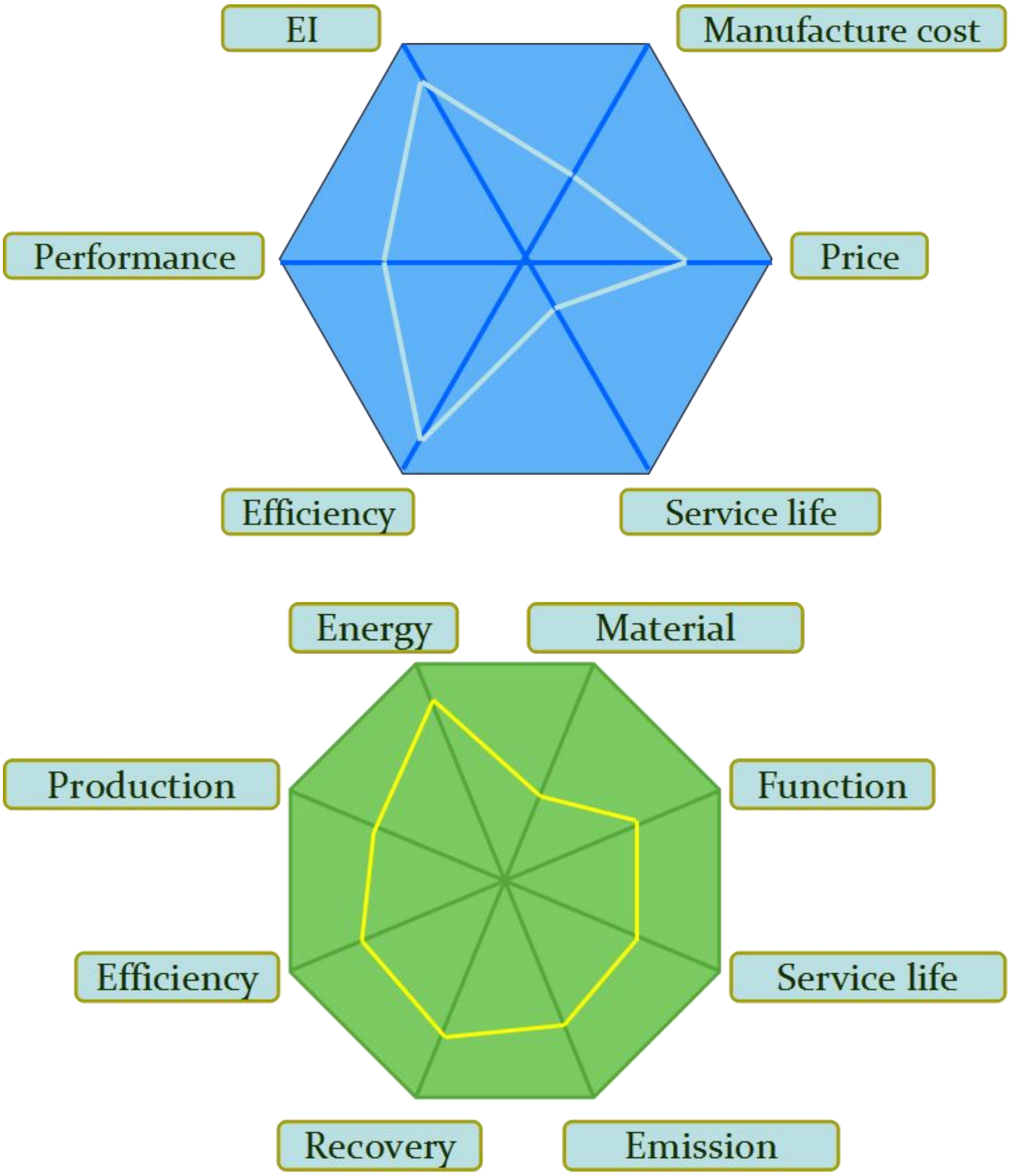


Figure 4.10 two examples of EI-COST

4.6 Concluding Remarks

A novel approach for sustainable design has been developed in this chapter. Within the approach, a three-tier modelling method for life cycle impact assessment is developed. In the approach, a product is broken into three tiers: part, subassembly, and assembly. Each level has their ecological impact from manufacture, process, material, assembling, human labour, and other aspects. The upper level combines the ecological impact from lower level. At last, ecological impact of assembly goes into its upper level, the final level, and the product life cycle. And then the product life cycle impact assessment is completed. Secondly in the chapter 4, the human labour's ecological impact is proposed. And the method to calculate the ecological impact of human labour in per hour has been developed. The calculation method considered four aspects including food, drink, metabolism, transport. The calculation method has been modelled into SimaPro database for future application and improvement. As mentioned before, the software package, SimaPro, and the LCIA method, ReCiPe, are chosen as the tool and method to conduct the LCIA in the research. A shaft in industrial gearbox is taken as an instance to illustrate the method and procedure to assess the product life cycle using SimaPro and ReCiPe. The modelling of the shaft is parametric. Underpinned with product life cycle, SimaPro and ReCiPe, the sustainable design approach has been developed, which uses three-tier method and considers human labour's ecological impact.. .. At last, a representation layout, EI-COST is proposed. It is a spider net chart applied to present and evaluate the product specification or illustrate product properties including ecological and manufacture cost.

Chapter 5 Sustainable design optimisation using genetic algorithm

5.1 Introduction

In general, the optimum design of mechanical product is implied in concept design, detail design, process planning, and manufacturing. Constraints like performance, reliability, and processing costs are considered during design stage. But for sustainable optimum design, whose aim is to minimise the ecological impact of product. Other sections in product life cycle, which includes service life, disassembly, disposal, recycle, reuse, etc. should be considered as well. Because of the entire product life cycle produce an impact to the environment, considering comprehensively is necessary for reducing the ecological impact of product. Eco-constraints like high recycle rate, low ecological impact, long service life, etc. should be considered in sustainable optimum design of mechanical product.

The optimisation of sustainable design is a multi-disciplinary and multi-objective one. Disciplinary such as mechanical design, engineering management, life cycle assessment, are involved. The objectives include to minimise the ecological impact, to minimise the manufacture cost, to maximise service life, to maximise recycle rate, etc. Variables include dimension parameters and other parameters involved in life cycle. Constraints include limitation of design, performance requirement, and strength check. The case studies in next chapter will show results of above factors involved in optimisation problem.

Due to the implementation of multi-disciplinary and multi-objective, the problem becomes very complex in nature and quite hard to solve by conventional optimisation techniques. (Singh, 1996) (Hitomi, 1996) A capable algorithm for the problem is needed. Nowadays, there are numbers of algorithms simulating living beings to solve optimisation problems. The genetic algorithms are the most widely applied one. (Gen&Cheng, 1997)

Genetic algorithms start with an initial set of random solutions called population. Each individual in the population is a solution set of the problem. After evaluating the fitness of every individual in the population of each generation, healthier individuals are randomly selected from the current population, and form a new generation through crossover or mutation. After several generations, the algorithm stops when one of the stopping criteria is met, and the optimum solution to the problem is obtained.

Genetic algorithms are different from traditional optimisation and have several advantages for applying to solve optimisation problems. Genetic algorithms do not need excessive mathematical knowledge about the optimisation problems, and can handle any kind of objective functions or multi-objectives and any kind of constraints such as linear or nonlinear. Because of its evolutionary property, it will search for solutions taking no account of specific inner workings of the problem. Therefore, The sustainable optimum design of the approach needs genetic algorithms.

The ergodicity of evolution operators makes genetic algorithms very effective at performing global search. The traditional approaches perform local search by a convergent stepwise procedure, which compares the values of nearby points and moves to the relative optimal points. Global optima can be found only if the problem possesses certain convexity properties that essentially guarantee that any local optima are global optima.

Genetic algorithms provide us a great flexibility to hybridize with domain-dependent heuristics to make an efficient implementation for a specific problem. (Goldberg, 1989)

5.2 Methodology

During the earliest, objectives, constraints, and variables should be defined before conducting optimum design. Objectives of the optimum design include minimum ecological impact and minimum manufacture cost. These are the fitness functions which can evaluate individuals in the population are meet the requirements or not. Some of parameters are set as variables in the optimum problem. All of other parameters, such as dimension, distance, time, weight, which are involved in the ecological impact calculation of gearbox life cycle, are assigned based on the design of gear box. Constraints include dimension bound, performance, strength check, and are expressed by inequality or equality. When objectives, variables, and constraints are defined, the optimisation can be conducted underpinned with the optimisation toolbox solvers of the software MATLAB.

Optimisation is to search for the solution that minimises the objective function. The algorithm begins by creating a random initial population. And then it creates a number of new populations. At each step, it uses the current population to create next generation. The algorithm selects some individuals in the current population, called parents, who contribute their genes to their children. It usually selects individuals that have better fitness values. (MATLAB, 2011)

The genetic algorithm creates three types of children for the next generation:

- Elite children are the individuals in the current generation with the best fitness values. These children survive to the next generation.
- Crossover children are created by combining the vectors of parents.
- Mutation children are created by random changes

Figure 5.1 Three types of children (MATLAB, 2011) [Removed due to Copyright restrictions]

As the number of generation increases, the individuals in the population get closer together and approach the minimum point.

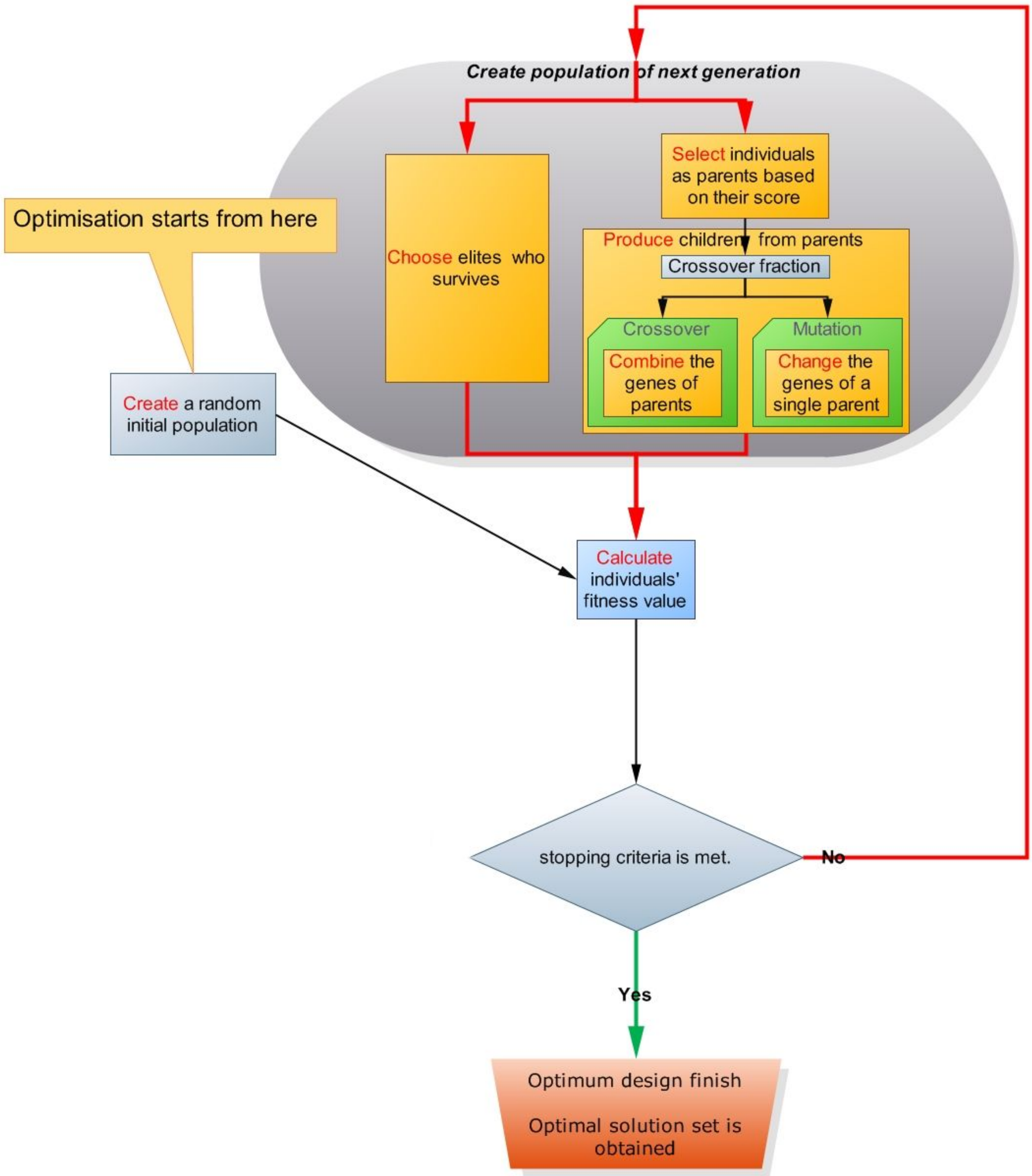


Figure 5.2 Genetic algorithm flow chart in MATLAB

The genetic algorithm uses the following stopping criteria:

- **Generations**
- **Time limit**
- **Fitness limit**
- **Stall generations**

- **Stall time limit**
- **Function Tolerance**
- **Nonlinear constraint tolerance**

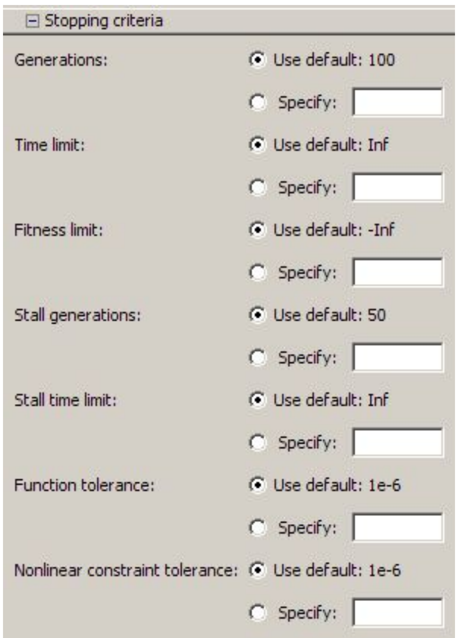


Figure 5.3 Stopping criteria pane in the optimisation tool

The algorithm stops if one of these conditions is met. Depends on vary cases and conditions, the values of these criteria can be modified in the Stopping criteria pane.

- **Determination guidelines of stopping criteria**

1) Generations, time limit

In this optimisation, generations and time limit are set as much as possible. This is because fitness and objective functions are concerned but not generations and time consumption. Certainly, they should be limited if the process of optimisation is too long that beyond designer's tolerance.

2) Fitness limit

Fitness limit is an upper boundary of value of fitness function. When the value of fitness function reaches or is less than the limit. The optimisation will stop. In this optimisation, minimum value of fitness function is a solution. Besides, less value is better solution. So, this option can be set to default value which is '-inf'.

3) Stall generations

This stopping criteria works based on function tolerance setting. If the weighted average change in fitness function value over stall generations, which is called iterative generations, is less than the function tolerance, the optimisation will stop. This setting should be set to an appropriate value, for example, default value is 50. If the value is too small, the solution may be the local minimum, which is not the best point to the optimisation. If the value is too large, the optimisation will be a time-consuming task, and most of working time may be waste. Certainly, it also relates to the set of function tolerance.

4) Function tolerance

As mentioned above, it works with stall generations. In the stage of checking function tolerance and weighted average change in fitness function value over stall generations, the solution may be the local minimum if the function tolerance is set to too large value. The process of optimisation will waste a lot of time or be endless if the value is set to too small.

5) Stall time limit

Usually, time cost is not too much to wait for a result over stall generations. So, default value of it is often kept.

When the process stopped by meeting one of stopping criteria, the optimal solution set is obtained. The optimisation process should be run several times under different settings of stopping criteria to avoid obtaining a larger local minimum in boundary. The methodology described here is validated in chapter 8.

5.3 The Procedure of sustainable product design approach

The procedure of sustainable product design approach is shown in Figure 5.4. When a new design produced based on the product specification, the key components of the design are broke into three sections firstly, they include parts, sub-assemblies and assembly. At the same time, ecological impact of human labour is considered in the production stage. The values of product are used as the inputs to the software SimaPro, where the midpoint ecological impact indicators are calculated first, followed by calculation of the endpoint ecological impact indicators. With the indicator values obtained from SimaPro, the assessment of the product's ecological impact is then carried out by RECIPE method. After LCIA, results are analysed comprehensively underpinned the powerful results presentation function of SimaPro.

If the analysis results are satisfied for the requirement of sustainable, then the design finishes; otherwise, the design parameters such as dimensions will be optimised using genetic algorithm in MATLAB. The optimised design will be conducted life cycle impact assessment again to compare with the original design. LCIA results comparison of previous design and optimised design in SimaPro will reveal whether the optimisation is satisfied or not. If not, the design flow will go back to optimisation stage again to re-design the product. If yes, the design is finished.

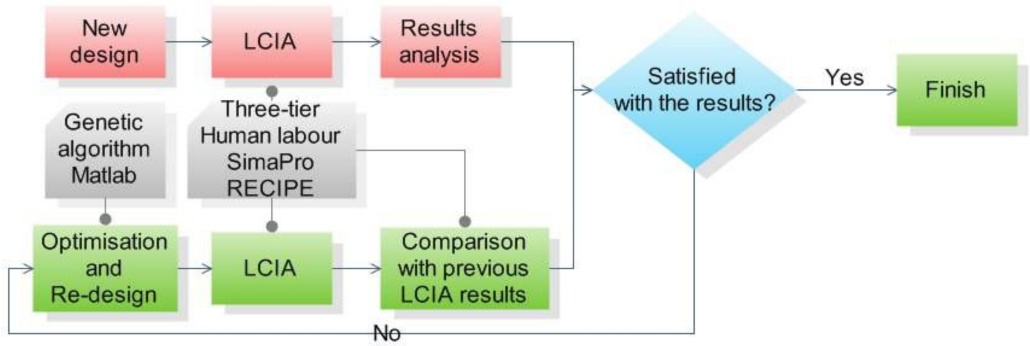


Figure 5.4 Procedure of sustainable product design approach

5.4 Concluding Remarks

An optimisation method for sustainable design using genetic algorithm is developed and presented in this chapter. The chapter starts from an introduction of optimisation, and genetic algorithm. Advantages of genetic algorithm are stated. After that, the methodology of optimisation and genetic algorithm are clarified. The optimisation consists of three essential elements, objective, constraint, variable. Three types of creating children include elite, crossover, and mutation. And stopping criteria of optimisation consists of generations, time limit, fitness limit, stall generations, stall time limit. Also, determination guidelines of stopping criteria are introduced. In the end, the procedure of sustainable product design underpinned by LCIA and design optimisation is presented. The procedure integrated previous researches into a complete flow, which is a systemic sustainable design approach.

Chapter 6 The ontology of a product life cycle

6.1 Introduction

This section introduces the existing Web service and search engine system, and then analyses some disadvantages and limitation of existing technology when apply it to manage a product life cycle such as a traditional industrial gearbox.

Nowadays, people are used to share and manage data through Internet even in an industrial environment. Usually, there is an intranet instead of the internet which provides network and database for people in the factory to communicate with each other. It is the same situation in the product life cycle. Supplier, manufacture, distributor, and retailer, even customer in some cases, can share and manage data through the intranet.

But, current Web service and search engine system are using keyword search. Sometimes, the search engine, using keyword search, makes some mistakes. For example, when people search for a keyword on Google, they usually get a lot of information included this keyword, but few one of them serve their purpose. For instance, ‘gear' is what mechanical designer want to find, so "gear" is the keyword. But after putting it into Google, some unwanted information appears on the browser such as Figure 6.1 shows.

Figure 6.1 Keyword search system often gets wrong information

Obviously, it is not a mistake made by Google. The reason is that Google does not understand the differences between mechanical gears and gears that people wear and their real meanings. The only way left is to add another keyword such as mechanical. In this way, people can get some correct information about it. However, people still lose some valuable information that can be found via only one keyword.

What will happen when this search system is applied in industry? In practice, engineers are busy with searching desirable information such as machine maintenance, number of component in stock, components/service supplier, etc. It may result in considerable lost in terms of time and money if the search for an important component is delayed. If the delay happened in the whole life cycle of a product, there will be a considerable amount of lost in time, money, and resources. The lost should be avoided to make the product life cycle more sustainable. To achieve this, ontology is applied in this research.

- **Ontology**

"An ontology is a description (like a formal specification of a program) of the concepts and relationships that can formally exist for an agent or a community of agents." (Gruber, 2001). This description is provided by Protégé homepage. "An ontology describes the concepts and relationships that are important in a particular domain, providing a vocabulary for that domain as well as a computerized specification of the meaning of terms used in the vocabulary. Ontologies range from taxonomies and classifications, database schemas, to fully axiomatised theories. In recent years, ontologies have been adopted in many business and scientific communities as a way to share, reuse and process domain knowledge. Ontologies are now central to many applications such as scientific knowledge portals, information management and integration systems, electronic commerce, and semantic web services."(Protégé homepage, 2009)

- **Protégé**

Protégé is a free, open source software developed by Stanford Centre for Biomedical Informatics Research at the Medicine School of Stanford University collaborated with University of Manchester. Now Protégé has 122,612 registered users and run to 4.0 version by 16 June 2009. It is an ontology editor and knowledge-based framework and provides user community with friendly interface and tools to construct domain models and knowledge-based applications with ontologies. Customisation provides domain-friendly support for creating ontology models and entering data.

There are two main ways of modelling ontologies: Protégé-Frames editor and Protégé-OWL editor. The Protégé-Frames editor enables users to build frame-based ontologies in accordance with the Open Knowledge Base Connectivity protocol (OKBC).The Protégé-OWL editor enables users to build ontologies for the Semantic Web, especially in the W3C's Web Ontology Language (OWL).(Protégé homepage, 2009) So, this project will build up the ontology by Protégé-owl editor.

The Protégé-owl editor is a part of Protégé which supports the OWL. OWL is the most recent developed standard ontology languages, and it is endorsed by the World Wide Web Consortium (W3C) to promote the Semantic Web vision. Usually, an ontology contains descriptions of classes, object or data type properties and their instances. In this way, The OWL formal semantics specifies how to derive its logical consequences. The interface of Protégé-owl editor is clear, flexible, so that is easy to create ontology model and modify it.

In another word, the ontology is a set of data around products. If putting it into computer, the computer would not only learn one keyword of the product like before, but also learn all related information and a network of these data. This is the way to make the computer understands what people search and give the desirable result with related information to the user.

So, an ontology model should be established to make the database of the product life cycle understandable to computers. Concepts and relationships between them will be recorded in computer. Based on relationships between these concepts, when users of the ontology search for specific words in a domain or terms in a product life cycle. They will get what they want and a set of other information related to the result. If this technology is applied to Google, Searching would be an easier and more precise thing. If it is applied for an engineering purpose, more benefits such as reducing cost and saving working hours will be obtained.

With the ontology developed, users can get accurate product data information easier and quicker than before. The efficiency will increases than that before the ontology is applied. In addition, many useful product data information, such as price, service life, supporter information, can be obtained at the same time because they are interrelated by ontology which is established. For example, if the user searches for the gear again, the mechanical gear will be obtained, and all dimension, supplier information, material, etc. will also appears with the gear awaiting user to check.

Based on the concept and features, ontology is also a powerful tool to manage products and the relationships between different parts, products, properties of parts, and factories in one specific area such as a factory or an industrial estate. It has more ability to communicate and connect among designer, manufacturer, consumer and applications used by them such as design optimisation and software.

6.2 Ontology modelling

As mentioned before, an ontology model of product life cycle is built up for reducing cost and saving working hours. In this section, all details of ontology model construction are listed. How to construct one domain ontology model will be illustrated step by step. The ontology modelling process will be conduct as shown in Figure 6.2. At first, all classes are listed after researching for this domain, such as research of product gearbox life cycle. And then, all the classes will be arranged in a logical hierarchy structure based on the analysis of relationships of them. Secondly, all properties relating to these classes are listed. There are two types of property, data-type property and object property. At the same time, all classes and properties will be arranged reasonably based on logic and experiences from engineers, workers, and customers. At the final stage, some instances will be input in the ontology model to support normal operation of the system and make the final demonstration goes well. In the meantime, ontology modelling tool named Protégé (Protégé, 2011) is used for input these data and construction of the ontology model. Also, the ontology construction and modelling in this research refer to Ontology Development 101(Noy et al, 2002).

Figure 6.2 Break down structure of ontology modelling.

The ontology which will be developed in the research is a collection of concepts and relationships relating to the product life cycle including classes, properties of classes, and relationships among these classes and properties. The classes consist of products, materials, processes, documents, roles, and other classes. The properties consist of dimensions, mechanical properties, and other properties. In classes, there are some instances such as gearbox is an instance of product class. An example of ontology is shown in Figure 6.3. Product, design optimisation method, assembly, subassembly, and components are classes in this ontology. The product and design optimisation method are on the same level. The assembly, subassembly, and components are on the same level. These three classes belong to the product class. Secondly, all properties relating to these classes are listed, such as dimension, ecological impact, and mass are properties of assembly. All classes and properties are arranged reasonably based on logic and experiences from engineers, workers, and customers. Property has two types: object property and data-type property. Object property means various relationships or objects between classes and that link them together, such as the product 'is optimised by' the design optimisation method. The 'is optimised by' is an object property linked two classes, product and design optimisation method together. Data-type property represents all data type property as the deep green symbols shown in Figure 6.3. Such as dimension, ecological impact, and mass are properties of assembly. At the final stage, gearbox is an instance of product class, subassembly of high speed shaft is an instance of subassembly. High speed shaft is an instance of component. Genetic algorithm and matrix are two instances of design optimisation method. Correspondingly, there are several instances of gearbox's property. Such as, 40.0 is an instance of the ecological impact property of the assembly, gearbox.70kg is an instance of the mass property of the assembly, gearbox.

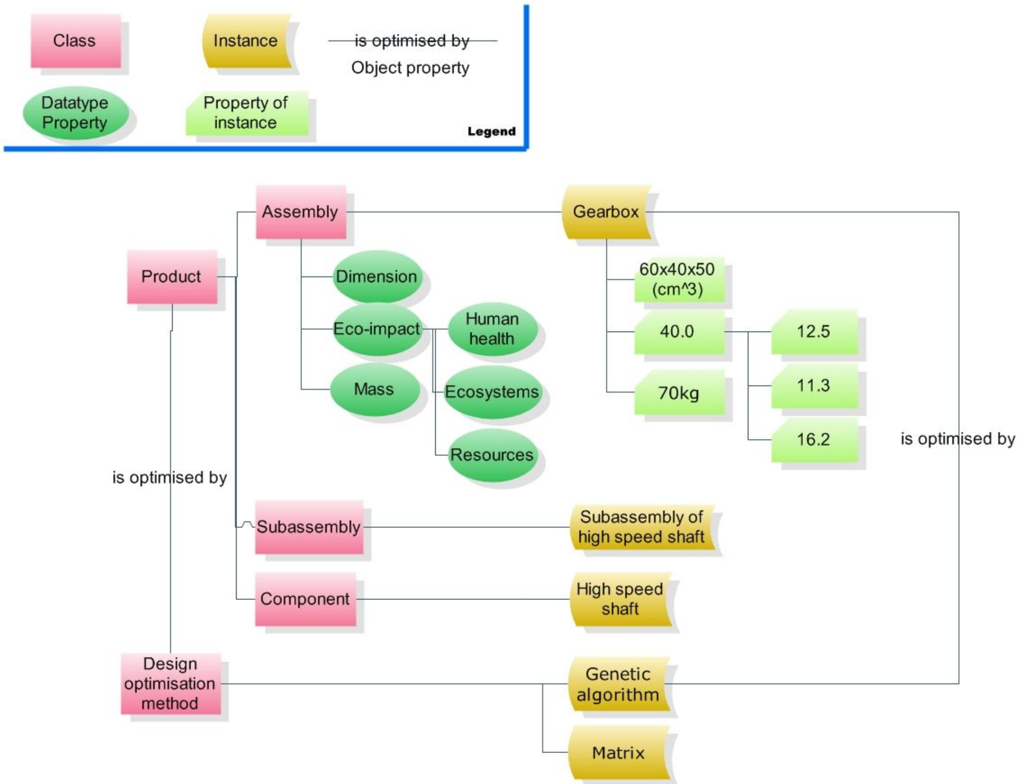


Figure 6.3 An example of ontology.

6.2.1 Class modelling

Class is the most important concept within an ontology, because it is the node of ontology. The ontology has many classes. As some nodes make up a network, these classes build up the ontology. Without these classes as the basic structure, the ontology is not existed. According to the guide of ontology construction named Ontology Development 101 from Noy et al (2002), Class modelling includes two stages, domain research and relationship analysis. Before the modelling, investigation and research for focused domain are extremely necessary for ontology construction. Because scope of ontology is depends on quantity and description for this domain of all classes in the ontology.

Domain research is an exhaustively scan of one specified domain to find out all of concepts, items, objects, etc. Relationship analysis is a process to arrange the hierarchy of the network, the classes in the ontology, into a logical structure.

- **Domain research**

As classes modelling is the most crucial stage of ontology construction, a completely research of specified domain is necessary. Domain scan can be conducted based on product life cycle stage. Classes in each stage should be considered including objects, people and roles, even logical concept. With research for the domain and experience of related knowledge, all the classes should be enumerated as a list of all domain concepts.

For example, product, factory, material, drawing, machine, tool, worker, manufacturer, forklift, etc. are classes in the manufacture stage of product life cycle. Truck, shop, retailer, distributor, product, package, road, etc. are classes in the distribution stage of product life cycle. Specific domain or product life cycle has specified classes and universal classes. Detailed specific research will be emerged in case studies.

- **Relationship analysis**

As Figure 6.3 shows, all the classes are in a hierarchy structure. They all have different hierarchic relationships. This stage is a process to break down the structure of the ontology with a logical relationship.

Product life cycle is a framework to arrange all of classes in a logical hierarchy from cradle to grave, even from cradle to cradle. All the classes within the whole product life cycle will be considered in this way. On the other hand, same type of classes will be arranged in the same group such as roles group has supplier, manufacturer, distributor, retailer, customer, recycler, etc. All the manufacturing process can be put in the same group, so do materials. All the life cycle stage can be in the same group. In other words, relationship analysis can sort out all of the classes and arrange them into different groups in a logical hierarchic structure. These groups are called top level classes.

At first of arrangement, the top level classes should be defined. Each top level class includes many classes under it. Each detail and concept about this class must be considered.

Relationship analysis is useful for later work, object properties. Because some of relationships will be expressed as object properties such as 'is optimised by' in Figure 6.3.

6.2.2 Property modelling

Properties have two types, data type and object. Data type property is the inherent property each class has. Object property represents the relationships among these classes as some lines connecting nodes. As the Figure 6.3 shows, an assembly has six data type properties including dimension, ecological impact, mass, human health ecosystems, and resources. One object property, is optimised by, links between product and design optimisation method.

Properties is very useful during the ontology utilisation stage because all the properties of classes may be the results user want to obtained for quote or calculation. The object properties are the relationships among all the classes, which will be an extra search option or extended search results.

- **Data type properties**

Data type properties enhance diversity of one ontology. Every class have their own property or datum, which makes classes unique and has more personalised. Data type property is also a crucial data for an instance such as gearbox. Dimension, ecological impact, mass, etc. are all the data type properties of the instance, gearbox. These are important attributes of product. Also, these data will be used to calculate ecological impact as parameters. Data type properties can be obtained by design, drawing of product, and other reference.

Data type properties can be name, mark, not only number. This function is friendly and flexible to describe classes. Also, there are many kinds of data type such as boolean, decimal, double, flout, positive integer, non-positive integer, rational, real, short, string, token.

- **Object properties**

Object property is the logical relationships between two classes. Modelling of object property is often a difficult task because all logical relationships are not easy to be considered sometimes. Usually, people will create some of logical relationships related to their application of the ontology not all of them. For product, make as much linkage among classes as possible is good for utilisation of ontology.

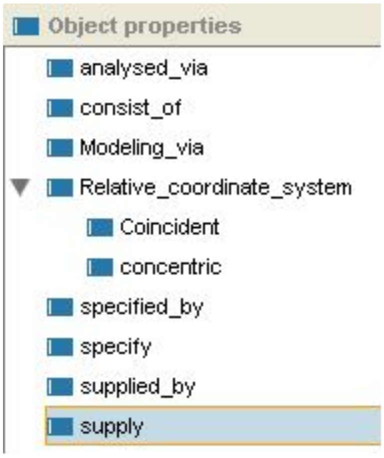


Figure 6.4 Object properties

Object properties like a description of relationships between two classes such as A is a part of B, B contains A, A is designed by C, C has B, etc. Others like analysed via, consist of, modelling via, specified by, specify, supplied by, supply are showed in Figure 6.4.

6.2.3 Instances

Instances input is the final stage of ontology model construction to support the ontology to operate normally. Instance is an example of class with data type properties and object properties. Classes and properties are only the framework of one ontology. So instances are the substances of the ontology. Instances have to be created after definition of class and their properties. For example, gear is an instance of class part.

At last, the ontology will be fill with instances of all the classes, and their data type properties and relationships. Usually, each class has one instance at least. And then, the ontology is set up. The modelling of ontology is finished.

6.3 Connecting Spread sheet between SimaPro and Protégé, LCIA and Ontology

The application of ecological impact assessment using SimaPro is a complicated process as shown in section 4.4. SimaPro only provides a framework for production stage, such as assembly, life cycle, disposal scenarios, reuse, disassembly, etc. and all the elements of each class should be created by user, such as materials and processes of parts, subassemblies, and assemblies, etc. The structure of product should also be established by user during the modelling process. In addition, disposal scenarios, reuse, disassembly, and recycle information are also required as the input data. Designer may master some information such as structure of product, parts, subassemblies, assemblies, materials and processes. Manufacturer may be familiar with processes, disposal scenarios, reuse, disassembly, and recycle. However, the user of the product often does not know all the information that SimaPro requires to assess the ecological impact of the product. Even some user may know some of the information, modelling the product in SimaPro is also a time consuming task. To obtain the information to calculation of material volume and mass also requires large amount of work as shown in the case study. Therefore, a connecting spread sheet is necessary for the user (designer or manufacturer) to effectively utilise SimaPro package to assess the product's ecological impact using the method developed in the research. This research will develop the connecting spread sheet of SimaPro for eco-design of gearbox.

The connecting spread sheet will collect and list all the parameters in the gearbox life cycle, including dimensions of all parts, material, process, and other parameters. When the user wants to input a new series of parameters or modify the parameters of existing gearbox, it can be done in the list of the connecting spread sheet. It is not necessary to open SimaPro to find and input or modify the parameters of each part or subassembly. This can avoid the troubles for inexperienced users to complete the time-consuming task inside SimaPro. The connecting spread sheet will send these inputs or modification into the corresponding positions of elements in SimaPro. Several seconds later, designer will obtained a result report of ecological impact assessment of the gearbox using the parameter which designer has just inputted or modified. The spread sheet will make the modelling of gearbox efficient and convenient and save a lot of time for the user. These advantages provide a valuable support for concept comparison and optimum design.

The development of the spread sheet will use the COM interface function of SimaPro. The spread sheet converts locating tasks which is time consuming in SimaPro into seeking the desired parameter in a parameter list. It also has a potential application for the designer to model more mechanical products in SimaPro and to use the software to assess the ecological impact of more mechanical product efficiently.

Furthermore, the spread sheet can exchange data with MATLAB and Protégé through spread sheet link EX and a plug-in named spread sheet master for Protégé. The spread sheet becomes an intermediary of these software.

6.4 System integration

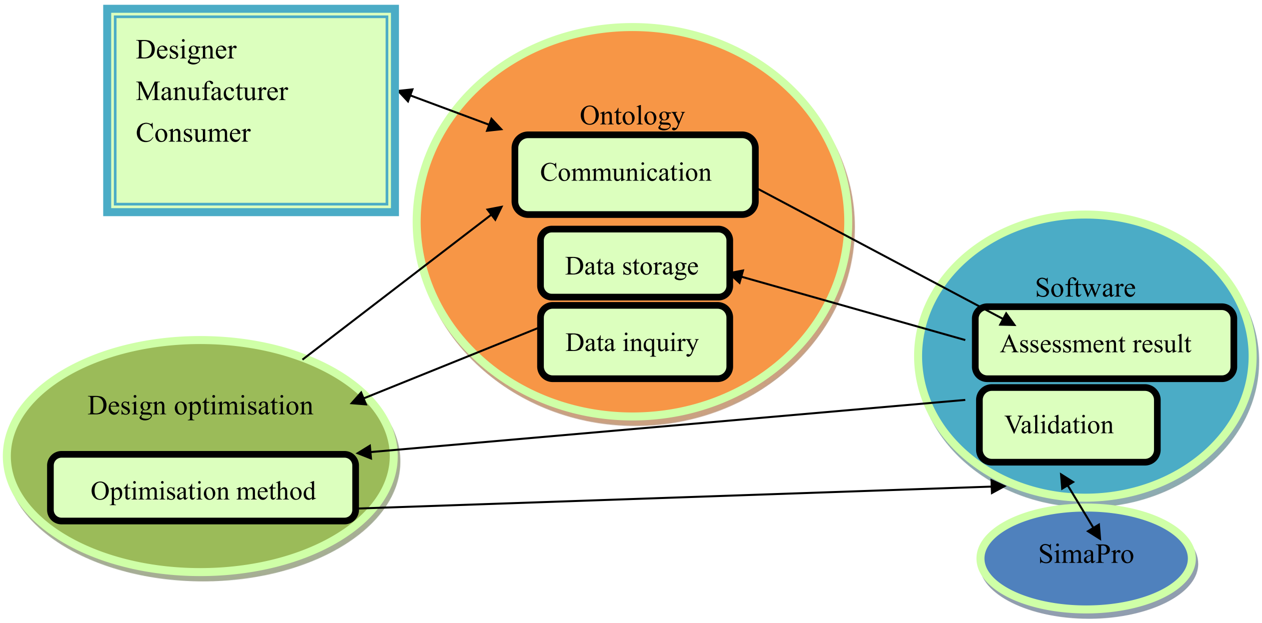


Figure 6.5 Integration of design optimisation, software and Ontology.

As shown in Figure 6.5, after the development of ontology for gearbox manufacturing. The ontology will link designer, manufacturer, consumer, design optimisation and the pre-processing software together to form an integrated system. The ontology stores information of parts, including drawing, dimension, properties, distributer, lifetime, recycle, eco-indicator values and reuse rate. The information is inputted by designer, manufacturer, and consumer, via the user friendly pre-processing software interface. In that case, all the information can be obtained by the people related to the product including manufacturer, designer, distributer, and consumer. In addition, they all can input new and useful data into this ontology. When design optimisation and software integrated into the system, software can assess any product stored in the ontology by inquiring the data of the product after assessment; the results are also stored in the ontology for designer to optimise. Even manufacturer and consumer can propose some advice for the optimisation through the ontology. In the design optimisation, the data of product can be explored. The optimisation concept and original design can be assessed and compared in the software. Once the optimisation concept is validated, it will be stored in ontology for data inquiry from manufacturer and consumer.

So far, designer, manufacturer, and consumer can collaborate together for the product life cycle assessment. Designer can inquires history data of the product and design a new product, or optimised existing product based on the advices provided by manufacturer and consumer. They can also use the software to optimise the product efficiently. The manufacturer can provides data to designer and propose new optimisation concept for more sustainable manufacture. Also, they can inquire advices from consumer and assess the ecological impact of product using the software. The consumer can purchase more sustainable product after assessing the product using the software. Meanwhile, they can propose new idea for improvement for product to designer and manufacturer. It will be a virtuous circle for production. There are many potential advantages will be found if ontology is applied in the research.

6.5 Concluding remarks

Start with introduction of current Web service and search engine system, this chapter analyses some disadvantages and limitation of existing technology and reveals the definition and superiority of the ontology. Afterwards, an ontology modelling method of product life cycle is described. After analysing the break down structure of ontology modelling, an example of ontology is presented. The modelling of ontology can be divided into three sections, class modelling, property modelling, and instance modelling. Class modelling comprises domain research and relationship analysis. Property modelling includes data type and object property modelling. The last step is to input instances of the classes to make the ontology operate normally. After that, an intermediary, a spread sheet, among SimaPro, MATLAB, and Protégé are proposed. The application of the spread sheet increases the compatibility of the whole approach and system. COM interface, Spread sheet link EX, and a plug-in for Protégé named spread sheet master can be used to exchange information between the spread sheet and these three software. With the help of the spread sheet, the scope of system integration is prospected in the end of the chapter. The system links all the users and their data together in the whole product life cycle. Through ontology, they can share their data with other users in the system or conduct the LCIA and optimisation together. There are numbers of potential application in future.

Chapter 7 Life cycle impact assessment of industrial gearbox

7.1 Assembly partition

A single stage industrial gearbox, as shown in Figure 7.1, is taken as an example to illustrate the methodology mentioned in the previous chapters. Following the eco-design procedure, the gearbox is broken into three tiers as shown in Figure 7.2 A: (1) parts, including one spur gear, one high speed shaft, one low speed shaft, two bearings for low speed shaft, two bearings for high speed shaft, five kinds of bolts, two kinds of nuts, one case base, one case cover, and four bearing end caps, etc. (2) sub-assemblies, including high speed shaft assembly, low speed shaft assembly, case, bolts, and nuts as shown in B; and (3) assembly, i.e., the gearbox. All the parts, subassemblies, and assembly are set up as models in the SimaPro as shown in Figure 7.2 B and C.

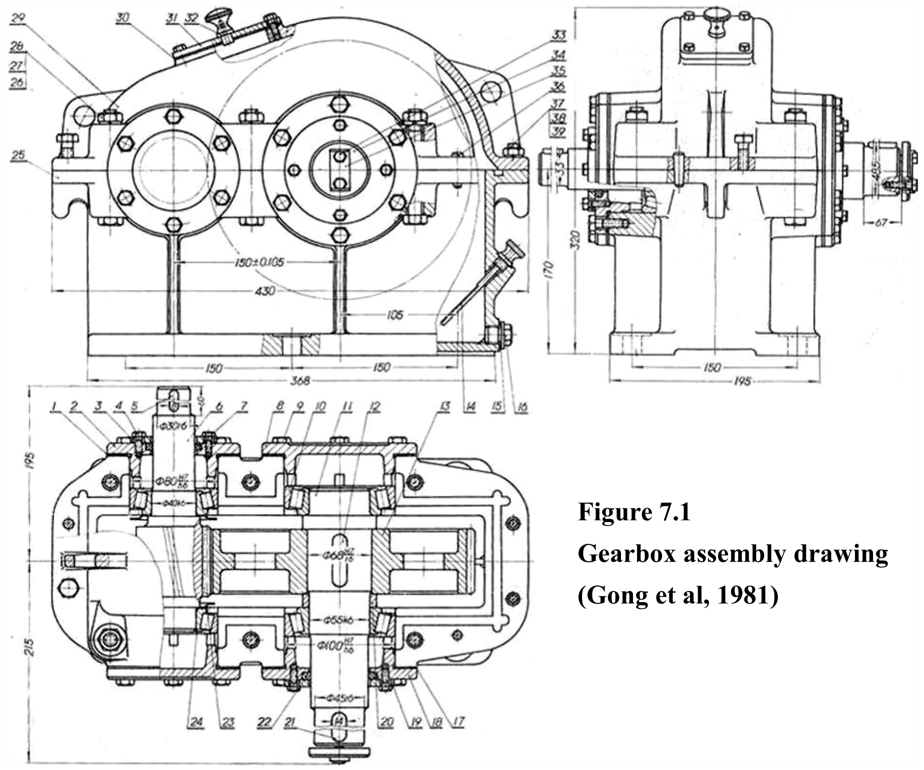
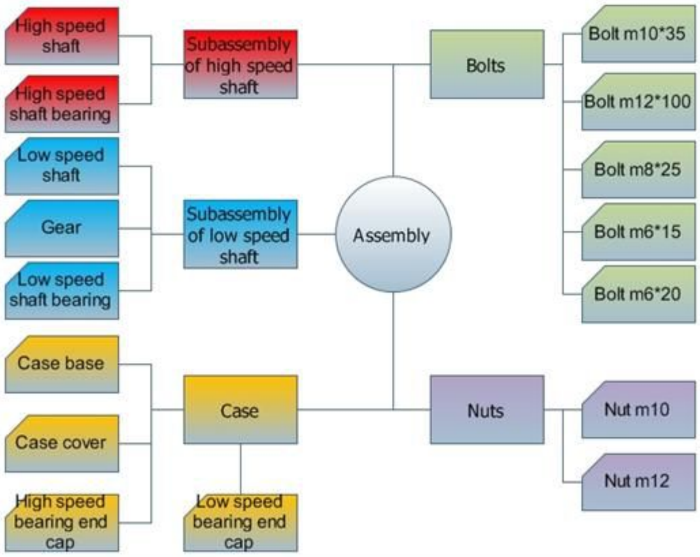


Figure 7.1
Gearbox assembly drawing
(Gong et al, 1981)

7.2 Life cycle modelling of gearbox and calculation of ecological impact

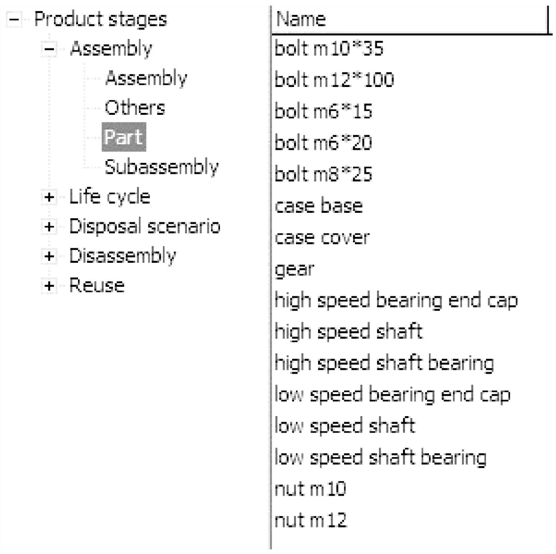
The next step is to model the gearbox into the SimaPro and calculate the ecological impact elements for all the three tiers. The sequence of modelling and calculation is parts, subassemblies, assembly, and life cycle including distribution, disposal, disassembly, and reuse. Step by step, each part has a value of ecological impact. When the parts are assembled together to form a subassembly, extra ecological impact will be produced during assembly process, such as human labour, electricity consumption or others. The same situation happens when subassemblies are assembled together to form the assembly. The situation is shown in the Figure 4.2 in section 4.2.



A. Assembly structure

Materials/Assemblies	Amount
case	1
subassembly of low speed shaft	1
subassembly of high speed shaft	1
Bolts	1
Nuts	1

B. Subassembly list



C. Parts list

Figure 7.2 Gearbox assembly breakdown structure

At first, all geometry dimensions of each part including the parameters and their values are inputted in 'input parameters' provided by SimaPro as shown in Figure 4.9. And then, all the calculated parameters are explained into formation in 'calculated parameters' provided below the 'input parameters'. In that case, the software, SimaPro, calculates them automatically. As mentioned in the methodology, volume and mass of all the parts are calculated in this way. After that, all amounts that the materials used for blanks of parts and cut off by each manufacture process are calculated. All these mass data are inputted in corresponding extrusion or manufacture process in input/output page provided by SimaPro as shown in Figure 4.9. In addition, human labour values involved in each part are inputted as well.

The modelling of all parts, subassemblies, assemblies, disposal, disassembly, reuse, and the recycle of gearbox are completed in corresponding menus provided by SimaPro. For the disposal of the gearbox after the end of its life, all the parts are assumed to be treated as waste scenario, which is a waste distribution list indicated different waste treatments for different waste types in England, provided by PRé in SimaPro.

7.2.1 Modelling of the gearbox assembly.

As shown in Figure 7.2 A, the gearbox assembly is consist of five subassemblies. Each subassembly has number of parts. There are sixteen kinds of parts as shown in Figure 7.2 C. Some of subassemblies have more than one piece of a kind of parts. Such as bearings and bearing end caps, they are always assembled in couples. Also, numbers of bolts and nuts are assembled to tighten the case base and case cover. Completed list of parts is illustrated in Table 7.1. In total, there are 68 parts. In each stage of modelling, number of parts will be multiplied and taken into account of whole results of LCIA.

Table 7.1 Parts list of each subassembly

Subassembly	Part	Piece
subassembly of high speed shaft	high speed shaft	1
	high speed shaft bearing	2
subassembly of low speed shaft	low speed shaft	1
	low speed shaft bearing	2
	gear	1
case	case base	1
	case cover	1
	high speed bearing end cap	2
	low speed bearing end cap	2
Bolts	bolt m10*35	3
	bolt m12*100	6
	bolt m8*25	24
	bolt m6*20	2
	bolt m6*15	12
Nuts	nut m10	2
	nut m12	6
Total		**68**

7.2.1.1 Part modelling

Modelling in SimaPro uses parametric manner. Input parameter is the value that user defined. Calculated parameter is automatically calculated from formula defined by user, which contains input parameters. Each parameter must have unique name in the whole project to avoid confusion. The ecological impact comes from two sections including material extraction and process. The modelling of parts is based on this point. The extraction of used material and manufacture process amount will be modelled for each part.

High speed shaft is a gear-shaft as shown in Figure 4.8. Material of blank is low-alloyed steel. Mass of material used for blank is a calculated parameter named *blank_mass*, which is calculated from input parameters below as Table 7.2. The *blank_mass* is obtained by *blank_volume* multiples density of the material, AISI1040, which is estimated as 7.85e-6 kg/mm^3. The density is valued by the average value of the range of density from 7.8e-6 to 7.9e-6 kg/mm^3. *Blank_volume* is the volume of a cylinder metal blank. The formula to calculate the volume is shown below and in Table 7.2.

$$blank\_volume = \frac{\pi}{4} * blank\_diameter^2 * blank\_length \qquad (1)$$

Input parameters include the length and diameter of the blank, *blank_length and blank_diameter*, and five different length and diameter of each stage of the gear-shaft, *gs_L1*, *gs_L2*, *gs_L3*, *gs_L4*, *gs_L5*, *gs_d1*, *gs_d2*, *gs_d3*, *gs_d4*, *gs_d5*. Calculated parameters include the volume and mass of the blank, and the volume of gear-shaft, *gear-shaft_volume*, which is calculated from input parameters as shown in formula (2).

$$gearshaft\_volume = \frac{\pi}{4} * (gs\_d1^2 * gs\_l1 + gs\_d2^2 * gs\_l2 + gs\_d3^2 * gs\_l3 + gs\_d4^2 * gs\_l4 + gs\_d5^2 * gs\_l5) \qquad (2)$$

And then, the scrap cut off during the process of gear-shaft manufacture is obtained. *gs_scrap_v* is the volume of the scrap which is equal to the difference between that of the blank and that of the gear-shaft. The mass of the scrap, *gs_scrap_m,* is acquired by multiplying the density of the material.

During the process of gear-shaft manufacture, the scrap is cut off by turning and milling. 0.1 kg is estimated as the mass of milling, which is finishing processing. The remind mass of scrap is the mass of turning. As the table shows, turning mass is equal to *gs_scrap_m*-0.1 kg. Human labour used for manufacture of high speed shaft is about one hour.

Table 7.2 High speed shaft modelling parameters

Name	Value	Unit	Comment
high speed shaft			
Materials/Assemblies			
Steel, low-alloyed, at plant/RER U	blank_mass	kg	
Processes			
Turning, steel, conventional, average/RER U	gs_scrap_m-0.1	kg	
Milling, steel, average/RER U	0.1	kg	
Human labour	1	hr	
Input parameters			
blank_length	253	mm	
blank_diameter	70	mm	
gs_L1	60	mm	gear-shaft_length1
gs_L2	70	mm	
gs_L3	38	mm	
gs_L4	20	mm	
gs_L5	65	mm	
gs_d1	30	mm	
gs_d2	38	mm	
gs_d3	40	mm	
gs_d4	48	mm	
gs_d5	65	mm	
Calculated parameters			
blank_volume	pi/4*blank_diameter^2*blank_length	mm^3	
gear-shaft_volume	pi/4*(gs_d1^2*gs_l1+gs_d2^2*gs_l2+gs_d3^2*gs_l3+gs_d4^2*gs_l4+gs_d5^2*gs_l5)	mm^3	
gs_scrap_v	blank_volume-gear-shaft_volume		
blank_mass	blank_volume*7.85e-6	Density of AISI1040 is 7.8e3-7.9e3 kg/m^3 =7.85e-6	
gs_scrap_m	gs_scrap_v*7.85e-6		

Low speed shaft is a shaft as shown in the bottom of Table 7.3. Material of blank is same as the high speed shaft. Mass of material used for blank is a calculated parameter named *blank_m*, which is calculated from input parameters below as Table 7.3. The *blank_m* is obtained by *blank_v* multiples density of the material, which is same as the high speed shaft. The *blank_v* is the volume of a cylinder metal blank. The formula to calculate the volume is shown below and in Table 7.3.

$$blank\_v = \frac{\pi}{4} * blank\_d^{2} * blank\_l \qquad (3)$$

Input parameters include the length and diameter of the blank, *blank_l* and *blank_d*, and five different length and diameter of each stage of the shaft, *s_l1*, *s_l2*, *s_l3*, *s_l4*, *s_l5*, *s_d1*, *s_d2*, *s_d3*, *s_d4*, *s_d5*. Calculated parameters include the volume and mass of the blank, and the volume of shaft, *shaft_v*, which is calculated from input parameters through formula 4.

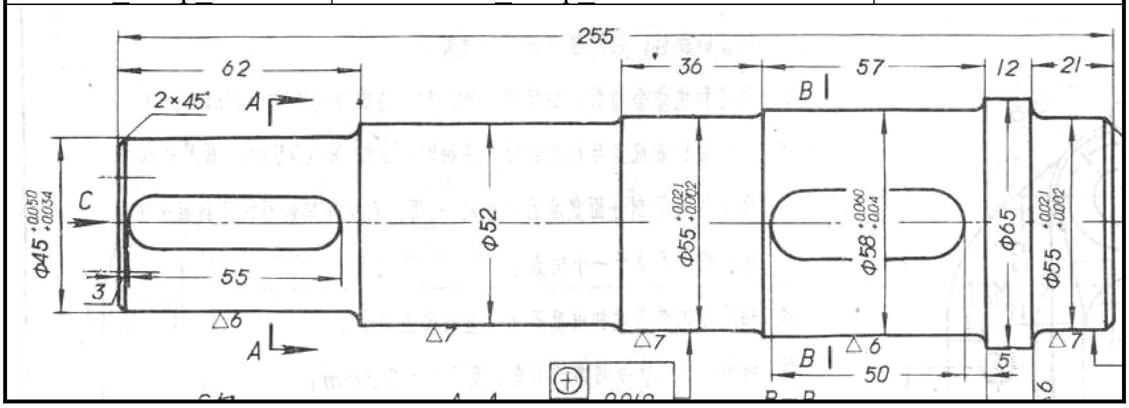
$$shaft\_v = \frac{\pi}{4} * (s\_d1^{2} * s\_l1 + s\_d2^{2} * s\_l2 + s\_d3^{2} * s\_l3 + s\_d4^{2} * s\_l4 + s\_d5^{2} * s\_l5) \qquad (4)$$

And then, the scrap cut off during the process of shaft manufacture is obtained. *s_scrap_v* is the volume of the scrap which is equal to the difference between that of the blank and that of the shaft. The mass of the scrap, *s_scrap_m,* is acquired by multiplying the density of the material.

During the process of shaft manufacture, the scrap is cut off by turning and milling. 0.1 kg is estimated as the mass of milling, which is finishing processing. The remind mass of scrap is the mass of turning. As the table shows, turning mass is equal to *s_scrap_m*-0.1 kg. Human labour used for manufacture of low speed shaft is about one hour.

Table 7.3 Low speed shaft modelling parameters

Name	Value	Unit
low speed shaft		
Materials/Assemblies		
Steel, low-alloyed, at plant/RER U	blank_m	kg
1Processes		
Turning, steel, conventional, average/RER U	s_scrap_m-0.1	kg
Milling, steel, average/RER U	0.1	kg
Human labour	1	hr
Input parameters		
blank_l	255	mm
blank_d	65	mm
s_l1	62	mm
s_l2	67	mm
s_l3	57	mm
s_l4	57	mm
s_l5	12	mm
s_d1	45	mm
s_d2	52	mm
s_d3	55	mm
s_d4	58	mm
s_d5	65	mm
Calculated parameters		
blank_v	pi/4*blank_d^2*blank_l	
shaft_v	pi/4*(s_d1^2*s_l1+s_d2^2*s_l2+s_d3^2*s_l3+s_d4^2*s_l4+s_d5^2*s_l5)	
s_scrap_v	blank_v-shaft_v	
blank_m	blank_v*7.85e-6	
s_scrap_m	s_scrap_v*7.85e-6	



Gear is perforated as shown in the bottom of Figure 7.3. Material of blank is the same as the high speed shaft. Mass of material used for blank is a calculated parameter named *b_m.* The *b_m* is obtained by *b_v* multiples density of the material, which is same as the high speed shaft. The *b_v* is the volume of a cylinder metal blank, which is calculated from input parameters through formula 5 shows below and in Table 7.4.

$$b\_v = \frac{\pi}{4} * b\_d^2 * b\_l \qquad (5)$$

Input parameters include the length and diameter of the blank, *b_l*, *b_d*, amount, length and diameter of holes, *h_a*, *h_l*, *h_d*, two diameters and depth of the ring groove, *r_d1*, *r_d2*, *r_l*, length and diameter of centre hole, *ch_l*, *ch_d*. Calculated parameters include the volume and mass of the blank and the gear, and the volume of holes, ring groove, and centre hole, *h_v*, *r_v*, *ch_v*. which are calculated from input parameters through formula 6, 7 and 8.

$$h\_v = \frac{\pi}{4} \times h\_d^2 \times h\_l \times h\_a \qquad (6)$$

$$r\_v = \frac{\pi}{4} \times (r\_d2 - r\_d1)^2 \times r\_l \qquad (7)$$

$$r\_v = \frac{\pi}{4} \times (r\_d2 - r\_d1)^2 \times r\_l \qquad (8)$$

$$g\_v = b\_v - (h\_v + r\_v + ch\_v) \qquad (9)$$

And then, the volume of gear, *g_v* is calculated by the volume of the blank minus the sum of the volume of the holes, ring groove, and centre hole. The formula 9 is shown above. Then, the scrap cut off during the process of the gear manufacture is obtained. *scrap_m* is the mass of the scrap which is equal to the difference between that of the blank and that of the gear.

Table 7.4 Gear modelling parameters

Name	**Value**	**Unit**	**Comment**
gear			
Materials/Assemblies			
Steel, low-alloyed, at plant/RER U	b_m	kg	
Processes			
Turning, steel, conventional, average/RER U	scrap_m-1	kg	
Milling, steel, average/RER U	1	kg	
Human labour	1	hr	
Input parameters			
b_l	60	mm	length
b_d	237	mm	diameter
h_d	35	mm	hole diameter
h_a	6	mm	hole amount
h_l	15	mm	hole length
r_d1	210	mm	ring diameter1
r_d2	90	mm	ring diameter2
r_l	45	mm	depth
ch_d	58	mm	centre hole
ch_l	60	mm	
Calculated parameters			
b_v	pi/4*b_d^2*b_l		
h_v	pi/4*h_d^2*h_l*h_a		
r_v	pi/4*(r_d2-r_d1)^2*r_l		
ch_v	pi/4*ch_d^2*ch_l		
g_v	b_v-(h_v+r_v+ch_v)		
b_m	b_v*7.85e-6		
g_m	g_v*7.85e-6		
scrap_m	b_m-g_m		

During the process of the gear manufacture, the scrap is cut off by turning and milling. 1 kg is estimated as the mass of milling, which is finishing processing. The remind mass of scrap is the mass of turning. As the table shows, turning mass is equal to *scrap_m*-1 kg. Human labour used for manufacture of gear is about one hour.

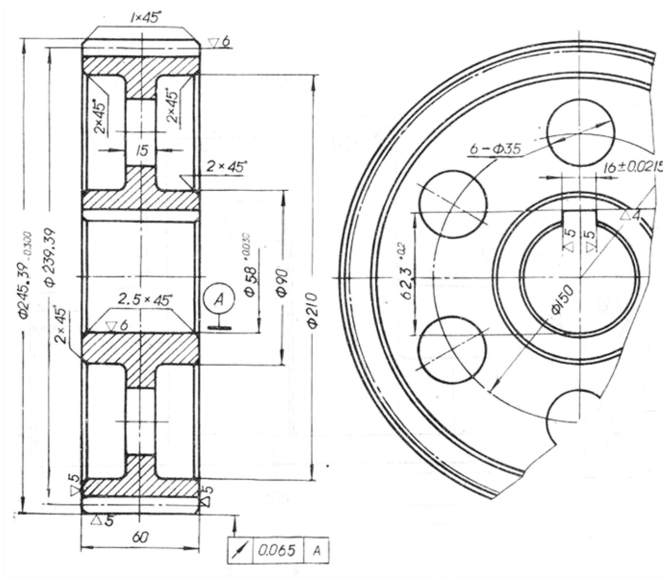


Figure 7.3. Gear (Gong et al, 1981)

Case base is the base of the gearbox as shown in Figure 7.4. Material used is cast iron. Mass of material used is a calculated parameter *cb_m* - *bec_m*, which is the difference from mass of case base and mass of the holes cut off for assembling bearing end caps. They are all calculated from input parameters below as Table 7.5. The *cb_m* is obtained by *cb_v* multiples density of the material, which is estimated as 7.125e-6 kg/mm^3. The density is valued by the average value of the range of density from 7.05e-6 to 7.2e-6 kg/mm^3. The *cb_v* is the volume used to make cast iron. The formula to calculate the volume is shown below and in table 7.5. The volume is equal to the difference from the cube outside to the cube inside of the case.

$$cb\_v = cb\_l \times cb\_w \times cb\_h - (cb\_l - cb\_t) \times (cb\_w - cb\_t) \times (cb\_h - cb\_t) \qquad (10)$$

Input parameters include the length, *cb_l*, width, *cb_w*, height, *cb_h*, and thickness, *cb_t*, of the case base, and five different lengths of bolts, *l1*, *l2*, *l3*, *l4*, *l5*, which are assembled in the case to tighten the case base and case cover. For convenient calculation, all the bolts are calculated with the case base but not case cover. Two diameters of two holes for assembling bearing end caps, *sbec_d*, *lbec_d*, are also included in the input parameters. Calculated parameters include the volume and mass of the case base, all the holes for assembling the bolts, *hole_v*, *hole_m*, and bearing end caps, *bec_v*, *bec_m*. They are all calculated from input parameters. The *hole_v and bec_v* is calculated from formula shown below.

$$hole\_v = \frac{\pi}{4}\times 6^2 \times (l2\times 2 + l1\times 12) + \frac{\pi}{4}\times 8^2 \times 24\times l3 + \frac{\pi}{4}\times 10^2 \times l4\times 3 + \frac{\pi}{4}\times 12^2 \times l5\times 6 \qquad (11)$$

$$bec\_v = \frac{\pi}{4} cc\_t \times (sbec\_d^2 + lbec\_d^2) \qquad (12)$$

During the process of case base manufacture, the mass of holes, *hole_m,* is processed by drilling. Before drilling holes, the case base should be processed by heat treatment. Turning is the finish process to plain the surface of the case base. The weight processed by turning is 1 kg. Human labour used for manufacture of case base is two hours.

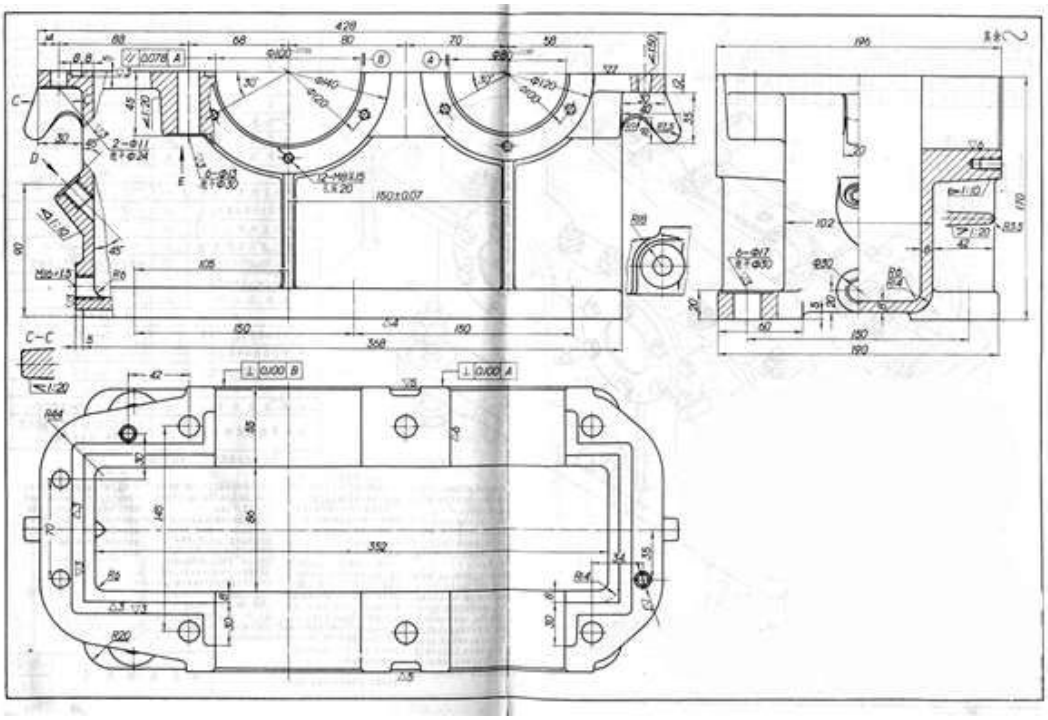


Figure 7.4. Case base (Gong et al, 1981)

Table 7.5 Case base modelling parameters

Name	Value	Unit	Comment
case base			
Materials/Assemblies			
Cast iron, at plant/RER U	cb_m-bec_m	kg	
Processes			
Drilling, conventional, cast iron/RER U	hole_m	kg	
Heat treatment, hot impact extrusion, steel/RER U	cb_m-bec_m	kg	
Turning, cast iron, conventional, average/RER U	1	kg	
Human labour	2	hr	
Input parameters			
cb_l	428	mm	
cb_w	190	mm	
cb_h	170	mm	
cb_t	8	mm	
l1	15	mm	
l2	20	mm	
l3	25	mm	
l4	35	mm	
l5	100	mm	
sbec_d	80	mm	small bearing end cap
lbec_d	100	mm	large bearing end cap
Calculated parameters			
cb_v	cb_l*cb_w*cb_h-(cb_l-cb_t)*(cb_w-cb_t)*(cb_h-cb_t)		
cb_m	cb_v*7.125e-6	Density (7.05e3 - 7.2e3 kg/m^3)=7.125e3	
hole_v	pi/4*6^2*(l2*2+l1*12)+pi/4*8^2*24*l3+pi/4*10^2*l4*3+pi/4*12^2*l5*6		
hole_m	hole_v*7.125e-6		
bec_v	pi/4*cb_t*(sbec_d^2+lbec_d^2)		
bec_m	bec_v*7.125e-6		

Case cover is the cover of the gearbox as shown in Figure 7.5. Material used is cast iron. Mass of material used is a calculated parameter *cc_m - bec_m*, which is the difference from mass of case cover and mass of the holes cut off for assembling bearing end caps. They are all calculated from input parameters below as Table 7.6. The *cc_m* is obtained by *cc_v* multiples density of the material, which is estimated as 7.125e-6 kg/mm^3. The density is valued by the average value of the range of density from 7.05e-6 to 7.2e-6 kg/mm^3. The *cc_v* is the volume used to make cast iron. The formula to calculate the volume shows below and in Table 7.6. The volume is equal to the difference from the cube outside to the cube inside of the case.

$$cc\_v = cc\_l \times cc\_w \times cc\_h - (cc\_l - cc\_t) \times (cc\_w - cc\_t) \times (cc\_h - cc\_t) \qquad (13)$$

Input parameters include the length, *cc_l*, width, *cc_w*, height, *cc_h*, and thickness, *cc_t*, of the case cover. For convenient calculation, all the bolts assembled in the case are calculated with the case base but not case cover. Two diameters of two holes for assembling bearing end caps, *sbec_d* and *lbec_d*, are also included in the input parameters. Calculated parameters include the volume and mass of the case base, *cc_v* and *cc_m*, all the holes for assembling the bolts and bearing end caps, *bec_v* and *bec_m*. They are all calculated from input parameters. The formula for calculate the *bec_v* is same as that in case base.

During the process of case cover manufacture, the case cover should be processed by heat treatment. Turning is the finish process to plain the surface of the case cover. The weight processed by turning is 1 kg. Human labour used for manufacture of case base is two hours.

Table 7.6 Case cover modelling parameters

Name	Value	Unit
case cover		
Materials/Assemblies		
Cast iron, at plant/RER U	cc_m-bec_m	kg
Processes		
Heat treatment, hot impact extrusion, steel/RER U	cc_m-bec_m	kg
Turning, cast iron, conventional, average/RER U	1	kg
Human labour	2	hr
Input parameters		
cc_l	428	mm
cc_w	196	mm
cc_h	140	mm
cc_t	8	mm
sbec_d	80	mm
lbec_d	100	mm
Calculated parameters		
cc_v	cc_l*cc_w*cc_h-(cc_l-cc_t)*(cc_w-cc_t)*(cc_h-cc_t)	mm^3
cc_m	cc_v*7.125e-6	Density 7.05e3 - 7.2e3 kg/m^3
bec_v	pi/4*cc_t*(sbec_d^2+lbec_d^2)	
bec_m	bec_v*7.125e-6	

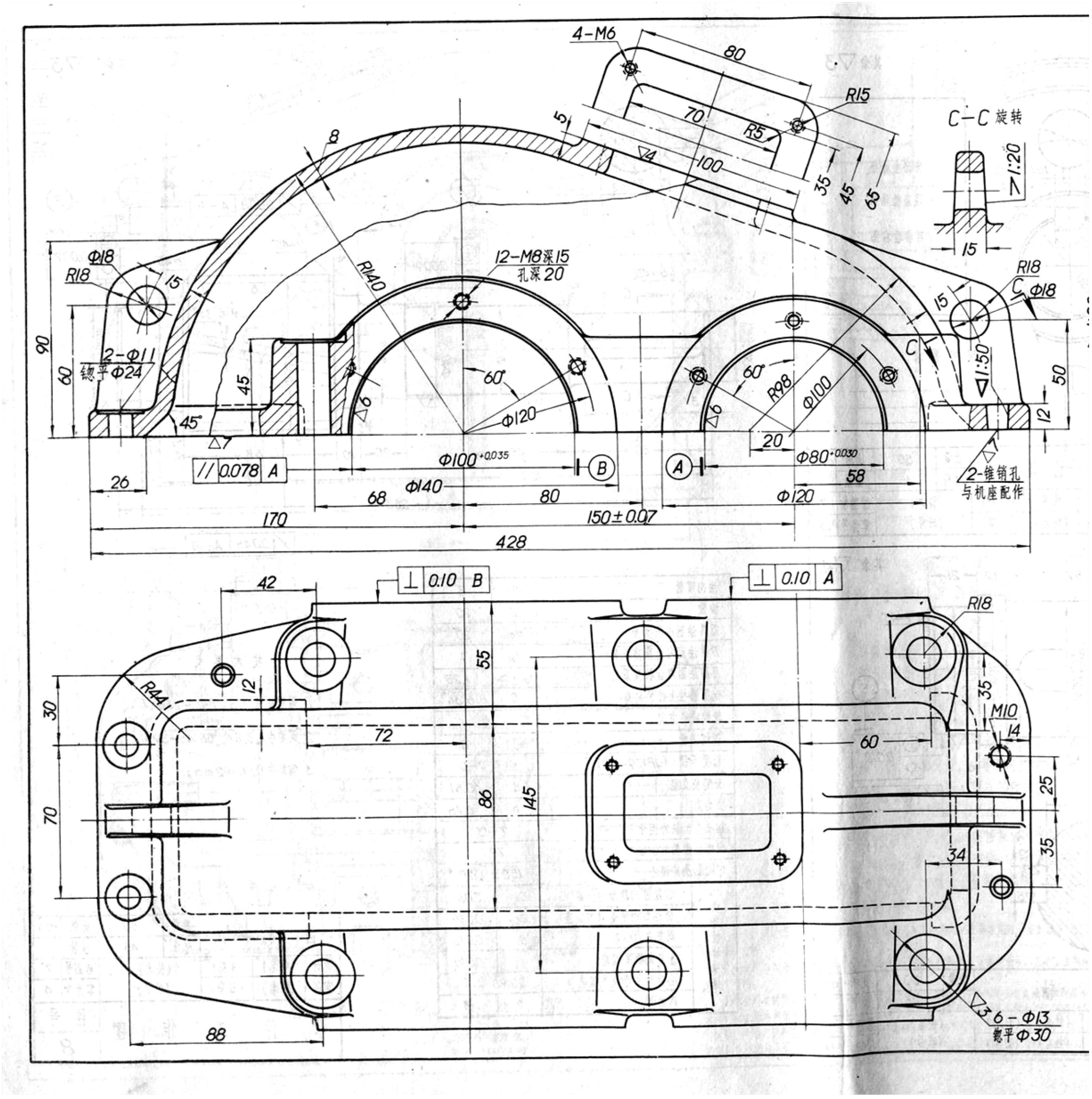


Figure 7.5. Case cover (Gong et al, 1981)

High speed bearing end cap is the end cap of the bearing as shown in Table 7.7. Material used is cast iron. Mass of material used is a calculated parameter, *m*, which is calculated from volume of material used and the density of cast iron, 7.125e-6 kg/mm^3. The *v* is the volume used to make cast iron. The formula to calculate the volume shows below and in Table 7.7. The volume is equal to the sum of a cylinder in left and a ring in right.

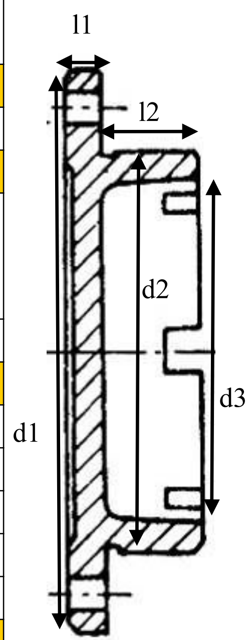
$$v = \frac{\pi}{4} \times d1^2 \times l1 + \frac{\pi}{4} \times l2 \times (d2^2 - d3^2) \qquad (14)$$

Input parameters include the length of the cylinder and the ring, *l1* and *l2*, and three, diameters of them, *d1*, *d2*, *d3*. Calculated parameters include the volume and mass of the bearing end cap, *v* and *m*. They are all calculated from input parameters.

During the process of end cap manufacture, turning is the finish process to plain the surface of the end cap. The weight processed by turning is 0.1 kg. Human labour used for manufacture of end cap is half an hour. The modelling of low speed bearing end cap is similar as that of high speed bearing end cap. The parameters table is presented in the appendix.

Table 7.7 High speed bearing end cap modelling parameters

Name	Value	Unit
high speed bearing end cap		
Materials/Assemblies		
Cast iron, at plant/RER U	m	kg
Processes		
Turning, cast iron, conventional, average/RER U	0.1	kg
Human labour	0.5	hr
Input parameters		
d1	120	mm
d2	80	mm
d3	60	mm
l1	10	mm
l2	50	mm
Calculated parameters		
v	pi/4*d1^2*l1+pi/4*l2*(d2^2-d3^2)	
m	v*7.125e-6	



High speed shaft bearing is the bearing of high speed shaft as shown in Table 7.8. It is a 7208c angular contact ball bearing of GB/T 292-1994 standard. Material used is chromium steel. Mass of material used is a calculated parameter, *m*, which is calculated from volume of material used and the density of the chromium steel, which is estimated as 8e-6 kg/mm^3. The density is valued by the average value of the range of density from 7.93e-6 to 8.09e-6 kg/mm^3. The *v* is the volume used to make chromium steel blank. The formula to calculate the volume shows below and in Table 7.8. The volume of blank is equal to the volume of whole cylinder.

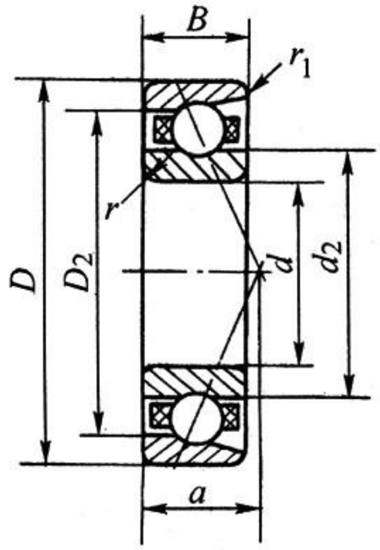
$$v = \frac{\pi}{4} \times b \times (cd^2 - d^2) \qquad (15)$$

Input parameters include four diameters, *d*, *d2*, *cd*, *cd2*, and the thickness of the bearing, *b*. Calculated parameters include the volume and mass of the blank, *v* and *m*. Based on the GB/T 292-1994 standard of 7208c angular contact ball bearing. The mass of the final bearing is about 0.37kg.

During the process of bearing manufacture, milling is the finish process. The weight processed by milling is m-0.37-0.1. Which is equal to the mass of blank subtracts the mass of the bearing, 0.37, and mass processed by turning, 0.1 kg. Human labour used for manufacture of bearing is half an hour. The modelling of low speed shaft bearing is similar as that of high speed shaft bearing. The parameters table presents in appendix.

Table 7.8 High speed shaft bearing modelling parameters

Name	Value	Unit	Comment
high speed shaft bearing			
Materials/Assemblies			
Chromium steel 18/8, at plant/RER U	m	kg	GB/T 292-1994
Processes			
Milling, chromium steel, small parts/RER U	m-0.37-0.1	kg	7208c m=0.37
Turning, chromium steel, conventional, average/RER U	0.1	kg	
Human labour	0.5	hr	
Input parameters			
d	40	mm	
d2	52.8	mm	
cd	80	mm	
cd2	67.2	mm	
b	18	mm	
Calculated parameters			
v	pi/4*b*(cd^2-d^2)	mm^3	
m	v*8e-6		AISI H12 density 7.93e3-8.09e3 kg/m^3



Bolt m10*35 is an m10 bolt with 35mm length followed by GB/T 5783-2000 standard as shown in Table 7.9. Material used is steel. Mass of material used is a calculated parameter, *m*, which is calculated from volume of material used and the density of the steel, which is estimated as 7.85e-6 kg/mm^3. The *v* is the volume used to make steel blank. The formula to calculate the volume shows below and in Table 7.9. The bolt consists of one cylinder and hexagonal column.

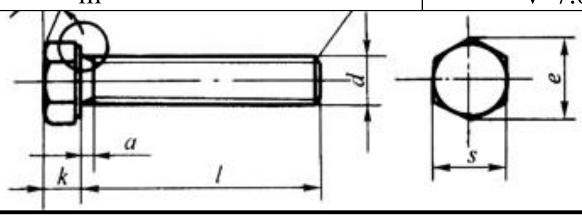
$$v = 0.75 \times e \times s \times k + \frac{\pi}{4} \times d^2 \times l \qquad (16)$$

Input parameters include five dimensions from the standard. Calculated parameters include the volume and mass of the blank, *v* and *m*.

During the process of bolt manufacture, hexagonal column is processed by cold impact extrusion, and cylinder is processed by heat treatment. Human labour used for manufacture of bolt is five minutes. The modelling of other bolts are similar as that of the bolt. The parameters tables of others is presented in the appendix.

Table 7.9 Bolt m10*35 modelling parameters

Name	Value	Unit
bolt m10*35		
Materials/Assemblies		
Steel, converter, unalloyed, at plant/RER U	m	kg
Processes		
Cold impact extrusion, steel, 1 stroke/RER U	0.75*e*s*k*7.85e-6	kg
Heat treatment, cold impact extrusion, steel/RER U	pi/4*d^2*l*7.85e-6	kg
Human labour	5	min
Input parameters		
d	10	mm
e	17.77	mm
s	15.73	mm
k	6.4	mm
l	35	mm
Calculated parameters		
v	0.75*e*s*k+pi/4*d^2*l	
m	v*7.85e-6	



Nut m10 is a standard m10 nut followed by GB/T 6170-2000 standard as shown in Table 7.10. Material used is steel. Mass of material used is the sum of mass of the nut, *mass*, mass of the hole, *hole_m*, and finishing allowance of the process, 0.02kg. Input parameters include five dimensions from the standard. Calculated parameters include the volume and mass of the nut, *v* and *mass*, and the mass of the hole. The *mass* is calculated from volume of material used and the density of the steel, which is estimated as 7.85e-6 kg/mm^3. The formula to calculated the volume, *v*, and the mass of the hole, *hole_m*, are shown below and in Table 7.10.

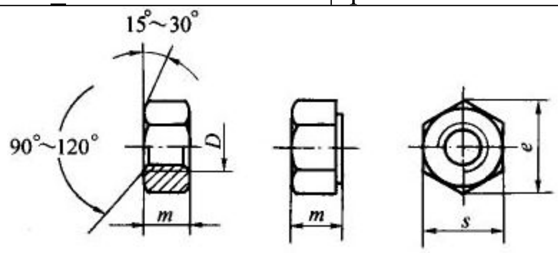
$$v = (0.75 \times e \times s - \frac{\pi}{4} \times d^2) \times m \qquad (17)$$

$$hole\_m = \frac{\pi}{4} \times d^2 \times m \times 7.85e\text{-}6 \qquad (18)$$

During the process of nut manufacture, the hole in the centre is drilled. Turning and milling are also involved. Human labour used for manufacture of nut is five minutes. The modelling of other nuts are similar as that of the nut. The parameters tables of others present in the appendix.

Table 7.10 Nut m10 modelling parameters

Name	Value	Unit&Comm
nut m10		A3 GB/T 6170-2000
Materials/Assemblies		
Steel, converter, unalloyed, at plant/RER U	mass+hole_m+0.02	kg
Processes		
Drilling, conventional, steel/RER U	hole_m	kg
Milling, steel, small parts/RER U	0.01	kg
Turning, steel, conventional, average/RER U	0.01	kg
Human labour	5	min
Input parameters		
d	10	mm
e	18	mm
s	16	mm
m	8	mm
Calculated parameters		
v	(0.75*e*s-pi/4*d^2)*m	mm^3
mass	v*7.85e-6	density 7.85e-6 kg/mm^3
hole_m	pi/4*d^2*m*7.85e-6	



7.2.1.2 Subassembly modelling

As shown in Table 7.1, there are five subassemblies in the gearbox including subassembly of high speed shaft, subassembly of low speed shaft, case, bolts, and nuts. As Table 7.11 shows, each subassembly defines kind and amount of part and time spend of human labour for assembling parts together.

Modelling of subassembly in the SimaPro is to integrate all parts and time spent for assembling these parts together. For example, modelling of subassembly of bolts has two steps including add corresponding amounts of five different types of bolts into the subassembly and add time spend for assembling these bolts to the case. The subassembly of bolts consists of three m10*35 bolts, six m12*100 bolts, twenty-four m8*25 bolts, 2 m6*20 bolts, 12 m6*15 bolts, and 15*(3+6+24+2+12) =705s human labour.

Time spends of assembling one bolt and one nut are estimated as 15 and 10 seconds respectively. Other modelling of subassembly have similar processes. Totally, there are 68 parts in all of these subassemblies, and 17min5s is spent to assemble these subassemblies.

Table 7.11 Subassembly modelling

Subassembly	Part	Piece	Human labour
subassembly of high speed shaft	high speed shaft	1	1min
	high speed shaft bearing	2	
subassembly of low speed shaft	low speed shaft	1	2min
	low speed shaft bearing	2	
	gear	1	
case	case base	1	1min
	case cover	1	
	high speed bearing end cap	2	
	low speed bearing end cap	2	
bolts	bolt m10*35	3	705s
	bolt m12*100	6	
	bolt m8*25	24	
	bolt m6*20	2	
	bolt m6*15	12	
nuts	nut m10	2	80s
	nut m12	6	
Total		**68**	**17min5s**

7.2.1.3 Assembly modelling

The assembly is the gearbox. As table 11 shows, modelling of assembly integrates all of the subassemblies together and add processes used during assembly. Assembly includes one for each subassembly modelling above. Processes used include 2 min human labour for assemble and 0.01 kWh electricity for lifting parts up.

Table 7.12 Assembly modelling

Name	Value	Unit
Original Gearbox		
Materials/Assemblies		
case	1	p
subassembly of low speed shaft	1	p
subassembly of high speed shaft	1	p
Bolts	1	p
Nuts	1	p
Processes		
Human labour	2	min
Electricity, medium voltage, production GB, at grid/GB U	0.01	kWh

7.2.2 Modelling of gearbox life cycle.

The life cycle of original gearbox includes one piece of gearbox, transport to retailer by van, disposal of the gearbox, and one additional life cycle of lubricating oils and greases. The transport is operated by a van with less than 3.5 ton weight load. Distance from factory to the retailer is 10 kilometres. The additional life cycle of lubricating oils and greases lasts one year. It will be replaced by new lubricating oils and greases once per year.

Table 7.13 Life cycle modelling

Name	Value	Unit
Original Gearbox life cycle		
Assembly		
Original Gearbox	1	p
Processes		
Operation, van < 3,5t/RER U	10	km
Waste/Disposal scenario		
disposal of original gearbox		
Additional life cycles		
lubricating oils and greases	1	To change once per year

Disposal of original gearbox refers to the gearbox assembly. Two hours human labour during the disposal process is added into the disposal as well. The waste scenario is estimated as 100% disassembly of the gearbox.

Table 7.14 Disposal of gearbox

Name	Value	Unit
disposal of original gearbox		
Referring to assembly		
Original Gearbox	1	p
Processes		
Human labour	2	hr
Waste scenarios		
Disassemblies		
disassembly of original gear box	100	%

As Table 7.15 shows, disassembly of the gearbox is referred to the assembly to set up connection between it to the assembly. One hour human labour is consumed during the process of disassembly of the gearbox. The separation of sub-assemblies is not considered for the original gearbox. All the waste for the original gearbox is treated by waste scenario for England. The waste scenario for England indicates waste flow for different type of waste in the end life of the product in England.

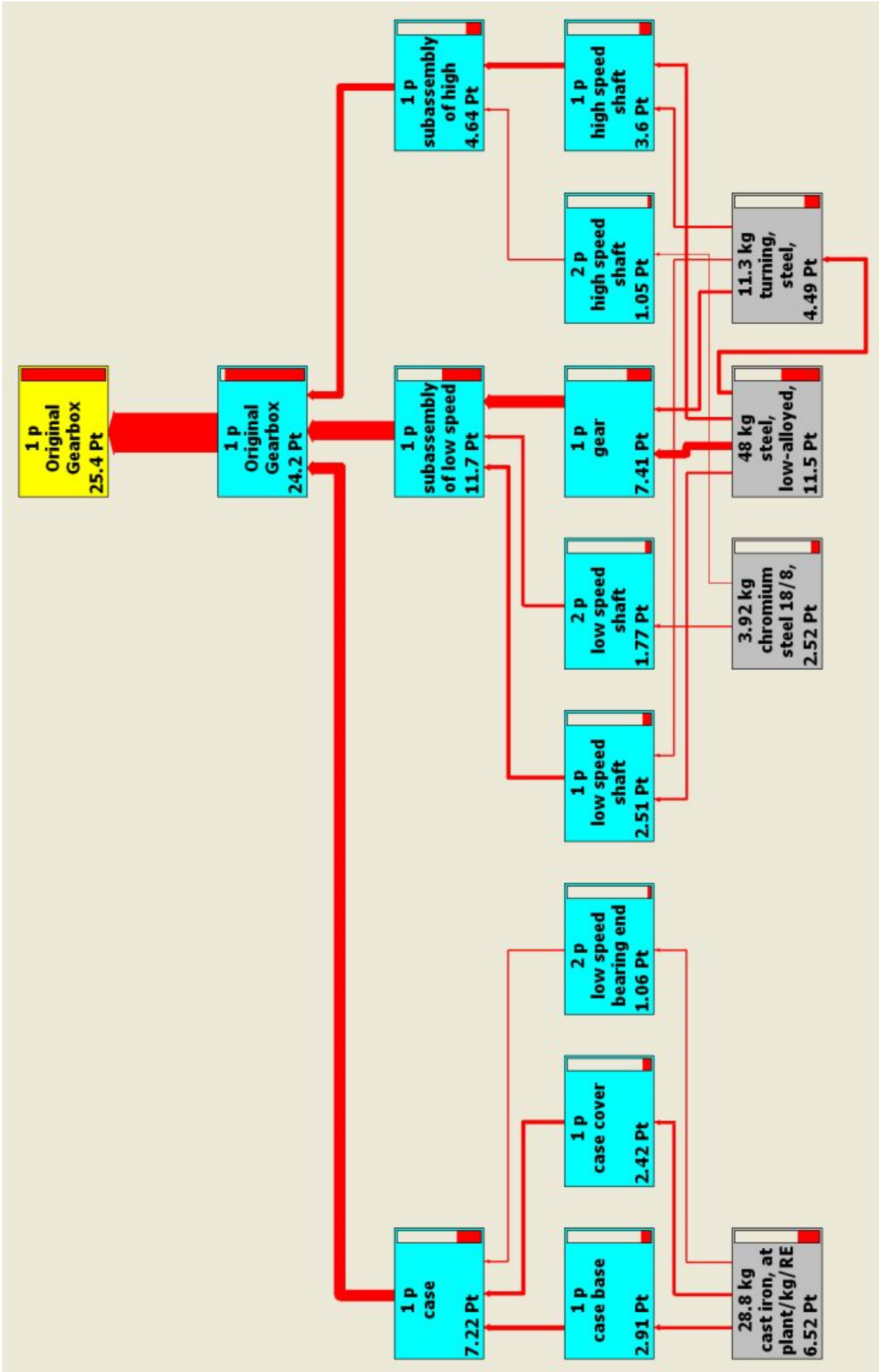
Table 7.15 Disassembly of gearbox

Name		
disassembly of original gear box		
Referring to assembly		
Original Gearbox	1	p
Processes		
Human labour	1	hr.
Separation of sub-assemblies		
Case	0	%
Bolts	0	%
Nuts	0	%
Subassembly of high speed shaft	0	%
Subassembly of low speed shaft	0	%
Treatment of remaining waste		
Waste scenario/Eng. U	100	%

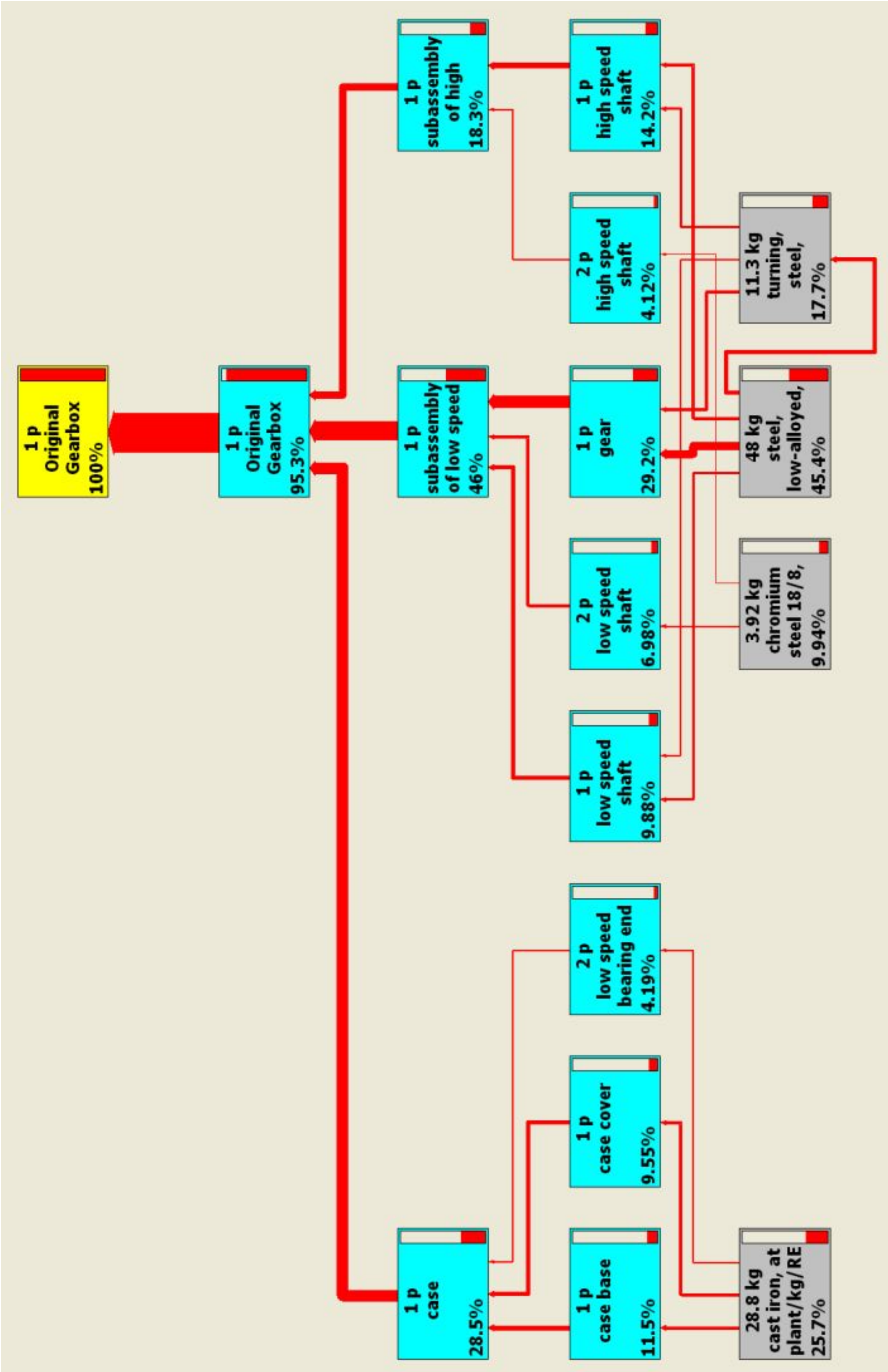
7.3 Assessment results of the gearbox

After the modelling of the gearbox life cycle, SimaPro assesses the model by hierarchist version of the ReCiPe method with normalisation value of world and the average weighting set mentioned in previous chapter.

The network results of ecological impact assessment of the gearbox are shown in Figure 7.6. Figure A shows the ecological impact network in Pt. Yellow box in figure refers to the life cycle of original gearbox. Light blue boxes refer to subassemblies and parts. The grey boxes refer to processes used. For better present of the network, 4% cut-off is applied for the results of the network. That means any ecological impact less than 4% of all the ecological impact have been cut off and hide. Each process has a numerical reading of eco-indicator in left bottom and a red colour bar indicator diagram in right side. A larger reading and larger red bar represent a larger ecological impact that the process generated. Also, a wider arrow represents larger ecological impact flows in and out. Figure 7.6 B shows it in percentage. It is clear to see how much ecological impact is shared by individual process, part, or subassembly. As the figure shows, cast iron, chromium steel, low-alloyed steel and turning process on steel has the most of ecological impact among all the processes and material used in the gearbox life cycle. They score 6.52Pt, 2.52Pt, 11.5Pt, and 4.49Pt and 25.5%, 9.86%, 45%, 17.6% of all ecological impact respectively. Obviously, the low-alloyed steel has the most ecological impact among the all processes and materials used in the gearbox life cycle. Nearly half ecological impact is contributed by the extraction of low-alloyed steel. The cast iron contributes to case base, case cover, and low speed bearing end. Actually, it also contributes to high speed bearing end but it is not displayed cause the 4% cut-off. The chromium steel contributes to low speed shaft bearing and high speed shaft bearing. The low-alloyed steel contributes to low speed shaft, gear, and high speed shaft. And it also processed by turning besides it. The turning contributes to the gear, the low speed shaft, the high speed shaft. And it also contributes to the low-alloyed steel as mentioned before.



A. Network results in Pt. (Point in ReCiPe) with 4% cut-off



B. Network results in percentage with 4% cut-off

Figure 7.6 Network of the gearbox LCIA results

Focusing on parts, which are light blue boxes shown above the grey process boxes, the gear shares the most ecological impact among them. Which is 7.41Pt sharing 29.2% of all the ecological impact. The high speed shaft bearing and low speed bearing end have almost least ecological impact, which are 1.05 Pt. sharing 4.12% and 1.06 Pt. sharing 4.19% respectively. The high speed shaft has the second high ecological impact of all these subassemblies, which is 3.6 Pt. sharing 14.2 %.The case base has the third high ecological impact of all these subassemblies, which is 2.91 Pt. sharing 11.5%. The ecological impact of case cover and low speed shaft are almost same, which are 2.42 Pt. sharing 9.55 % and 2.51 Pt. sharing 9.88 %. The two pieces of low speed shaft bearing has 1.77 Pt. ecological impact, which shares 6.98 %.

Focusing on subassemblies, the subassembly of low speed has the highest ecological impact as 11.7 Pt. sharing 46%. The main reason is the gear has the highest ecological impact. The case and the subassembly of high speed got second and third high ecological impact score, which are 7.22 Pt. sharing 28.5 % and 4.64 Pt. sharing 18.3 %.

The manufacture of gearbox assembly which is shown as the light blue box named original gearbox contains 95.3 % ecological impact of all processes in the gearbox life cycle. That means transport, disposal of gearbox, disassembly of gearbox, additional life cycle of lubricating oils and greases have remaining 4.7 % of ecological impact.

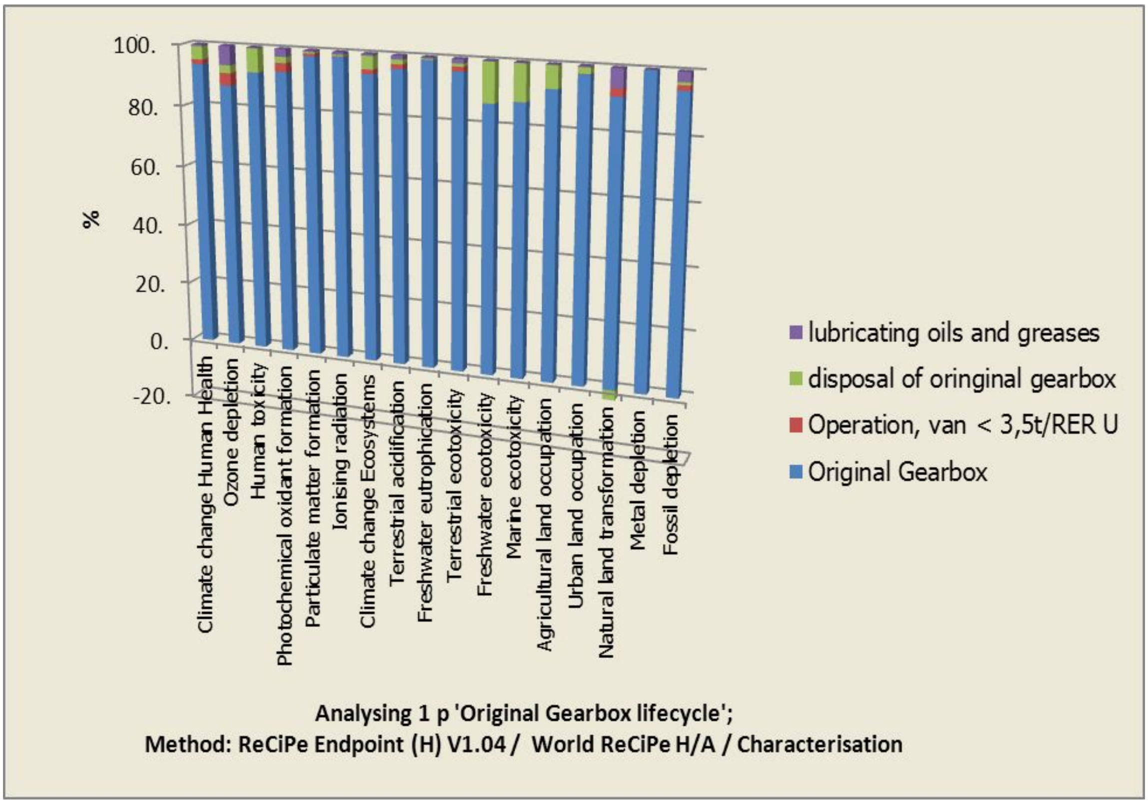


Figure 7.7 Assessment characterisation result of the original gearbox life cycle

Figure 7.7 shows characterisation of ecological impact assessment results. Using different colours, it indicates the ecological impact of gearbox in midpoint categories. Purple, green, red, and blue represent additional life cycle of lubricating oils and greases, disposal of original gearbox, operation of van, and original gearbox assembly respectively. Obviously, the original gearbox shares the largest ecological impact among others. In freshwater eco-toxicity, marine eco-toxicity, and agricultural land occupation, the disposal of original gearbox shares the most of remaining ecological impact. In climate change human health, human toxicity, and climate change ecosystem, disposal of original gearbox shares a lot. In ozone depletion, photochemical oxidant formation, terrestrial acidification, terrestrial eco-toxicity, and fossil depletion, three data share equally. In natural land transformation, lubrication oils and greases and operation of van share most of remaining ecological impact except that of the original gearbox. The ecological impact of original gearbox generates from 85 % to 99 % of all. But these data have not been normalised yet. It only shows the ecological impact percentage of different life cycle stage shared.

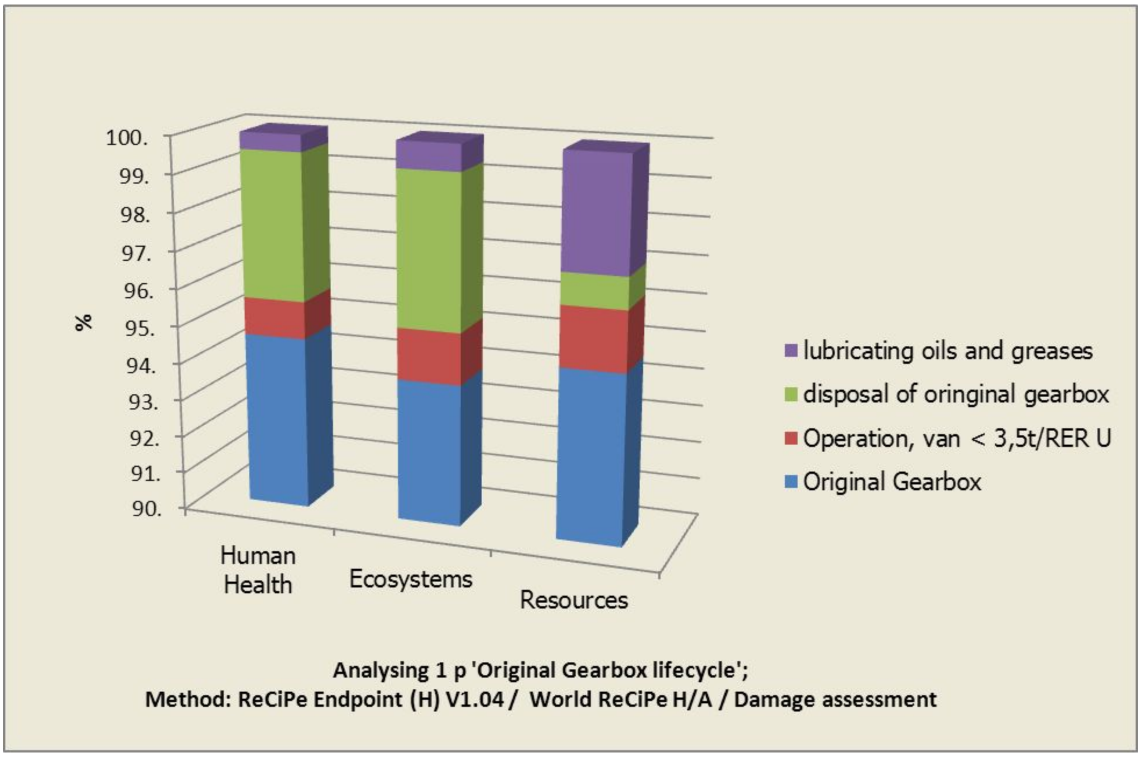


Figure 7.8 Damage assessment result of the original gearbox life cycle

Figure 7.8 shows the damage assessment result in endpoint categories including human health, ecosystems, and resources. The original gearbox still shares the largest ecological impact, which is shown as blue bar sharing from 93% to 94% of all three categories, among others. In resources category, the additional life cycle of lubricating oils and greases shares about 3%. Disposal of original gearbox shares about 1%. Operation of van shares about 2%. In human health category, operation of van shares about 1%, disposal of original gearbox shares about 4%. The additional life cycle of lubricating oils and greases shares less than 1%. In ecosystems category, the situation is similar as that in the human health but these three shares a little bit more than that in the human health.

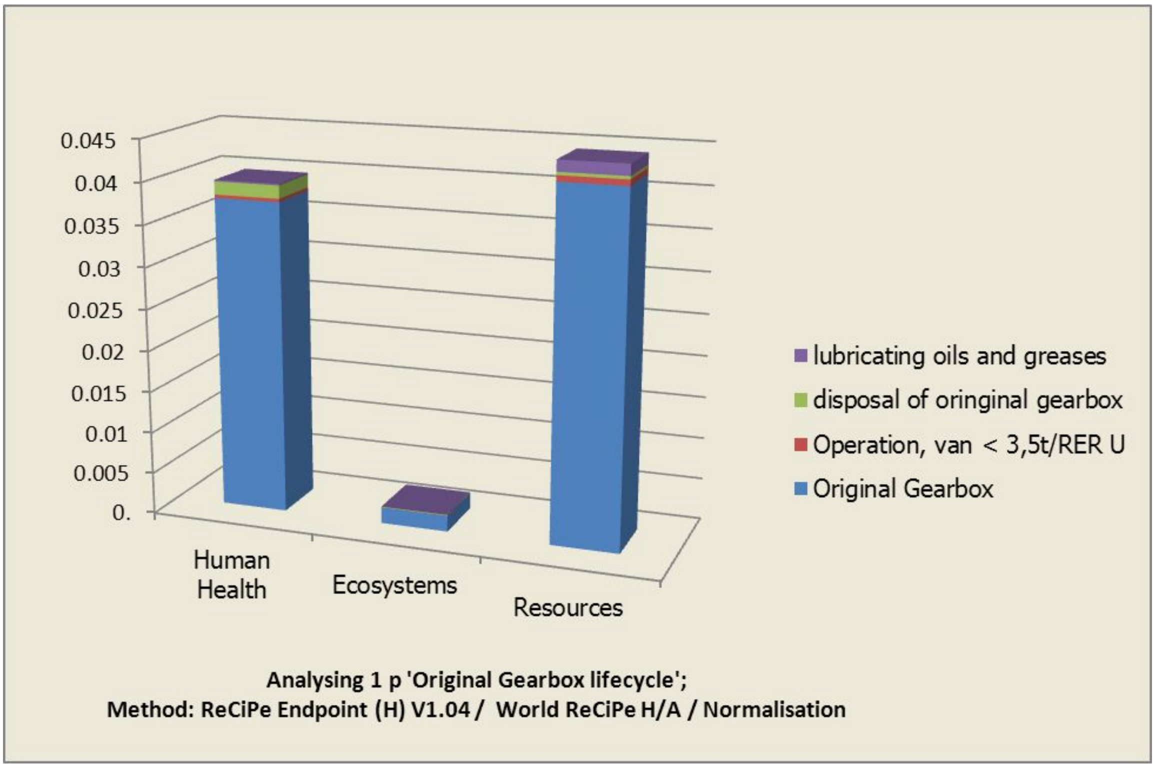


Figure 7.9 Normalisation assessment result of the original gearbox life cycle

Figure 7.9 shows normalisation assessment results which is normalised by different normalisation values of each endpoint category defined by ReCiPe endpoint method Hierarchist version. In world ReCiPe endpoint hierarchist version 1.04, the normalisation values are shown in Table 7.16. After normalisation, the result turns into the bar chart as shown in the Figure 7.9. The ecological impact of human health and resources is much higher than that of ecosystems. The original gearbox still shares the largest ecological impact in both categories. Disposal of original gearbox shares most of remaining ecological impact in human health. And the additional life cycle of lubricating oils and greases shares most of remaining ecological impact in resources. After weighting using the factor shown in the Table 7.16, resources reduces half of ecological impact as shown in Figure 7.10. Because the weighting factor for resources is 200 and that of other two categories are 400.

Table 7.16 normalisation and weighting values defined in the ReCiPe endpoint world hierarchist version 1.04 (ReCiPe Mid/Endpoint method, 2011)

Normalization-Weighting set	World ReCiPe H/A
Normalization	
Human Health	74.6
Ecosystems	1170
Resources	0.0000456
Weighting	
Human Health	400
Ecosystems	400
Resources	200

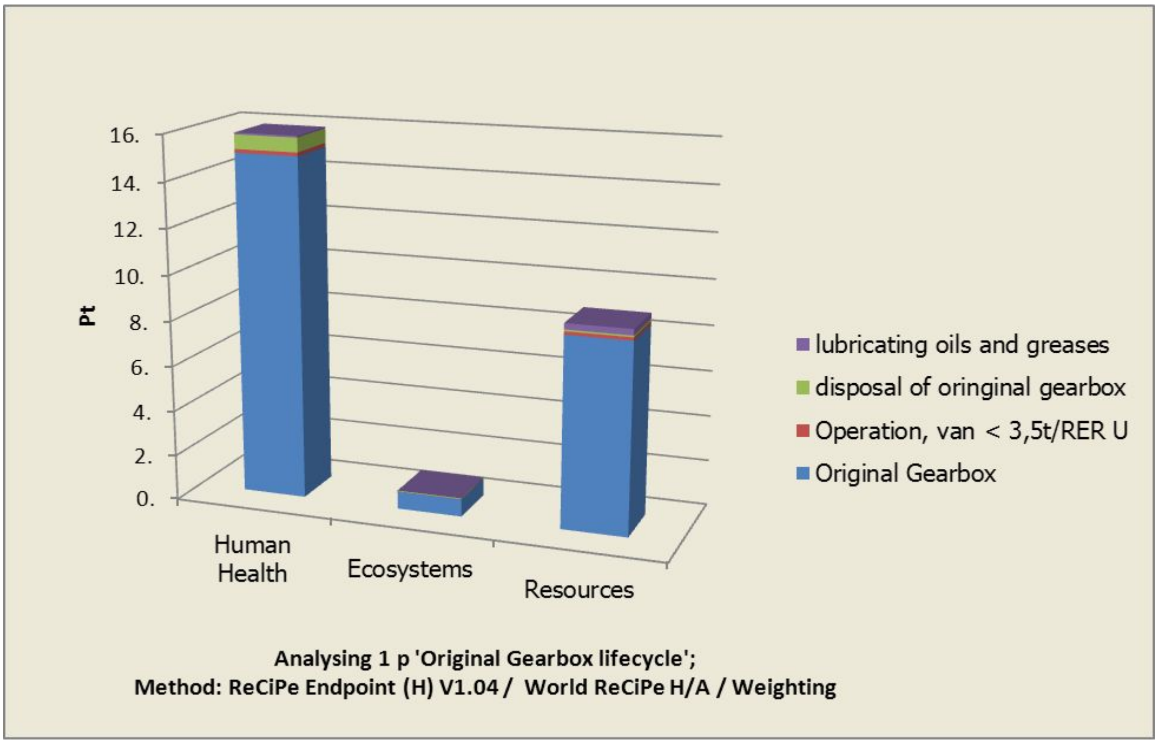


Figure 7.10 Weighting assessment result of the original gearbox life cycle

Figure 7.11 shows a single score assessment result of each life cycle stage in endpoint categories. Original gearbox has the largest ecological impact, almost 25Pt in total. For original gearbox, ecological impact of human health shares the largest part, about 14 Pt. ecological impact of resources shares the second large part, about 10 Pt. ecological impact of ecosystems shares the remaining Pt., about 1 Pt. Other three have a little ecological impact only.

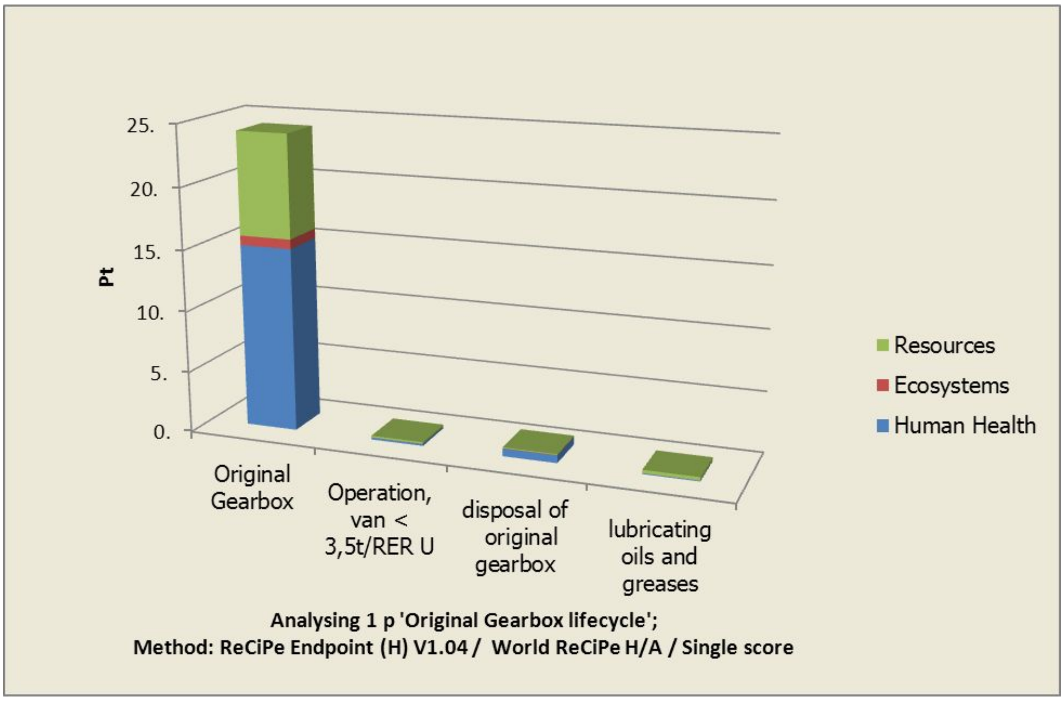
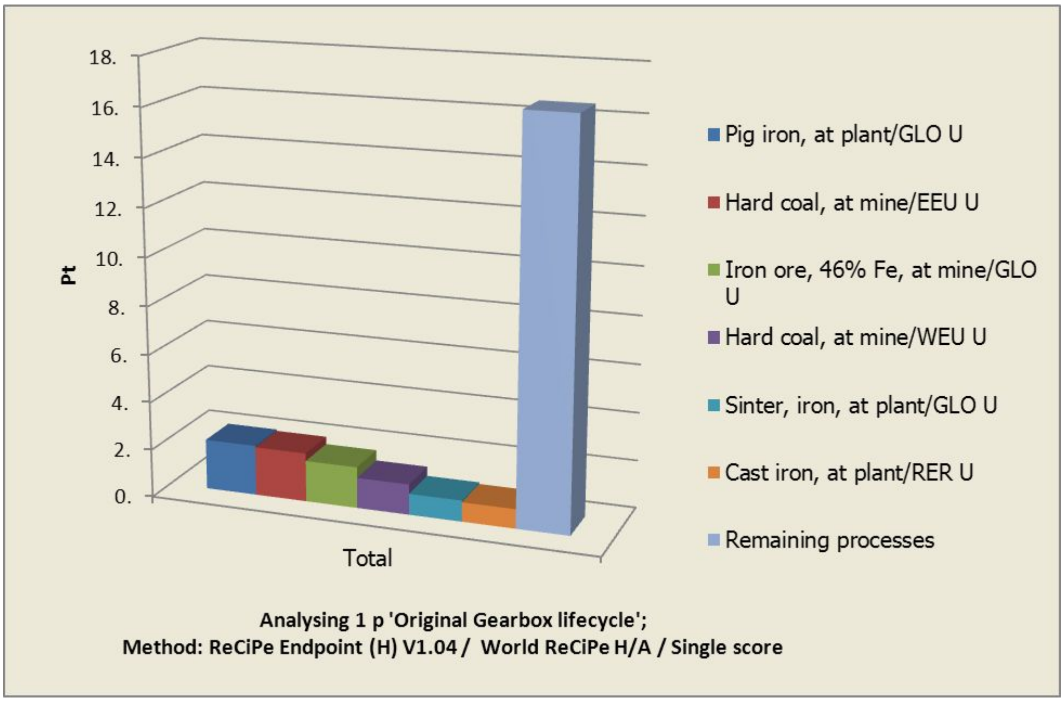
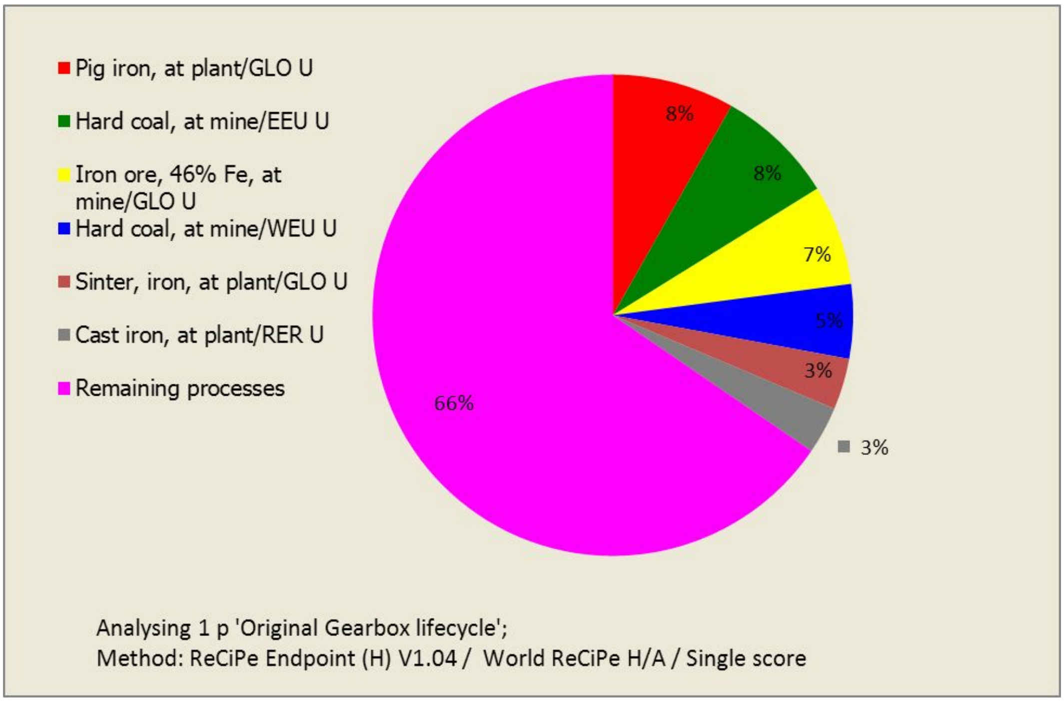


Figure 7.11 Single score assessment result of the original gearbox life cycle

Figure 7.12 shows bar chart and pie chart of process contribution, which indicate the most contributed processes or materials in the life cycle. 3% cut-off is applied to these two charts to make the presentation clearly. Pig iron and hard coal share 8% for each. They are the most contributed materials and get about 2Pt of ecological impact for each. Iron ore with 46% Fe shares 7% as the third place. Hard coal shares 5% as the fourth place. Sinter of iron and cast iron are tied for the fifth place, sharing 3%. Remaining processes share other 66%.

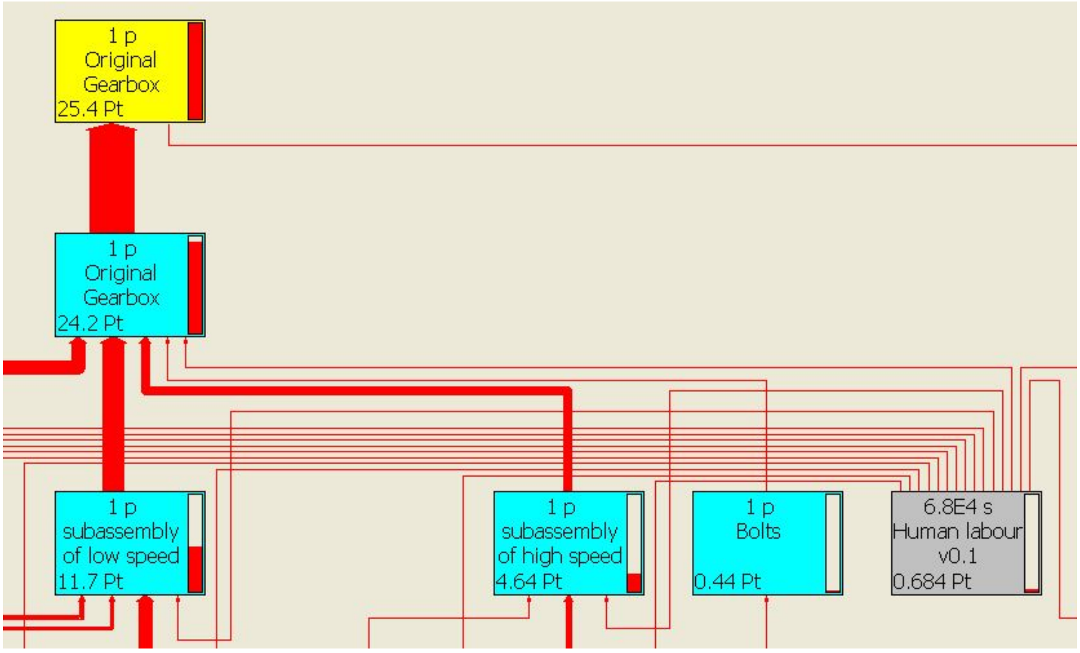


A. Single score bar chart of process contribution

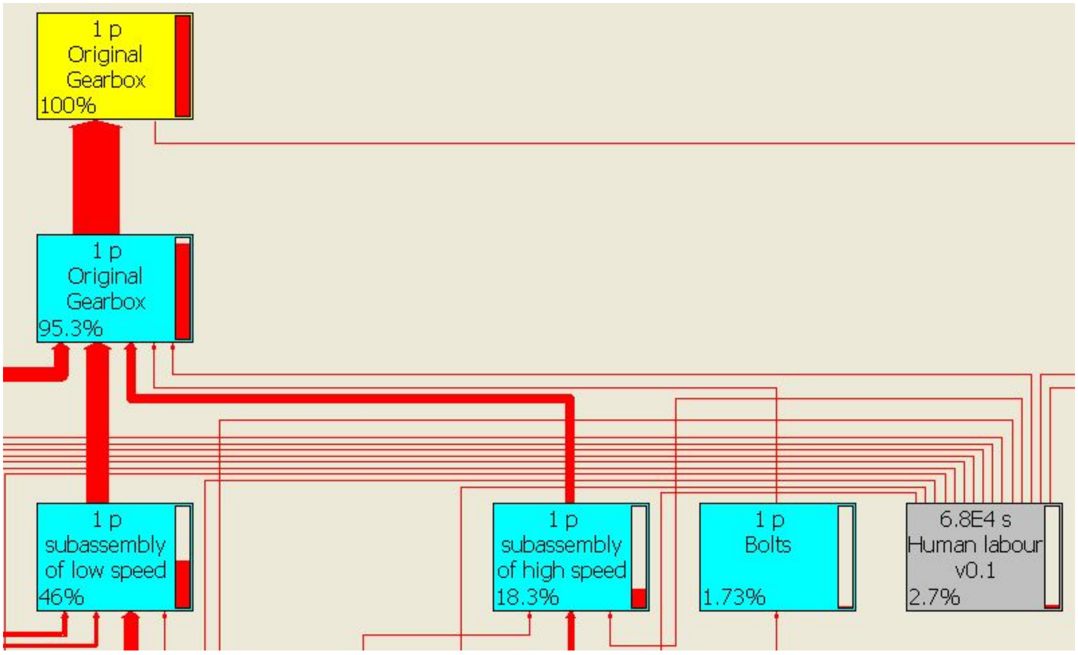


B. Single score pie chart of process contribution

Figure 7.12 Single score of process contribution

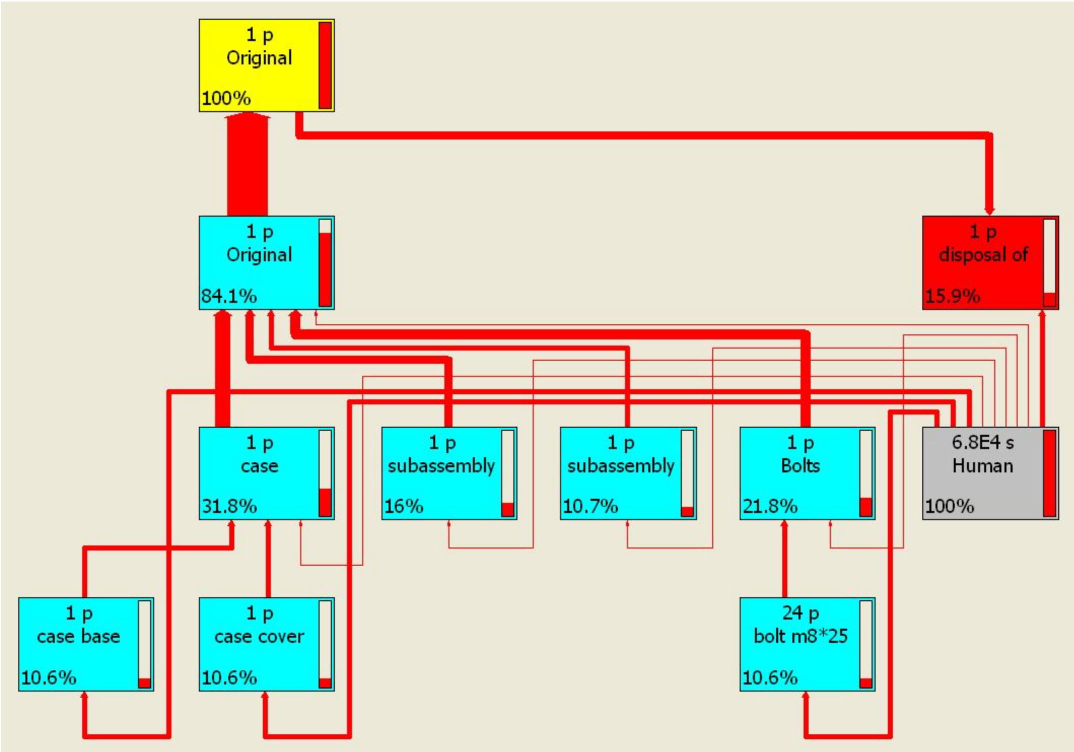


A. **Ecological impact contribution of human labour distributed in Pt**

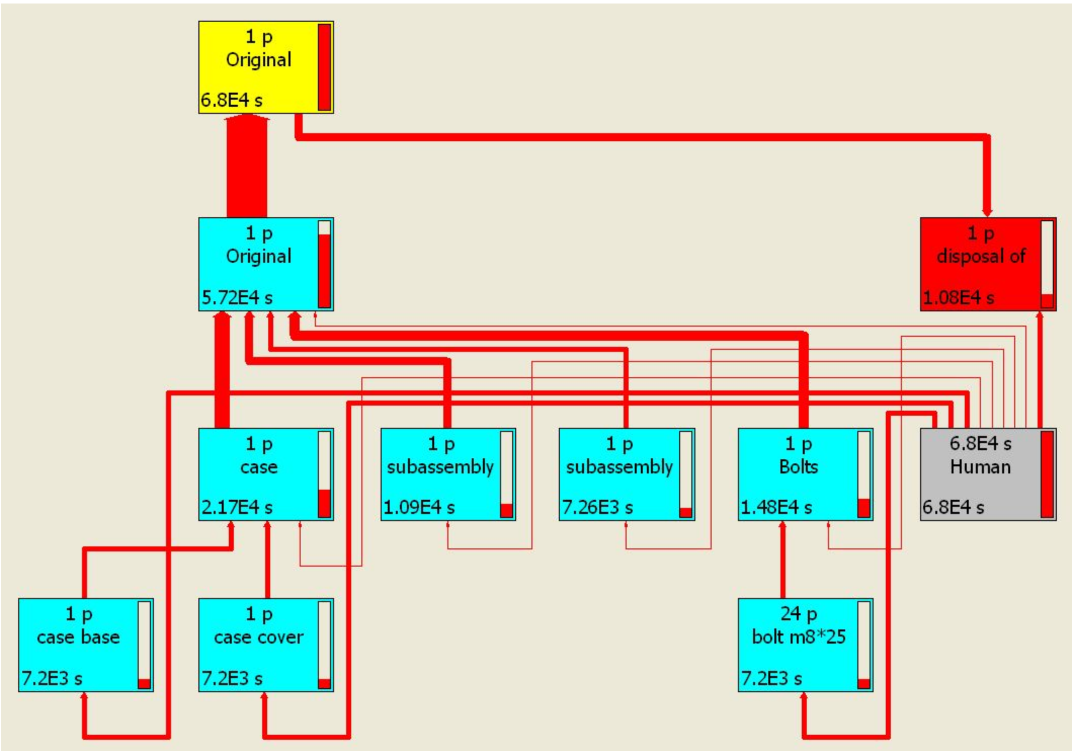


B. Ecological impact contribution of human labour distributed in %

Figure 7.13 Ecological impact contribution of human labour in the life cycle.



A. Distributed in %



B. Distributed in Pt

Figure 7.14 Single process flow of human labour (8% cut-off applied)

Figure 7.13 shows the contribution in ecological impact of human labour in the gearbox life cycle. Human labour contributes 0.684Pt and shares 2.7% of the ecological impact of original gearbox life cycle, which is 25.4Pt. In total, human labour involved 6.8E4 s in the life cycle. Because the figure is too large to illustrates in one page. Figure 7.13 is cropped to fit the page. The distribution of human labour in the whole gearbox life cycle shows in Figure 7.14. The values below 8% have been cut off. Red bar in right hand side of each box indicates the ecological impact of human labour in every part or subassembly. Manufacture of gearbox shares 84.1% of all ecological impact of human labour. The disposal of gearbox shares remaining 15.9% of all. The subassembly of case including case base and case cover, shares the most ecological impact, 31.8% of all. Each of the case base and the case cover shares 10.6% of all. The subassembly of low speed shaft shares 16%. The subassembly of high speed shaft shares 10.7%. The subassembly of bolts shares 21.8%. 24 pieces of bolt m8*25 shares 10.6%, which is the largest ecological impact causing by human labour of bolts.

7.4 Analysis of results and proposal of optimisation

After the presentation of the LCIA results, there are several points should be highlighted below.

- Turning process on steel has the most of ecological impact among all the processes used in the gearbox life cycle.
- The low-alloyed steel has the most ecological impact among the all materials used in the gearbox life cycle. Nearly half of all, 45%.
- Most of the low-alloyed steel is used for manufacture of gear.
- The gear has the most ecological impact among all the parts, 29.2%.
- The subassembly of low speed has the highest ecological impact, because the gear within it has the highest ecological impact.
- The manufacture of gearbox assembly produces 95.3 % ecological

impact in the gearbox life cycle in this case.

- The disposal of gearbox has the second high ecological impact besides the manufacture of gearbox in the whole life cycle.
- To arrange the ecological impacts in endpoint categories in descending order are human health, resources, and ecosystems.
- The human labour contributes 0.684Pt and shares 2.7% of the ecological impact of original gearbox life cycle, which is 25.4Pt.

Based on the results obtained, redesign or optimisation should be carried out in order to reduce the gearbox's ecological impact. Potential plans of optimisation may include:

- To extend the service life of gearbox
- To increase the recycle rate of used material
- Optimisation design of original gearbox life cycle with eco-constraints using Genetic Algorithm (GA)

7.5 Concluding remarks

For validation of the developed approach, a sustainable design of industrial gearbox is conduct. After structure analysis of the gearbox, three-tier modelling method is used to model the life cycle of the gearbox in SimaPro. The ecological impact of human labour is also involved. It shares 2.7% of ecological impact of gearbox life cycle. The whole modelling is parametric to keep a potential for future application of the LCIA model. The three-tier modelling includes part modelling, subassembly modelling, and assembly modelling. After that, modelling of gearbox life cycle is presented. Based on the life cycle model of gearbox, an LCIA has been conducted using SimaPro with ReCiPe method. The results of LCIA consist of network, characterisation, damage assessment, normalisation, weighting, and single score. These figures comprehensively analyse the life cycle impact of gearbox. In additional, the ecological impact of human labour is also presented. Based on the analysis of results, optimisation plan is proposed.

Chapter 8 Design Optimisation of gearbox life cycle

Based on the analysis of results and proposal of optimisation mentioned in last chapter, three design optimisation plans are conducted in this chapter.

8.1 To extend the service life of gearbox

Service life of gearbox can be extended to reduce the ecological impact allocated in each year. For instance, the designated service life of the gearbox is one year. The ecological impact of gearbox life cycle is 25.4Pt. Therefore, the ecological impact allocated in each year is equal to 25.4Pt. If the service life of gearbox is extended to ten years for example, the ecological impact allocated in each year turns into 25.4Pt divided by ten, 2.54Pt, which is only one tenth of original one. The method to extend the service life of gearbox could be exchanging the lubricating oils and greases more frequently than before. For example, changing it twice replaces changing it once only in this case. That means the amount of additional life cycle of lubricating oils and greases will be increased. In another word, the ecological impact of additional life cycle of lubricating oils and greases will be increased as well. If the ecological impact caused by increasing additional life cycle is less than the reducing amount of ecological impact caused by extending the service life of gearbox, the object of optimisation is achieved. The calculated formula is shown below. y is the ecological impact of gearbox life cycle allocated for each year. x is the amount of increased year of service life of gearbox besides the original one year. Reviewing the formula, the ecological impact for each year, y, is getting smaller and infinitely close to zero if increasing year, x, getting larger as Figure 8.1

shown. So, it is a practicable optimisation plan for the gearbox life cycle. Theoretically speaking, if the service life of gearbox can be extended as much as possible, the ecological impact produced by the gearbox life cycle would be as less as possible.

$$y = \frac{25.4 + 0.344 \times 2x}{1 + x} \qquad (19)$$

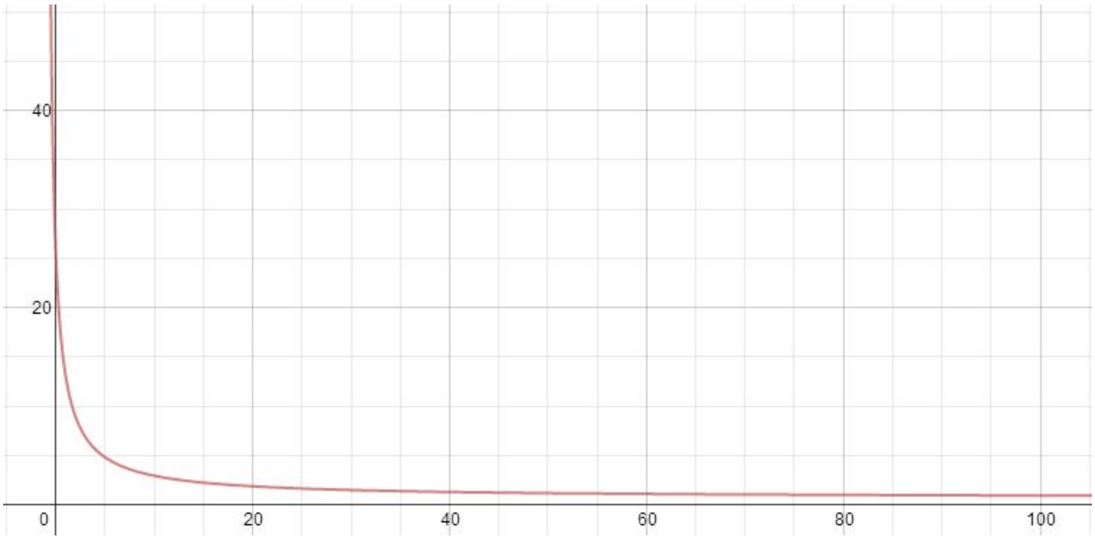


Figure 8.1 Graph of formula 18

8.2 To increase the recycle rate of used material

The manufacture of gearbox assembly produces 95.3 % ecological impact in the gearbox life cycle in this case. The extraction of low-alloy steel produces nearly half of all the ecological impact, 45%. Furthermore, the turning process on steel has the most of ecological impact among all the processes used in the gearbox life cycle. These are all related to the used material. Therefore, to increase the recycle rate of used material in the end of life of gearbox is an effective approach to reduce material, energy input and the waste, emission output at the same time.

For demonstration of the optimisation results, two optimised gearbox model with the same dimensions mentioned in previous sections are built in

SimaPro. Their life cycles are named as ‘gearbox life cycle’ and ‘gearbox life cycle disposal separately’. The optimised gearbox life cycle is assumed to reuse 65.5% of the whole assembly of gearbox after disassembly. The remaining 34.5% goes to the waste scenarios of England. The 65.5% is referred to a survey of commercial and industrial waste from Defra in 16 Dec 2010. The survey states that recycling and reuse rate for Machinery and equipment including other manufacturing is 65.5%. (Defra, 2010) There is another gearbox life cycle with more specified disposal scenario. The gearbox life cycle with disposal separately is assumed to disassemble 95% of the subassemblies of high speed shaft, low speed shaft, and case, and to reuse 70% of the first two and 95% of the last. Other remaining waste including 100% of bolts and nuts go to the waste scenarios of England. Dis-assembly processes with human labour of all the parts are implemented in the disposal processes.

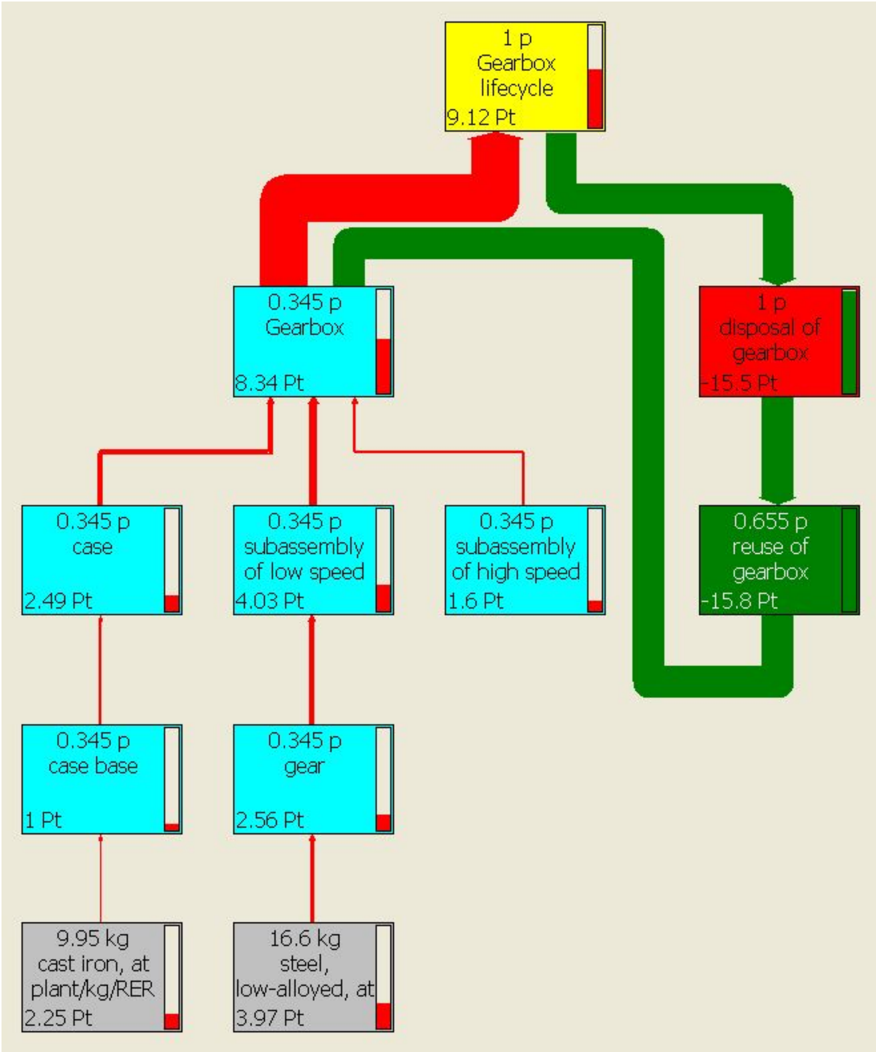


Figure 8.2 LCIA network result of optimised gearbox life cycle (10% cut off)

Figure 8.2 shows the network of gearbox reusing 65.5% of gearbox assembly which is coloured by yellow. Green flow in the right is the disposal and reuse of the gearbox. In the end, the flow goes back into the assembly of gearbox. That means the recycled material is reused as the input of materials. The disposal of gearbox has -15.5Pt and the reuse of gearbox has -15.8Pt. The difference of 0.3Pt is caused by the human labour involved. The disposal flow has minus scores of ecological impact which means that they are beneficial to the environment. The total score of gearbox is much lower than the original one because the disposal process scores are minus. The manufacture of gearbox only scores 8.34Pt this time.

For better presentation, 10% cut off is applied in the network result. The total score of life cycle of the gearbox is 9.12Pt.

Figure 8.3 shows the network result of optimised gearbox life cycle with specified disposal scenario. Disposal, disassembly, and reuse are coloured by red, pink, and green respectively. Yellow, little blue and grey represents life cycle, assembly, subassembly, or parts, and process respectively. It also shows that the disposal has minus ecological impact to the environment. The disposal flow consists of three flows after the disassembly of gearbox including disposal of case, disposal of subassembly of high speed shaft, disposal of subassembly of low speed shaft. These three flows all go back to the corresponding subassemblies as the input of materials as figure shows. For better presentation, 2% cut off is applied in the network result. The total score of life cycle of the gearbox is 7.48Pt.

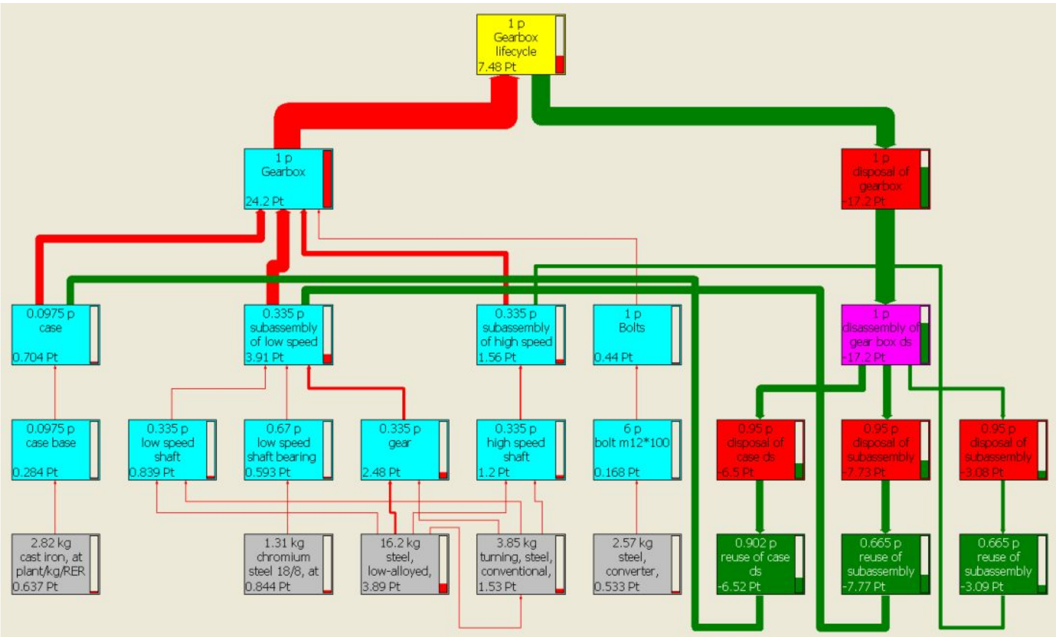
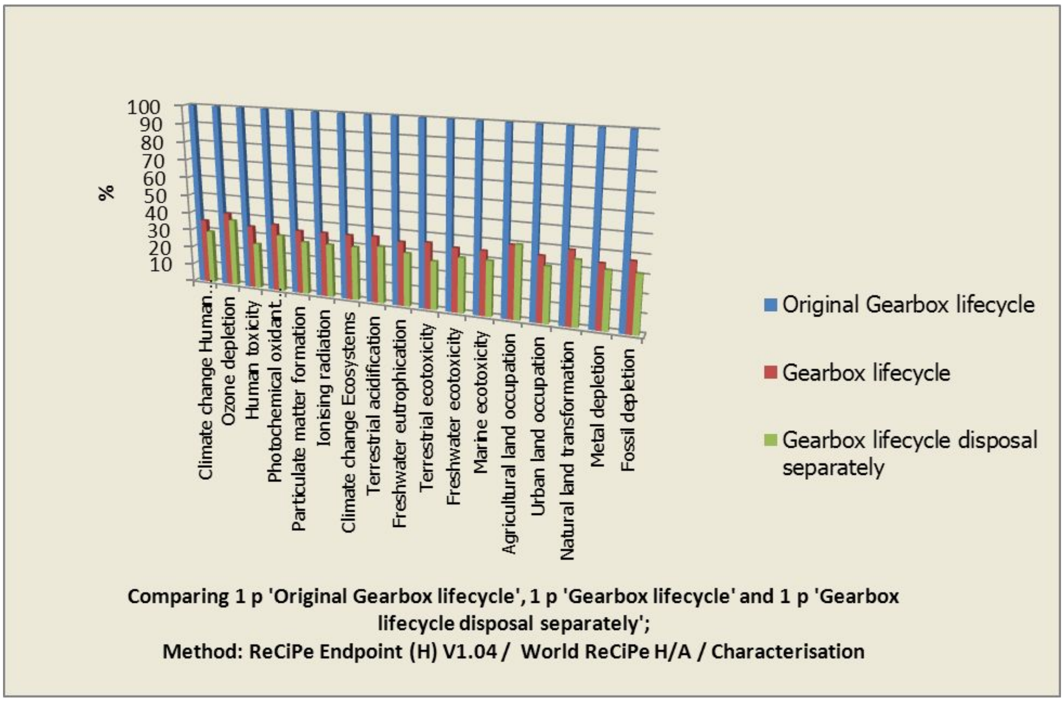


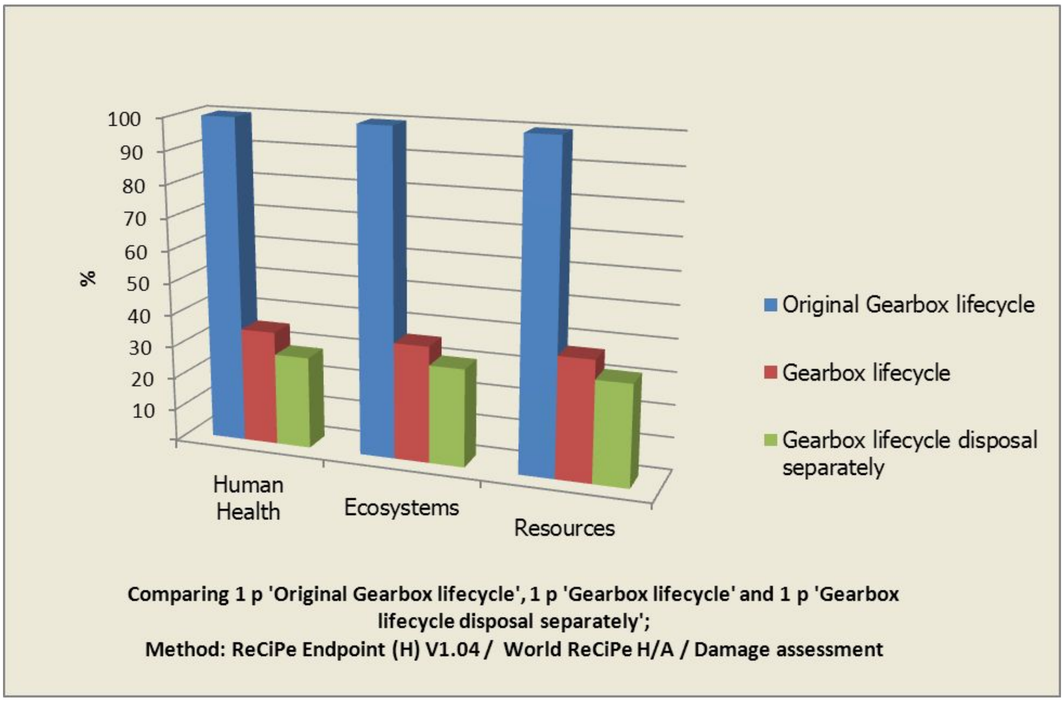
Figure 8.3 LCIA network result of optimised gearbox life cycle with specified disposal scenario (2% cut off)

SimaPro has a comparison function to compare the LCIA results of different processes, materials, products or life cycles. It is a clear and easy way to distinguish whether the new design is better than the original one. Now, these three gearbox life cycles are compared to illustrate the results of optimisation of life cycle by increasing the recycle rate of gearbox.

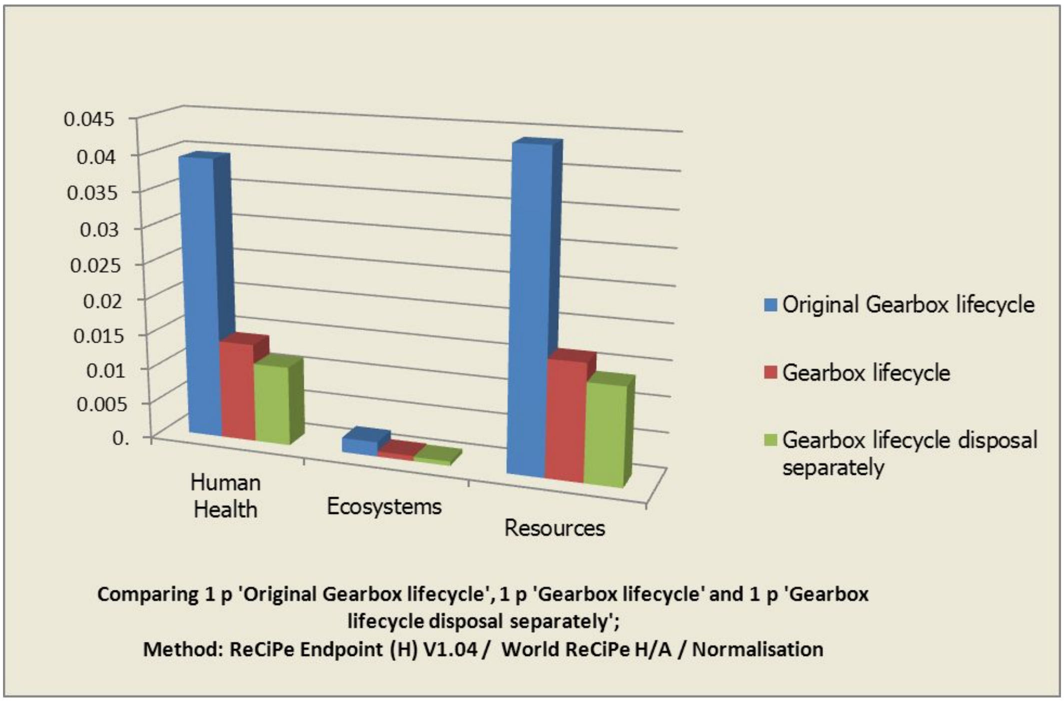
The comparison result of characterisation is shown in Figure 8.4 A, blue bars represent the original gearbox life cycle which does not reuse and put all the waste into the waste scenario of England. Red bars represent the optimised gearbox life cycle which reuses 65.5% of gearbox. Green bars represent the optimised gearbox life cycle which has specified disposal scenario as mentioned above. The result shows the second and the third gearbox life cycle have lower ecological impact than the original one in each aspect of midpoint including climate change, ozone depletion, human toxicity, fossil depletion, et al. The results of two optimised gearbox life cycle are very close. The third one has a little bit lower than the second one. Figure 8.4 B shows the damage assessment results of comparison in the endpoint categories. The result is similar as that of characterisation.



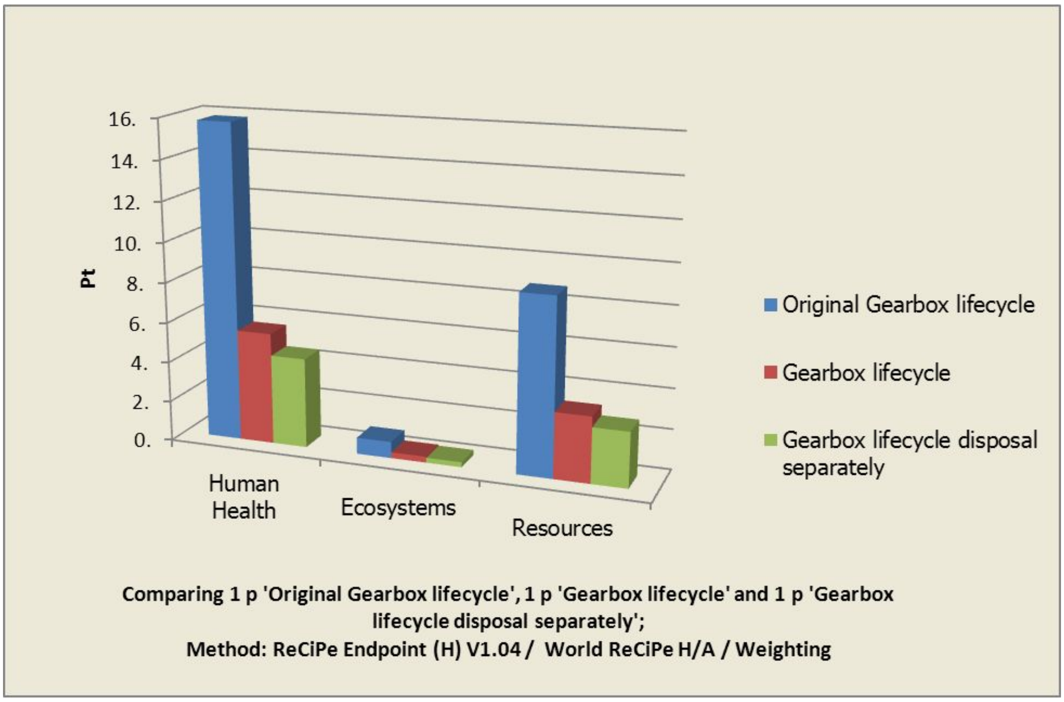
A. Characterisation midpoint result of comparison among three gearboxes



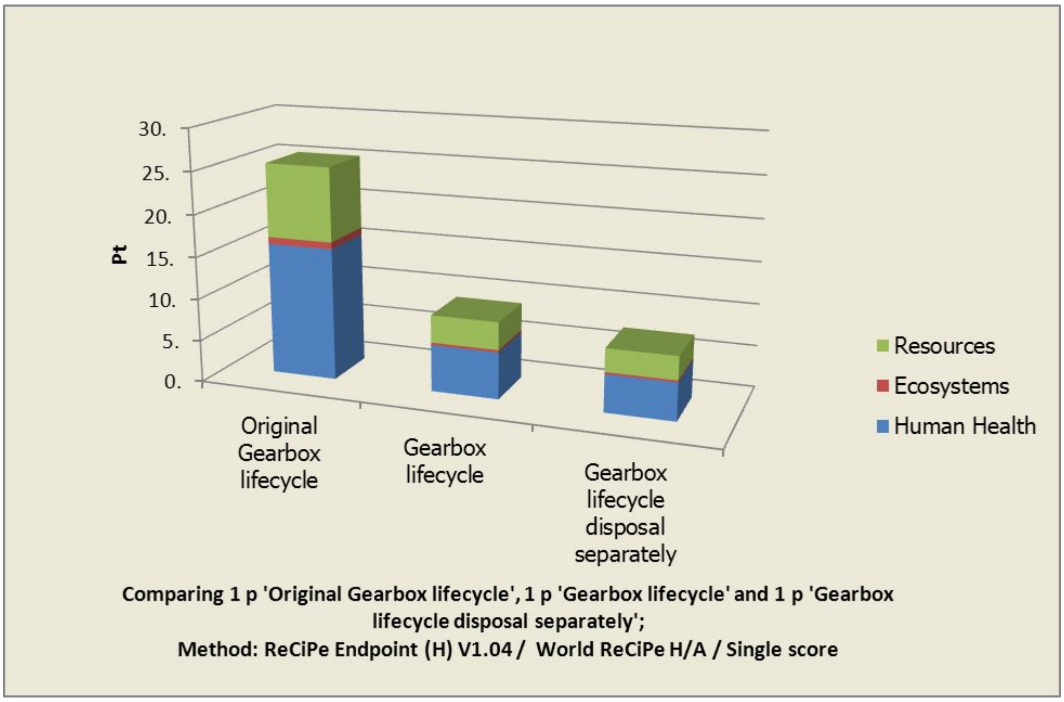
B. Damage assessment endpoint result of comparison among three gearboxes



C. Normalisation endpoint result of comparison among three gearboxes



D. Weighting endpoint result of comparison among three gearboxes



E. single score endpoint result of comparison among three gearboxes

Figure 8.4 Result of comparison among three gearboxes

Normalisation result and weighting result are shown in Figures 8.4 C and D. It illustrates the ecological impact of optimised gearbox life cycle whose reuse 65.5% of gearbox is lower than the original one for more than half. The weighting ecological impact of life cycle of the original gearbox in endpoint categories are 15.778, 0.815, 8,7774 in human health, ecosystems, and resources respectively. The weighting ecological impact of life cycle of 65.5% reused gearbox in endpoint categories are 5.5669, 0.2929, 3.2647. The gearbox life cycle with specified disposal scenario has even lower ecological impact than the second one. The results are 4.4795, 0.2464, and 2.7502. In Figure 8.4 E, single score result shows the distribution of ecological impact in three endpoint categories for each life cycle. It also reveals the positive effects of the optimisation are distinct. The final scores of them are 25.4, 9.12, and 7.48. The ecological impact of the original one in three endpoint categories all decrease in considerate amount as the figure shows. More relative details of all the modelling and results are listed in the appendix.

8.3 Design Optimisation of original gearbox life cycle using GA

After ecological impact assessment of gearbox, it has a potential to reduce the ecological impact through optimum design method such as multi-objective optimisation using genetic algorithm. The ecological impact of material is significant in the assessment result of gearbox as shown in the case study. So, a structural optimum design method considering eco-constraints should be developed to reduce the ecological impact of product. Structural optimum design method has two phases including size optimisation and shape optimisation. They can reduce the material of product while meet the requirements rising by the designer, manufacturer, or consumer. After applying the method to reduce the material of product, the results will be compared with the original design using SimaPro and analysed to prove the feasibility of optimised design. Mathematical modelling will be used to calculate and find the solution of optimum design with eco-constraints. And mathematical software MATLAB is used as a tool for optimisation and calculation.

The parameters to be optimised include dimensions of parts, materials consumption, energy consumption, stress, recycle rate, harmful emission, and waste etc. As mentioned, before conducting the optimum design, objectives, constraints, and variables should be define at the beginning. And then all these data will be input into optimum tool box of MATLAB for calculation. When the optimised solution set is obtained, SimaPro can do the comparison of LCIA results between the original gearbox and optimised gearbox.

A spread sheet contains all the data of optimisation design of gearbox is written. These data include all the parameters mentioned above, the ecological impacts of gearbox and parts, objectives, variables, constraints, optimisation bounds, and the results of optimisation. SimaPro and MATLAB can easily read the data through the spread sheet to calculate the ecological impact. This will be described in detail in following sections.

8.3.1 Objectives

The sustainable optimum design in the research is a multi-objectives optimum problem. There are two objective function in the optimum problem including ecological impact of gearbox and manufacture cost. Objective function for ecological impact is expressed by the summation of all ecological impact calculation function of all the parts, subassemblies, assemblies, and stages in the whole life cycle as states in previous sections. Objective function for manufacture cost is calculated from the sum of material cost, conversion cost, and transportation cost.

8.3.1.1 Ecological impact of gearbox

As mentioned in parametric modelling section, the calculation formation of ecological impact of gearbox contains four main parts which are EI of assembly of gearbox, EI of additional life cycle, EI of disposal of gearbox, and EI of transport (20). EI of assembly of gearbox is the sum of that of subassemblies, human labour, and electricity for lifting parts up (21). EI of subassembly is the sum of ecological impact of corresponding amount of each subassembly including high speed shaft, low speed shaft, case, bolts and nuts, and human labour during assembling of them (22).

$$EI_{gb} = EI_{as} + EI_{a} + EI_{dis} + EI_{t} \qquad (20)$$

EI_{gb}: ecological impact of gearbox life cycle

EI_{as}: EI of assembly of gearbox

EI_{a}: EI of additional life cycle

EI_{dis}: EI of disposal of gearbox

EI_{t}: EI of transport

$$EI_{as} = EI_{sub} + EI_{hl} + EI_{e} \qquad (21)$$

EI_{sub}: EI of subassembly

EI_{hl}: EI of human labour

EI_{e}: EI of electricity

$$EI_{sub} = EI_{s\_hss} + EI_{s\_lss} + EI_{s\_c} + EI_{s\_bn} + EI_{hl} \qquad (22)$$

EI_{s_hss}: EI of subassembly of high speed shaft

EI_{s_lss}: EI of subassembly of low speed shaft

EI_{s_c}: EI of subassembly of case

EI_{s_bn}: EI of subassembly of bolts and nuts

EI_{hl}: EI of human labour

EI of subassembly of high speed shaft is the sum of that of high speed shaft, two high speed shaft bearing, and human labour involved during manufacture (23).

$$EI_{s\_hss} = EI_{hss} + EI_{hssb} + EI_{hl} \qquad (23)$$

EI_{hss}: EI of high speed shaft

EI_{hssb}: EI of two high speed shaft bearing

EI_{hl}: EI of human labour

EI of high speed shaft consists of two parts, ecological impact of processing and material production. The ecological impact of processing is calculated by mass of cut pieces from blank multiplies ecological impact of process applied on high speed shaft manufacture per unit. The ecological impact of material production is calculated by mass of material used for blank multiplies ecological impact of the material extraction per unit. Also, the mass can be turned into product of volume and density of material (24). As illustration in the previous modelling section. Other subassemblies are followed the same calculation principle as the ecological impact of subassembly of high speed shaft.

$$EI_{hss} = M_p \times EI_p + M_b \times EI_e = (V_b - V_{hss}) \times \rho \times EI_p + Vb \times \rho \times EI_e \qquad (24)$$

M_p: Mass of cut pieces from blank

EI_p: EI of process applied on high speed shaft manufacture per unit

M_b: Mass of blank

EI_e: EI of material extraction per unit

V_b: Volume of blank

V_{hss}: Volume of high speed shaft

ρ: Density of material

As description in section of life cycle modelling of gearbox and Calculation of ecological impact. These data has been written in the spread sheet and ready for use by MATLAB to do the optimisation. The complete formation to calculate the ecological impact of gearbox life cycle is attached in the appendix.

8.3.1.2 Manufacture Cost:

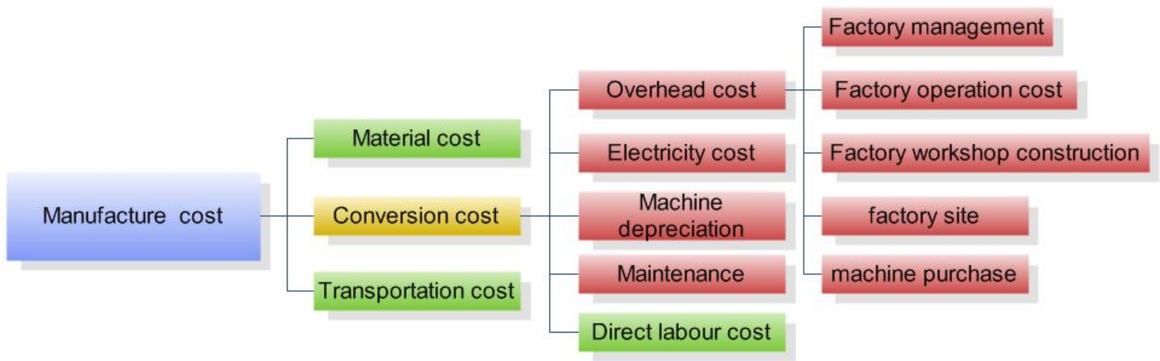


Figure 8.5 Manufacture cost

Manufacture Cost can be divided into three aspects which are material cost, conversion cost, and transportation cost. Material cost is the expense of raw material that is used to produce parts. In another word, it is the expense of blank. So, scraps are included. As formation (25) shows, it equals to the product of mass of blank and price of material. The prices and densities used in the research is refer to the data in CES EduPack 2010 database (Granta Design, 2010).

$$Cm = V \times \rho \times Pm \qquad (25)$$

Cm : cost of material

V : volume of blank

ρ : density of material

Pm : Price of material

Transportation cost is the fuel expense of distribution to customer after production. Vehicle depreciation is not considered cause vehicle used in different company is varied and it should be classified to a part of overhead cost. (26) For convenient calculation, assume that speed of vehicles are stable, price of fuel is 1.38GBP/L, distance from factory to customer is 10 km, and volume of fuel consumption in unit mass is 0.001 L/kgkm. And these data can be modified by user later. Weight of gearbox can be obtained by calculation with provided parameters.

$$C_t = W_G \times S \times V_{fc} \times P_f \quad (26)$$

C_t *: cost of transportation*

W_G *: weight of gearbox*

S : distance from factory to customer

V_{fc} *: volume of fuel consumption in unit mass (L/kg)*

P_f *: price of fuel*

Conversion cost is the expense of conversion from raw material to end product. It is consist of overhead cost, electricity cost for office facilities, machine depreciation, maintenance, and direct labour cost. Direct labour cost is the expense of hourly wage of workers. It can be obtained through calculation based on processing time, which is the quotient of processing material amount and processing speed. In current stage, direct labour cost is estimated and calculated as the total of human labour hours multiple average hourly wage. Hourly wage is estimated as 11.08 GBP/hour based on the report of 2011 Annual Survey of Hours and Earnings (Labour Force Survey, 2011). Detailed estimation based on material amount and processing speed will be described in future work.

Overhead cost contains factory management cost, factory operation cost, factory workshop construction cost, and purchase of factory site and machine. Because, standard and method to calculate overhead cost varied among different companies and factories. Overhead cost is out of consideration of calculation. And, which type and brand does the factory use is uncertain. So, electricity consumption, machine depreciation, and maintenance are unclear. For now, costs in green frame are considered.

Which means manufacture Cost is the sum of material cost, direct labour cost, and transportation cost.

8.3.2 Variables

Three parameters are set as variables in the optimum problem, including module of gear, x(1), number of teeth of gear x(2), and face-width of gear-shaft, x(3). The default values of them are 3, 79,65. The three variables replace existing corresponding parameters to produce new objective function with variables, x(1), x(2), x(3). Replacement is presented in the following table.

Table 8.1 Variables

Name	Design parameter	Default value	Calculation parameter	Variable
Blank diameter of gear-shaft		70	gs_blank_d=gs_d5+5	x(1)*20+10
Reference circle diameter of gear-shaft (mm)	d1	65	gs_d5	x(1)*20+5
Reference circle diameter of gear (mm)	d2	237	g_b_d	x(1)*x(2)
Face-width of gear-shaft	b1	65	gs_l5	x(3)
Face-width of gear	b2	60	g_b_l	x(3)-5

Other parameters consist of all calculation parameters and design parameters of gearbox relating to the three variables. The former includes distance between factory to customer, time consumption, etc.. The latter includes parameters involved during gear design procedure. Table 8.2 and Table 8.3 shows a part of calculation parameters and design parameters separately. All calculation parameters list in appendix.

Table 8.2 Calculation parameters

Name	abbreviation	default value
case base	**parameter**	
case base length	cb_l	428
case base width	cb_w	190
case base height	cb_h	170
case base thickness	cb_t	8
length 1	cb_l1	15
length 2	cb_l2	20
length 3	cb_l3	25
length 4	cb_l4	35
length 5	cb_l5	100
diameter of hole for high speed (small) bearing end cap	sbec_d	80
diameter of hole for low speed (large) bearing end cap	lbec_d	100
human labour for subassembly of bolts	hl_s_b	0.195833333
human labour for subassembly of nuts	hl_s_n	0.022222222
human labour for subassembly of case	hl_c	0.016666667
human labour for subassembly of low speed shaft	hl_s_lss	0.033333333
human labour for subassembly of high speed shaft	hl_s_hss	0.016666667
human labour for assembly of gearbox	hl_a_g	0.033333333
electricity consumption of assembly of gearbox	e_a_g	0.01
transport distance	dis	10
human labour for reuse	hl_re	2
human labour for disposal of gearbox	hl_dispo_g	2
human labour for disposal of bolts, nuts, subassembly of high&low speed shaft	hl_disa	1

Design parameters are correlative with each other in mathematics which is expressed in constraints. Details will be explained in constraints section below. During design stage, designer can use default value of each one or modify any one of them if necessary.

Table 8.3 Design parameters (reference are listed in the appendix)

name	abbreviation	reference	default value
power (KW)	p		5
rotate speed(r/min)	n1		327
torque (N.mm)	t	t=9549000*p/n1	146009.1743
transmission ratio	u	u=z2/z1	3.95
number of teeth	z1		20
application factor	ka	table su	1
dynamic factor	kv	table su	1.1
load distribution factor	kbeta	table su	1.0525
allowable contact stress (MPa)	sigmahp	table 1	647
elastic coefficient	ze	table su	191
allowable bending stress of gear (MPa)	sigmafp	table 2	260
tooth form factor	yfa	table 3	2.8
stress correction factor	ysa	table 3	1.55
length for crankle stress calculation	l_crankle		85
allowable crankle stress	sigma-1b	table 5	40
a factor for bending stress of shaft	a	table 5	0.5385

8.3.3 Constraints

Nonlinear programming, also called constraint optimisation, optimises an objective function with equality and inequality constrains. Performance and strength can be expressed as equality or inequality. They are constraints in this optimisation problem. MATLAB is a leading calculation and simulation software in optimisation discipline. It has a genetic algorithms tool called gatool available. Now, gatool is integrated into optimtool in MATLAB. The following works of this research will be operated underpinned with it in MATLAB.

Usually, strength and stress are only check on gear-shaft or pinion, because they are smaller than gear. Strength and stress check details shows below. Table 8.4 shows allowable contact stress and allowable bending stress of carbon steel, which the material gear-shaft is made of. 647HBS and 260HBS are chosen as allowable contact stress and allowable bending stress when quality of heat treatment of gear-shaft is ME, which indicates high level. Based on Table 8.5, 2.80 and 1.55 are chosen as tooth form factor Y_{sa} and stress correction factor $Y_{fa.}$ When number of tooth (z_1) is 20.

Table 8.4 Allowable contact and bending stress of carbon steel (Zhong, 2001)

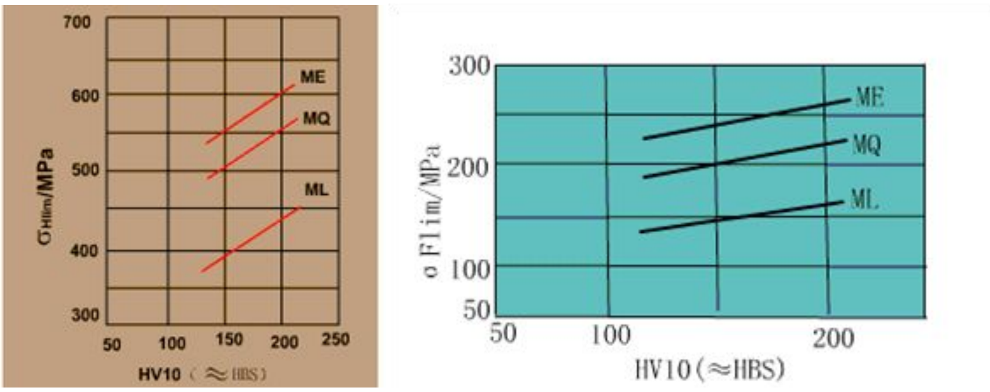


Table 8.5 Tooth form factor yfa and stress correction ysa (Zhong, 2001)

$z(z_v)$	17	18	19	20	21	22	23	24	25	26	27	28	29
Y_{Fa}	2.97	2.91	2.85	2.80	2.76	2.72	2.69	2.65	2.62	2.60	2.57	2.55	2.53
Y_{Sa}	1.52	1.53	1.54	1.55	1.56	1.57	1.575	1.58	1.59	1.595	1.60	1.61	1.62
$z(z_v)$	30	35	40	45	50	60	70	80	90	100	150	200	∞
Y_{Fa}	2.52	2.45	2.40	2.35	2.32	2.28	2.24	2.22	2.20	2.18	2.14	2.12	2.06
Y_{Sa}	1.652	1.65	1.67	1.68	1.70	1.73	1.75	1.77	1.78	1.79	1.83	1.865	1.97

Now, these factors are put into following design formula to obtain other design parameters and constraint inequalities and equalities that shows in constraints section.

- **Contact stress**

$$\sigma_H = Z_H Z_\varepsilon Z_e (\frac{K_a K_v K_\beta F_t (\mu+1)}{b_1 d_1 \mu})^2 \le [\sigma_H] \quad (27)$$

σ_H : calculated contact stress (MPa)

Z_e : elastic coefficient

Z_H: node area coefficient

Z_ε: contact ratio coefficient

K_a : application factor

K_V : dynamic factor

K_β : load distribution factor

F_t : periphery force on reference circle (N)

μ : transmission ratio

b_1 : face width of gear-shaft (mm)

d_1 : Reference circle diameter of gear-shaft (mm)

$[\sigma_H]$: Allowable contact stress (MPa)

- **Bending stress**

$$\sigma_f = \frac{K_a K_v K_\beta F_t Y_{sa} Y_{fa}}{b_1 m} \le [\sigma_f] \quad (28)$$

σ_f : calculated bending stress of gear (MPa)

K_a : Application factor

K_V : Dynamic factor

K_β : load distribution factor

F_t : Periphery force on reference circle (N)

Y_{sa} : Tooth form factor

Y_{fa} : stress correction factor

m : Module of gear

b_1 : face width of gear-shaft (mm)

$[\sigma_f]$: Allowable bending stress of gear (MPa)

8.3.4 Optimisation Bounds

Optimisation bounds are come from all inequalities of gear dimension constraints (27), (28), minimum number of teeth, and minimum module. The intersection of these sets is a range of optimisation solution sets.

At first, bounds are calculated based on gear dimension constraints of forging gear whose diameter is less than 500mm as Figure 8.6 shows. And then teeth number of the gear must not less than 17 to avoid undercut. Moreover, teeth number of gear-shaft is 20. The teeth number of gear must not less than 20 to insure that the machine is a reducer not increaser. Usually, module of gear is equal to or greater than 2.

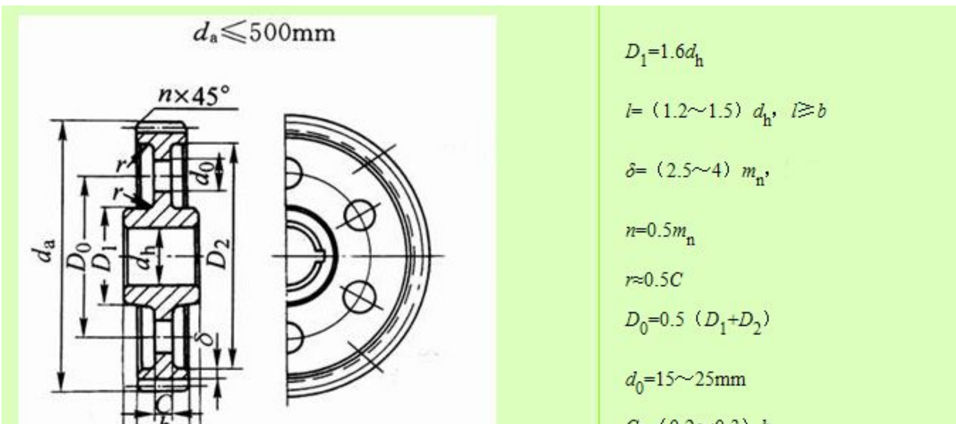


Figure 8.6 Dimension of forging gear.

Constraints	**Reference**	**Formation in MATLAB**
gear stress	sigmah<=sigmahp (1)	ze*(ka*kv*kbeta*2*t /(x(1)*x(2)+5)*(x(2)/z1+1)/x(2)/z1/x(3)/(x(1)*x(2)+5))^2 - sigmahp<0
	sigmaf<=sigmafp (2)	ka*kv*kbeta*2*t /(x(1)*x(2)+5)*ysa*yfa/x(3)/x(1) - sigmafp<0
crankle stress of shaft and gear-shaft	sigmab_s<=sigma-1b (2)	1.03*((2*(2*t /(x(1)*x(2)+5)*tand(20))*l_crankle/2)^2+(a*t)^2)^(-1/2)/0.1 /(x(1)*x(2)+5)^3 - sigma_1b<0
	sigmab_gs<=sigma-1b (2)	1.03*((2*(2*t /(x(1)*x(2)+5)*tand(20))*l_crankle/2)^2+(a*t)^2)^(-1/2)/0.1 /s_d4^3 - sigma_1b<0
Gear dimension constraints		
	g_b_l=(1.2~1.5)*g_ch_d	74.6<=x(3)<=92
	d2-g_r_d1>10	220 - x(1)* x(2)<0
	g_h_l=(0.2~0.3)*g_b_l	55<=x(3)<=80
	d2<=500	x(1)*x(2)<=500
Minimum number of teeth	z2>=20	X(2)>=20
Minimum module	m>=2	X(1)>=2
Calculated optimisation bounds		
lower bound	[2,20,55]	
upper bound	[inf,inf,80]	

Table 8.6 Constraints and bounds

8.3.5 Optimisation results

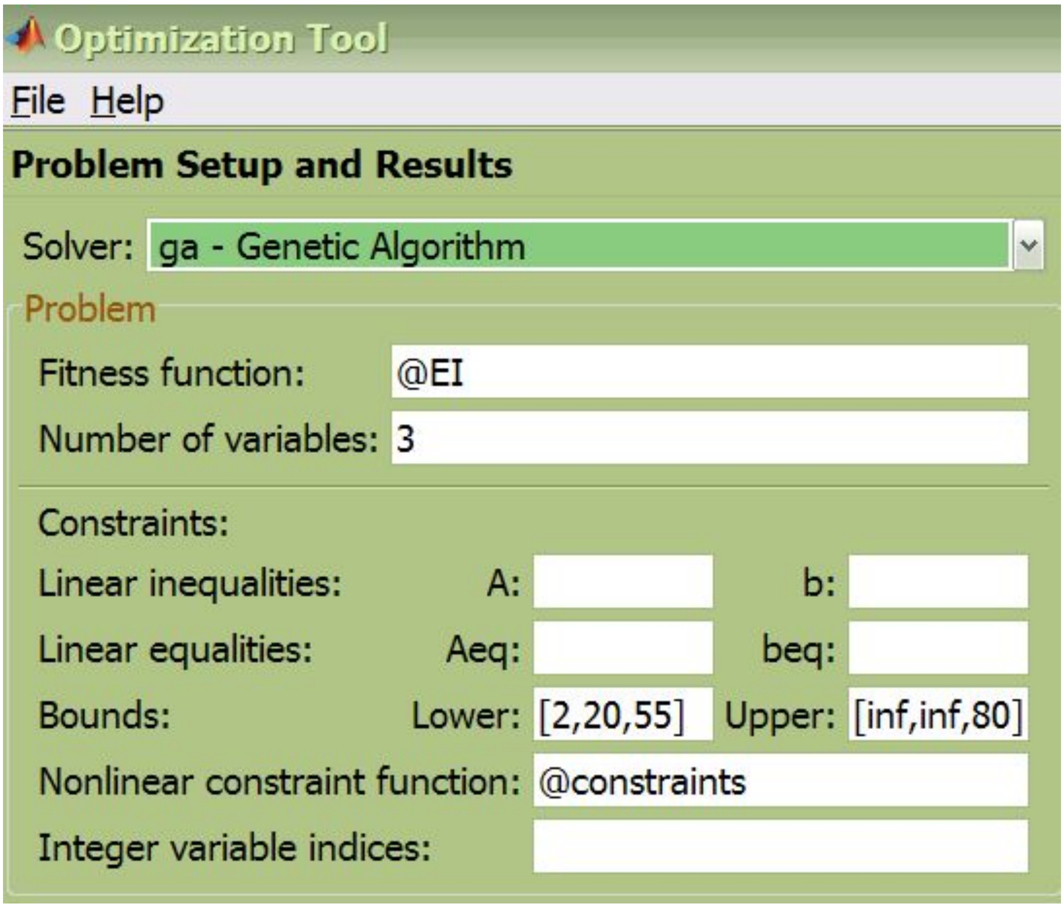


Figure 8.7 optimisation tool in MATLAB

After the definition of objectives, constraints, variables, and optimisation bounds, the optimisation process can be transferred into optimisation tool of MATLAB as the Figure 8.7 shows above. During execution process, some of options is changed for the optimisation. The initial population is set as [3, 79,65] which are the default value of variables. It means the optimisation starts from the point of these default values. Plenty of time is saved after setting the option. Function tolerance in the stopping criteria is set as zero, because the best solution set is concerned but not the time consumption. For now, the multi-objective optimisation using GA cannot use the non-liner constraints. So, the research use GA optimisation tool, which has only one objective, to execute the optimisation twice. The first time, the objective is set as ecological impact of gearbox life cycle. The second time, the objective is set as manufacture cost of gearbox life cycle.

Results of ecological impact

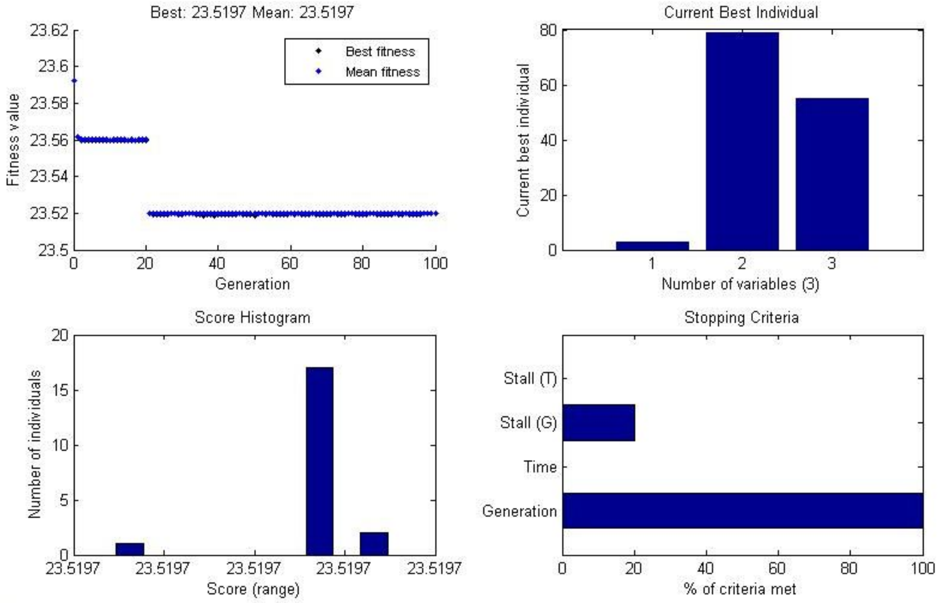


Figure 8.8 Best fitness, best individual, score diversity, and stopping criteria of optimisation

The optimisation results of ecological impact is illustrated in the Figure 8.8 above. The best objective value is 23.5197 as the figure in left top corner. The score is approaching the best point after about 20 generations. In the end it is close to the best score. The original value is 25.3511 when variables are the default values, [3,79, 65]. The solution set are [2.781, 79.103, 55] as the figure in right top corner. The figure in left bottom corner shows that most of score are around 23.5197. The figure in right bottom corner shows the generation reaches 100 is the stopping criterion of the optimisation. Before obtaining the results, the optimisation always stoped by met the criterion of the stall generation. So the option of stall generation has changed from default value, 50, to 100. The score after optimisation is smaller than the original one, so the optimisation is achieved.

Results of manufacture cost

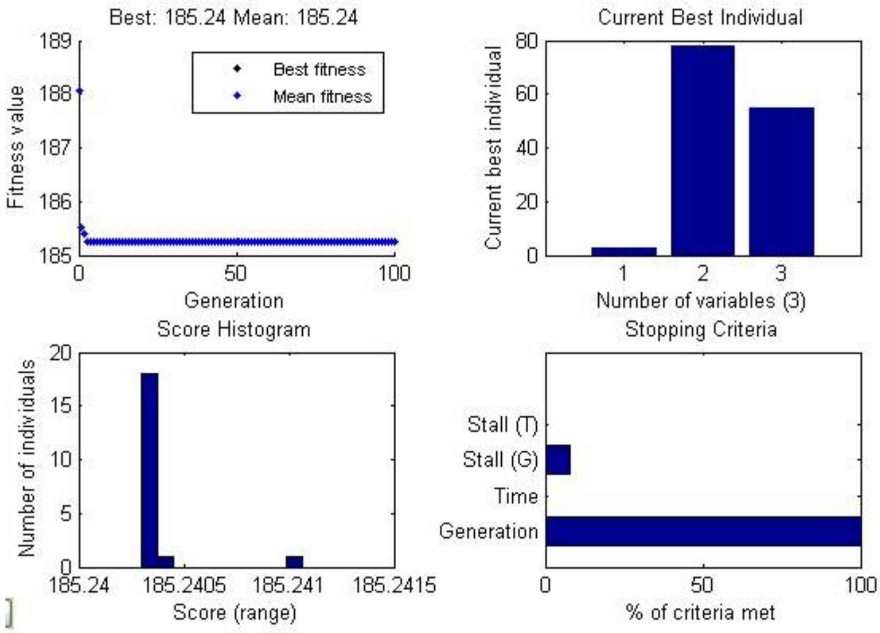


Figure 8.9 Best fitness, best individual, score diversity, and stopping criteria of optimisation

The optimisation results of manufacture cost is illustrated in the Figure 8.9 above. The best objective value is 185.24 as the figure in left top corner. The variation trend of the score is getting smaller. In the end it is close to the best score. The original value is 188.0766 When variables are the default values, [3,79, 65]. The solution set are [2.823, 77.944, 55] as the figure in right top corner. The figure in left bottom corner shows that most of score are around 185.2404. The figure in right bottom corner shows the generation reaches 100 is the stopping criterion of the optimisation. The score after optimisation is smaller than the original one, so the optimisation is achieved.

Based on these two results, solution set is balanced as [2.8, 78, 55]. After put these values into the function of objectives, the value of objective function of ecological impact and manufacture cost are 23.5104 and 185.1084.

Comparison results of ecological impact in SimaPro

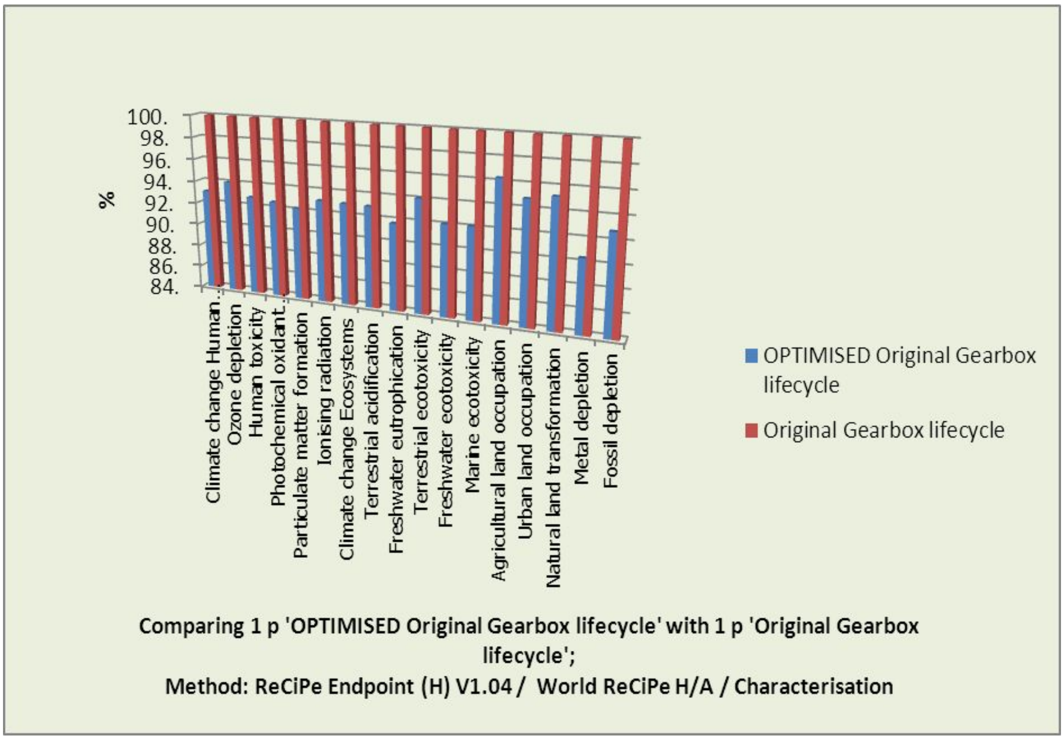
Before LCIA comparison between original gearbox life cycle and optimised one, variables in the optimisation function of EI should be replaced by calculation parameters again as that before the optimisation. The replacement details is presented in table 8.7 below.

Table 8.7 Replacement values of variables

Name	Design parameter	Default value	Optimised value	Calculation parameter in SimaPro	Variable
Blank diameter of gear-shaft		70	66	gs_blank_d=gs_d5 +5	x(1)*20+10
Reference circle diameter of gear-shaft (mm)	d1	65	61	gs_d5	x(1)*20+5
Reference circle diameter of gear (mm)	d2	237	218.4	g_b_d	x(1)*x(2)
Face-width of gear-shaft	b1	65	55	gs_l5	x(3)
Face-width of gear	b2	60	50	g_b_l	x(3)-5

Figure 8.10 shows the comparison of two LCIA, red bars represents the impacts of original gearbox life cycle. Blue bars represents the impacts of optimised gearbox life cycle.

Comparison of characterisation results shows the impacts of optimised one is average 94% of the impacts of original one in midpoint categories, except for metal depletion, which is only 90% of that.



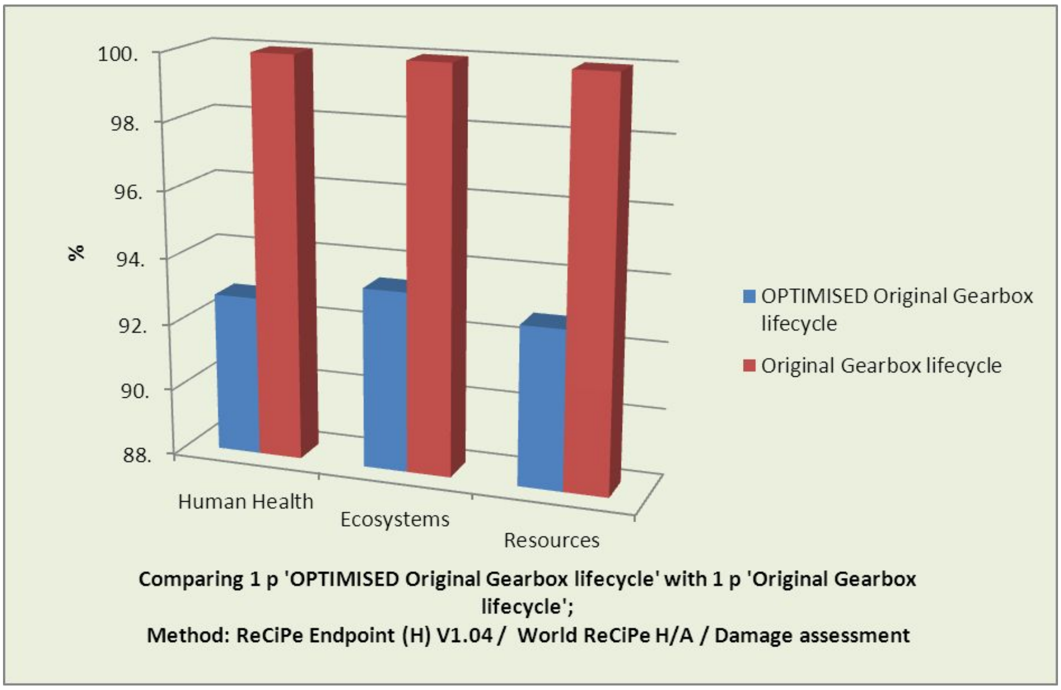
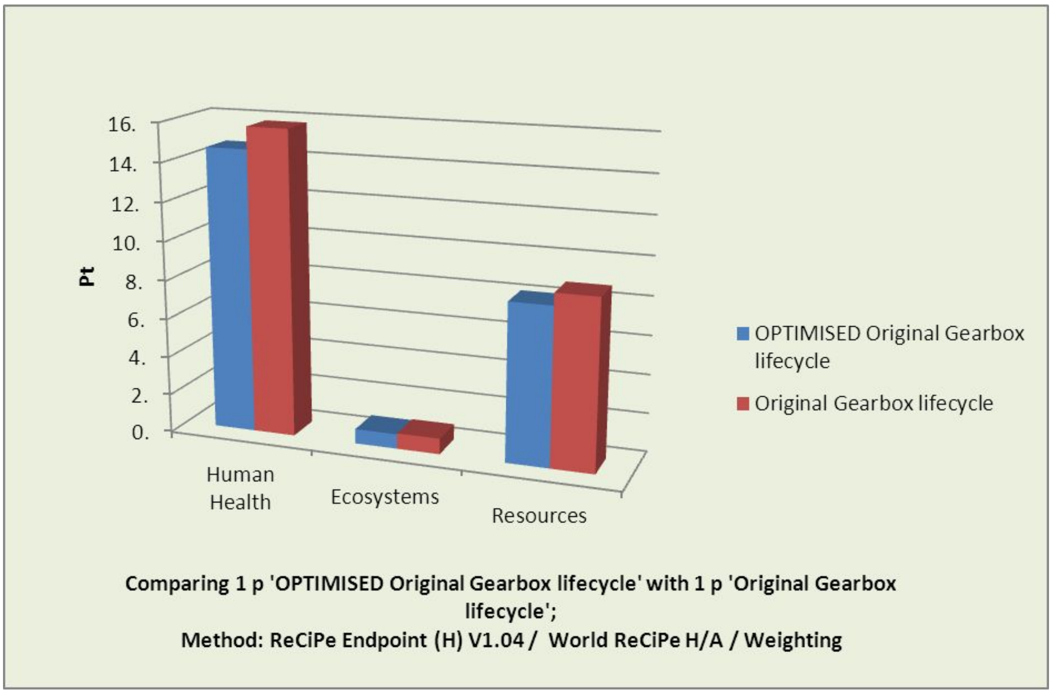


Figure 8.10 Characterisation and damage assessment

Comparison of damage assessment shows the impacts of optimised one is 92% of the impacts of original one in human health and resources categories, and 93% in ecosystems.

Comparison of weighting illustrates the results after weighting. The impact of optimised one in human health is about 1pt lower. The impact in ecosystems and resources is less than 1pt lower than before.



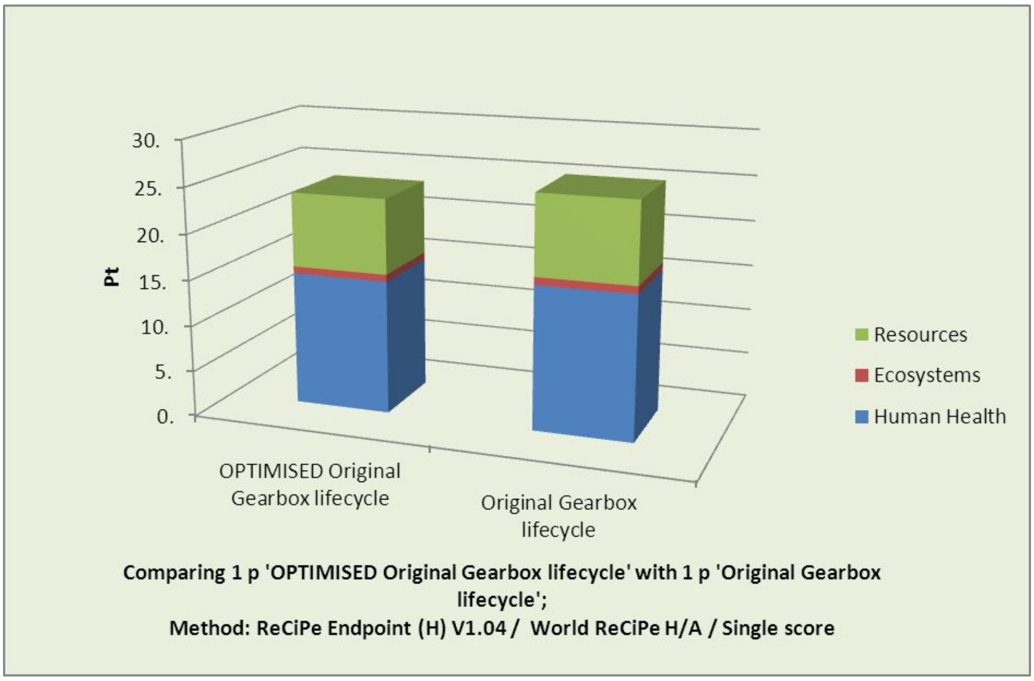


Figure 8.11 LCIA comparisons between original gearbox life cycle and optimised gearbox life cycle.

The last figure presents single score of two life cycle. The result is similar as that of weighting. The impact of two life cycle is 23.51pt and 25.35pt respectively. The decrement of impact is approximately 7%. The optimisation design of gearbox life cycle is proved.

8.4 Concluding remarks

Three design optimisation plans are conducted in this chapter. Plans include to extend the service life of gearbox, to increase the recycle rate of used material, and optimisation design using GA. They are all successfully achieve the aim to decrease the ecological impact of gearbox life cycle. The optimisation result of increasing the recycle rate shows the ecological impact decreases around 70%. Moreover, the optimisation design using GA has two objective functions including ecological impact and manufacture cost of the gearbox life cycle. the optimisation using GA has four elements including objective, variable, constraint, and bounds. According to the comparison results of ecological impact between optimised and original design, the ecological has reduced 7%.

Chapter 9 Ontology modelling of gearbox life cycle

An ontology of gearbox is modelled for communication among users and data storage and exchange. Users consist of designer, supplier, customer, distributor, manufacturer, recycler, and retailer. They can contribute their works into the same one ontology to collaborate with others in the whole gearbox life cycle.

9.1 Class modelling

Class modelling includes two stages, domain research and relationship analysis. An investigation and research for gearbox life cycle are necessary for ontology construction to find out all of concepts, items, objects, etc. After research, relationship of these concepts are analysed and rearranged to form a logical hierarchical network.

- **Domain research**

A completely research of gearbox life cycle is necessary during classes modelling. Classes in each stage should be considered including objects, people and roles, even logical concept. Using brainstorm and experience of related knowledge, all the classes should be enumerated as a list.

The life cycle stage of gearbox can be a clue to conduct the brainstorm to discover classes of the ontology. The brainstorm starts from the gearbox and production to other stage in the life cycle. The classes list below is obtained by the brainstorm and research of the gearbox life cycle. To avoid confusion during modelling and application of the ontology, all classes are singular and lower case. For demonstration, classes in list are capital letter. Classes in the life cycle, user, optimisation design and others are considered.

Table 9.1 List of classes

Gearbox	Factory	Drawing	Production line	Specification
Building	Production storage	Machine	Material	Metal
Process	Turning	Milling	Assembly	Subassembly
Part	Box	Label	PVC film	Wood box
Distribution routine	Distribution map	Raw material	Supply vehicle	Supply routine
Supply storage	Supply map	Use	Electricity	Fuel
Lubricant oil	Human labour	Food	Loss	Customer
Designer	Distributor	Driver	Manufacture r	Worker
Recycler	Retailer	Supplier	Supplier driver	Bound
Constraint	Objective	Variable	Facility	Disposal

- **Relationship analysis**

As the list shows, all the classes are not arranged in a hierarchical structure. But they all have different hierarchical relationships. Relationship analysis is necessary to execute to break down the structure of the ontology with a logical relationship.

Product life cycle is a clue to arrange all of classes in a logical hierarchy from cradle to grave. Same type of classes for the same stage of life cycle are arranged in the same group. Some classes have a classification functions, they are called top level classes. Such as gearbox life cycle. User is also a top level class. It consists of roles in the life cycle such as supplier, manufacturer, distributor, retailer, customer, recycler, etc. Optimisation design is another top level class, it includes bound, constraint objective and variable. Other is the last top level class which has others classes besides previous classes. It includes loss, human labour, and food.

In the life cycle classes group. There are five children including design, production, distribution, use and disposal. The largest one is production, which includes factory, material, package, process, product, and supply. Classes under the production group are listed below.

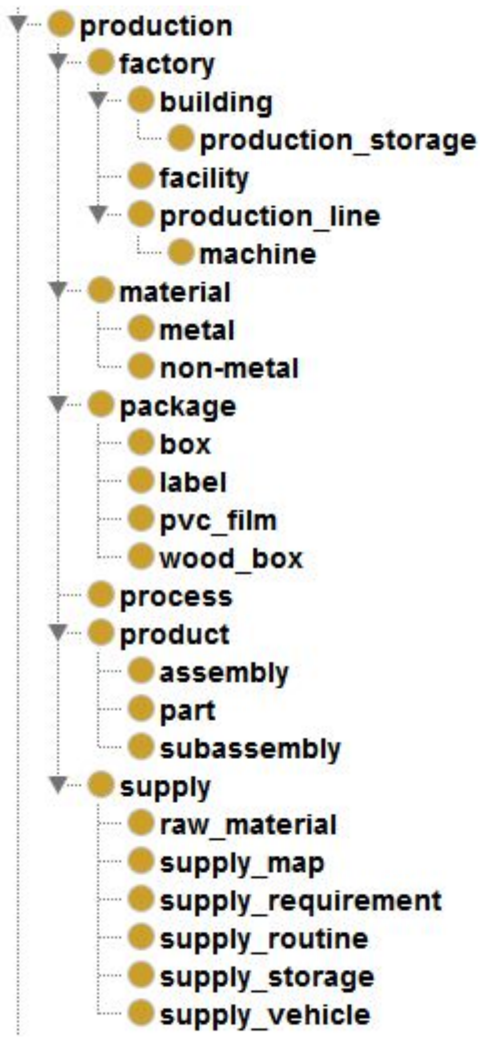


Figure 9.1 Production classes

The complete chart of classes is illustrated in Figure 9.2. Relationship analysis is also useful for modelling of object properties. Because some of relationships will be expressed as object properties.

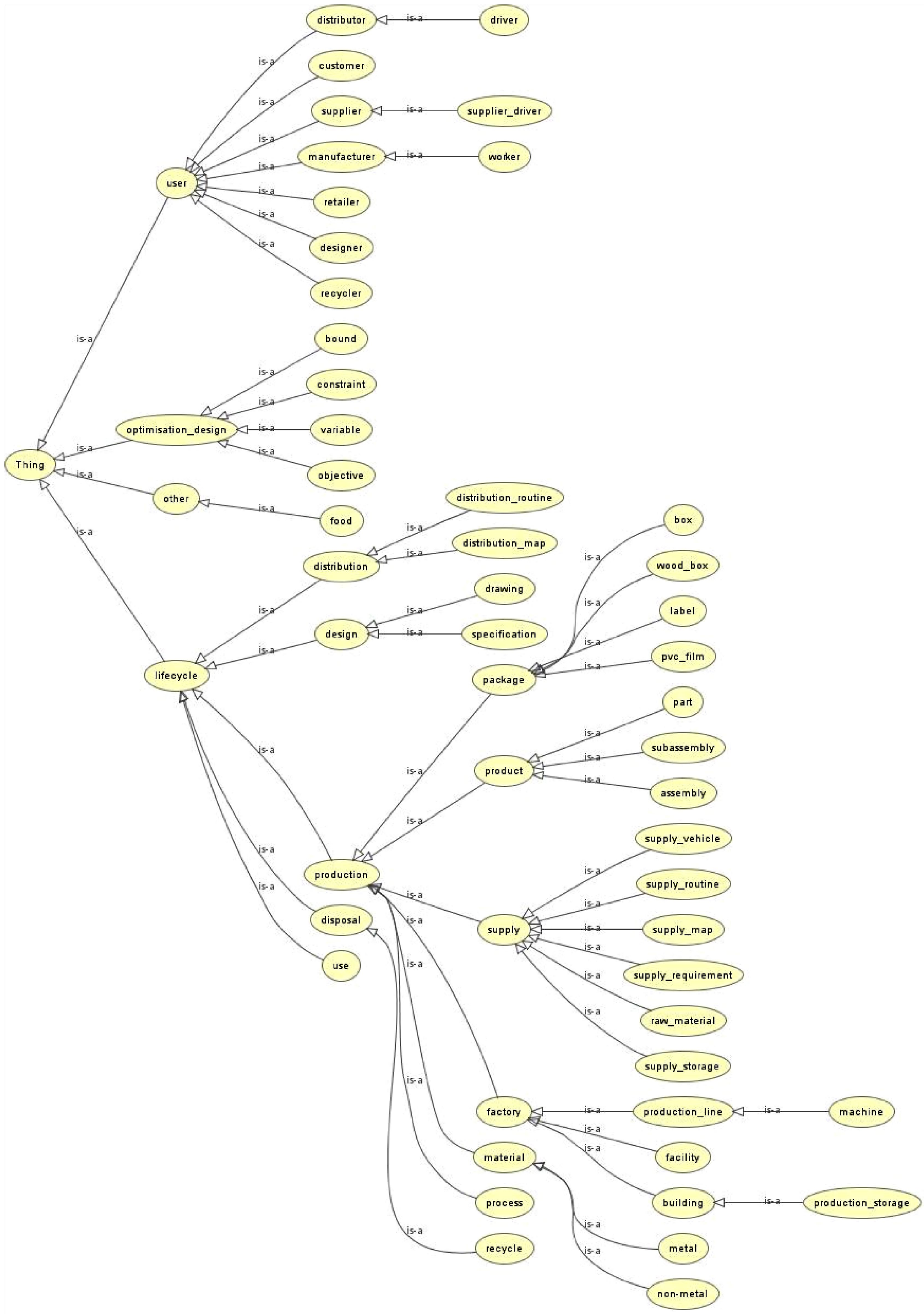


Figure 9.2 ontology of gearbox life cycle

9.2 Property modelling

Properties have two types, data type and object. Data type property is the property each class has. Object property is the relationships between these classes.

- **Data type properties**

Data type properties are properties of classes in data type. Data type property for gearbox life cycle includes dimension, ecological impact, mass, etc. These data type properties are obtained by design and drawing of the gearbox and other users' data related to the life cycle. There are many kinds of data type such as boolean, decimal, double, float, positive integer, non-positive integer, rational, real, short, string, token. In this case study, the main type is positive integer and decimal.

- **Object properties**

After the relationships analysis, object property modelling can be carried out. As Figure 9.3 shows, some logical relationships related to the individuals of the ontology in this case study.

Some object properties are inverse properties of each other. Such as 'is_one_of' is an inverse property of 'consist of', 'optimise' is an inverse property of 'is optimised by' etc..

Figure 9.3 Properties of the ontology

9.3 Instances

Instances are also called individuals in ontology. Modelling of instances is the final stage of ontology model construction to support the ontology to operate normally. Instance is an example of class with data type properties and object properties. The gear in class of part is taken as an example to show the modelling of instances. The Figure 9.4 shows two types of property the gear has. Dimensions, amount, ecological impact are included in data type property. Other logical relationships between other individuals are considered in object property.

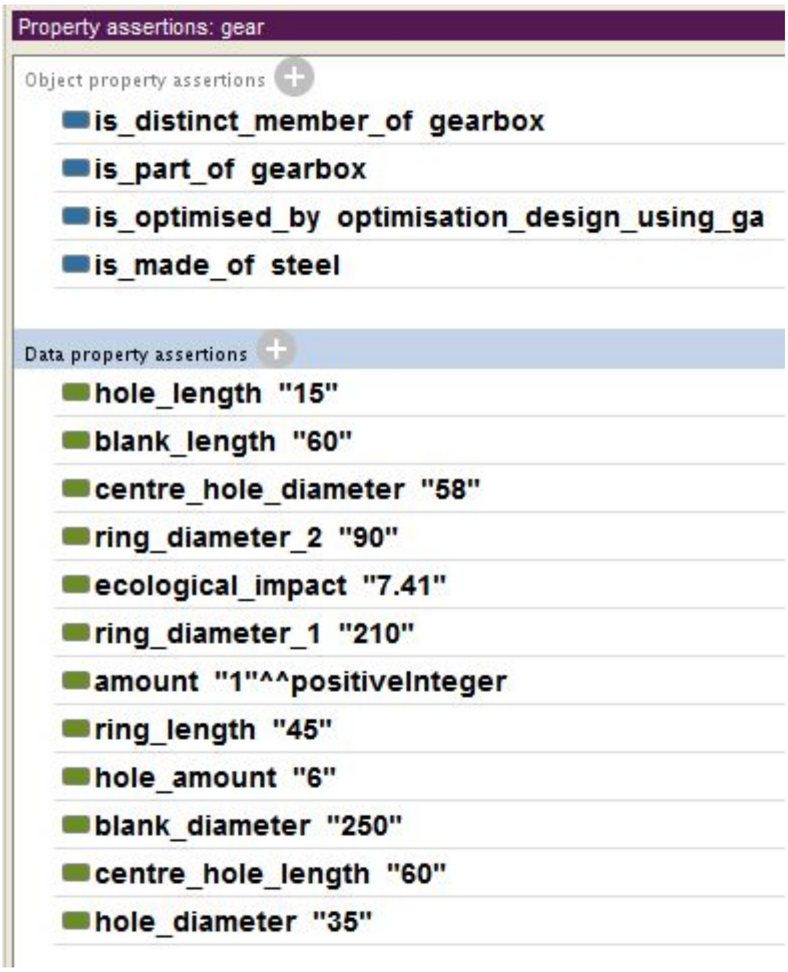


Figure 9.4 properties of gear

Finally, the ontology is filled with instances of all the classes, and their data type properties and relationships. Each class has one instance at least. And then, the ontology is set up. The modelling of ontology is finished.

9.4 Communication between software tools

In order to communicate with SimaPro, MATLAB, Protégé and present to other researcher who is not familiar with software interfaces, an excel file that contains all parameters and ecological impact calculation process and results has been created. With the excel file, parameters can be located by SimaPro MATLAB and imported for further calculations. As Figure 9.5 shows, there are several tabs in the excel file which represent many different section of whole process of ecological impact calculation and optimisation design. At first tab, material usage and process involved are listed. It includes density of material and ecological impact per kg of each material and process.

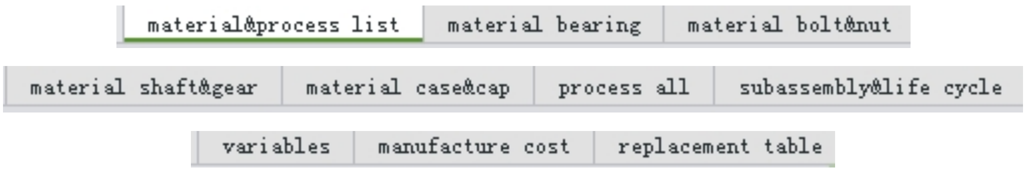


Figure 9.5 tabs in the excel file

As Figure 9.5 shows, ecological impact calculations of material for each part are listed in tab 2 to 5. All parameters and formation are the same as that in SimaPro. Drawings of each part are also attached on the right of calculations' area for reference. The tab called process all lists all process involved during manufacture of each part and ecological impact produced by them. Total impacts of each part are obtained by adding the ecological impact of material which is calculated in previous tab. In the final tab named subassembly and life cycle, the rest of product life cycle including distribution, disposal, and reuse are calculated here. The tab named variables, manufacture cost and replacement tab are related to the optimisation design using MATLAB gatool. The variables tab lists all the design and calculation parameters, and objective function of EI. The function of objective function of manufacture cost is written in the tab named manufacture cost. The last tab is the replacement tab describes the relationships among design parameter, calculation parameter, default value, and variable. More details can be seen in the attached excel file because the print page is limited.

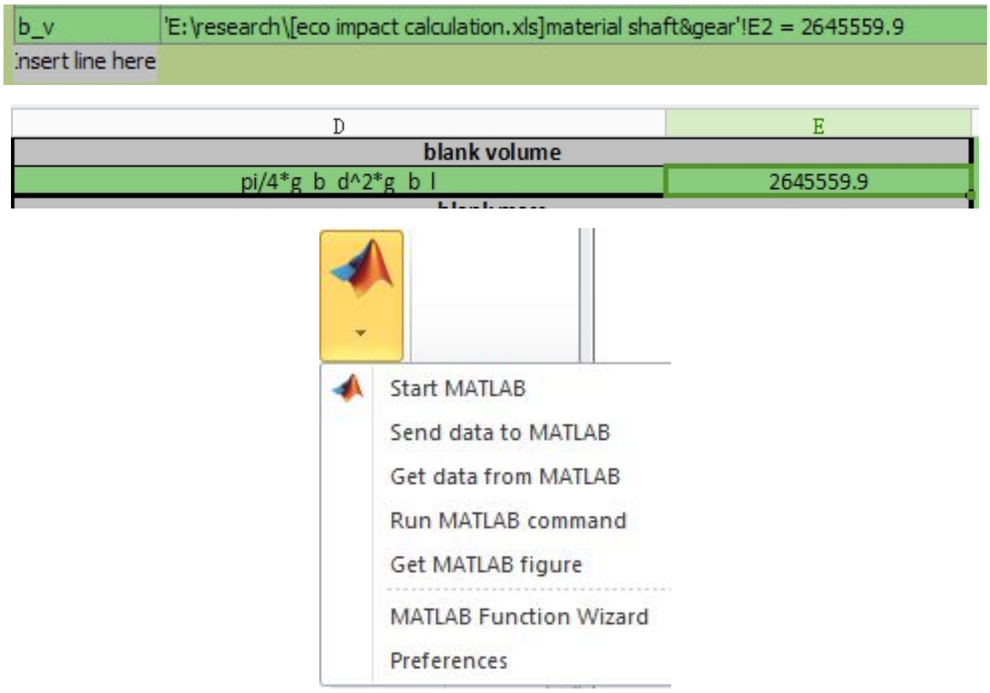


Figure 9.6 COM interface of SimaPro and spread sheet EX link of MATLAB

Data import and export can be achieved through a COM interface between excel and SimaPro. As Figure 9.6 shows, SimaPro can easily call the value in the excel. This function is only available in developer version of SimaPro for business uses. MATLAB and excel can communicate with each other using the spread sheet link EX as Figure 9.6 shows. Ontology and spread sheet can be linked together with spread sheet master plug-in. The Protégé is capable for acquiring the data in spread sheet. Now, the Protégé is updated to version 4. But for new version of Protégé, the plug-in has not been updated for a while, new solution should be figured out.

9.5 Concluding remarks

Ontology modelling of gearbox life cycle is presented in this chapter. Through class, property, and instance modelling, the ontology has been successfully constructed. The class modelling including domain research of gearbox life cycle, and relationships analysis. The property modelling consists of modelling of data type and object properties. Some instances of classes are added into the ontology. The spread sheet for communicate with SimaPro, MATLAB, Protégé, and other software is created.

Chapter 10 Sustainable design of farm food

10.1 Life Cycle Impact Assessment of Farm Food

This chapter presents results of life cycle impact assessment (LCIA) of farm food. And proposal of optimisation is followed after analysis of the results. Finally, ontology of farm food is modelled as a database and a medium to communicate with others.

The functional unit considered in the life cycle of farm food is the vegetables produced in one year by a farm. 7 tons of vegetables are estimated as the production of the farm in one year from a piece of land of 2 hectares. Vegetables may include carrots, potatoes, onions, and some fruit such as apples and strawberries. As Figure 10.2 shows, the production, distribution and disposal of farm food life cycle are mainly considered at current stage of research. Further consideration of other impacts such as impact of usage including cooking, and recycle will be taken into account in future works.

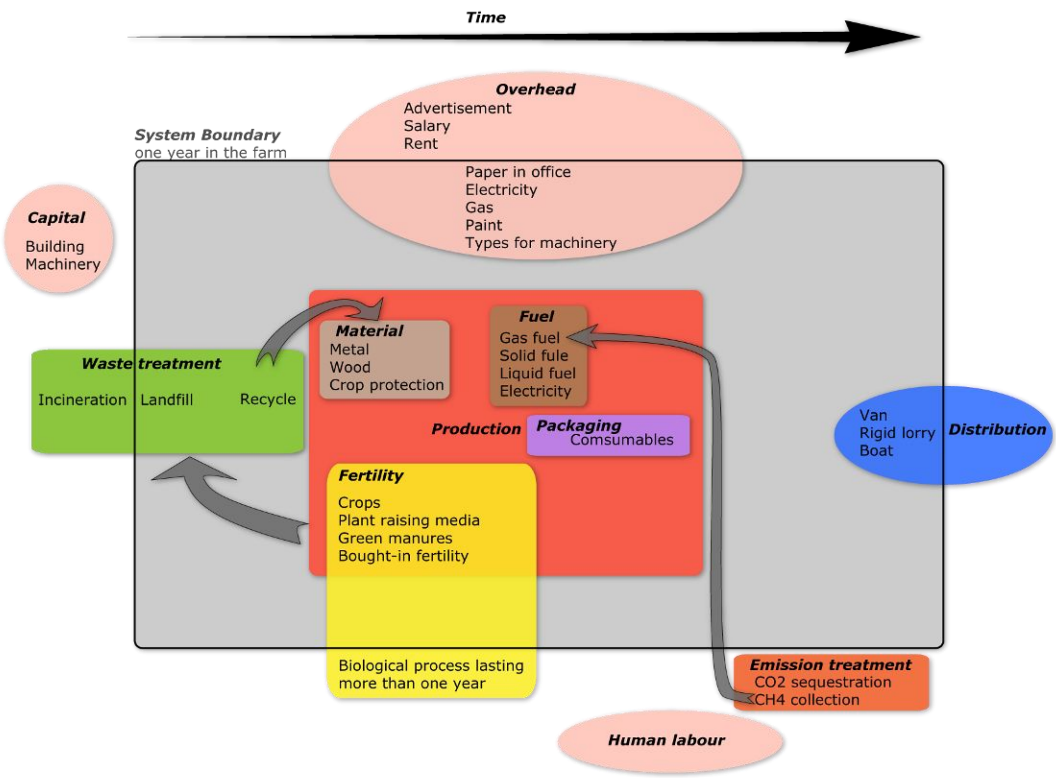


Figure 10.2 System boundary of farm food LCIA

As the LCIA of gearbox, LCIA of farm food is conducted using SimaPro and following ReCiPe Hierarchist (H) V1.04 method.

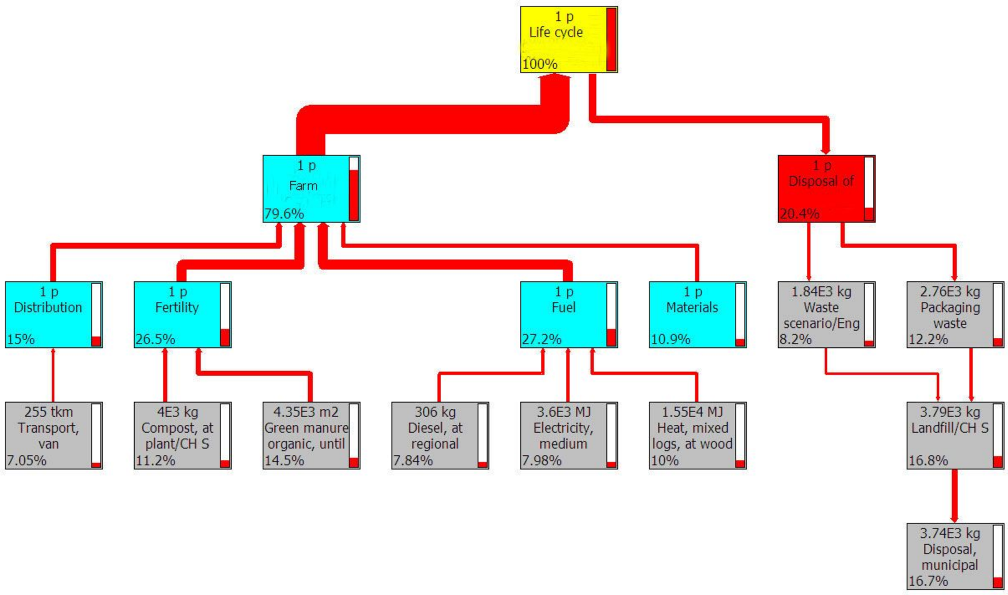


Figure 10.2 Network results of LCIA (7% cut-off).

As Figure shows, impacts and its percentage of following processes are outstanding.

- Fuel (27.2%);
- Fertility (26.5%);
- Disposal of farm (20.4%);
- Distribution (15%);
- Materials used in the farm, or main overheads (10.9%).

Figure 10.3 shows single score of LCIA.

- Disposal of municipal solid waste produce the most of impacts. (17%);
- Green manure presents a lot of impact. (15%);
- Compost produced the third large contribution to the impact (11%);
- Energy mix from heat, electricity, diesel, and petrol (27% in total) contributes more than a quarter of the total impacts.

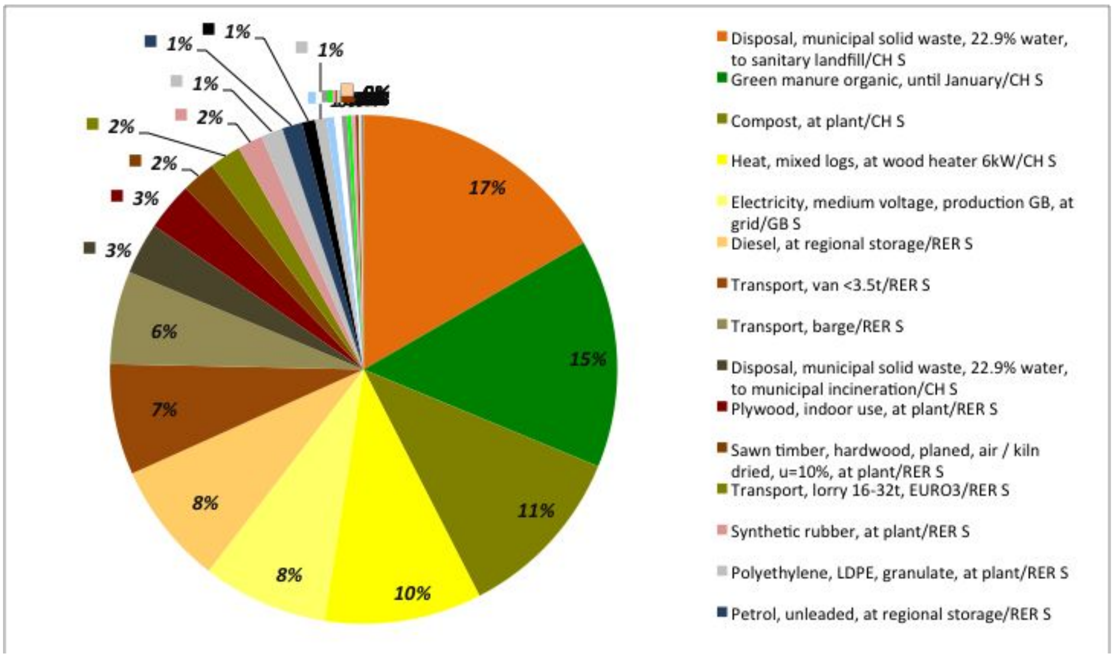


Figure 10.3 Single score of LCIA

Figure 10.4 shows the damage in endpoint level. The disposal of farm produces considerable impact in the human health, while it reduces in ecosystems and resources.

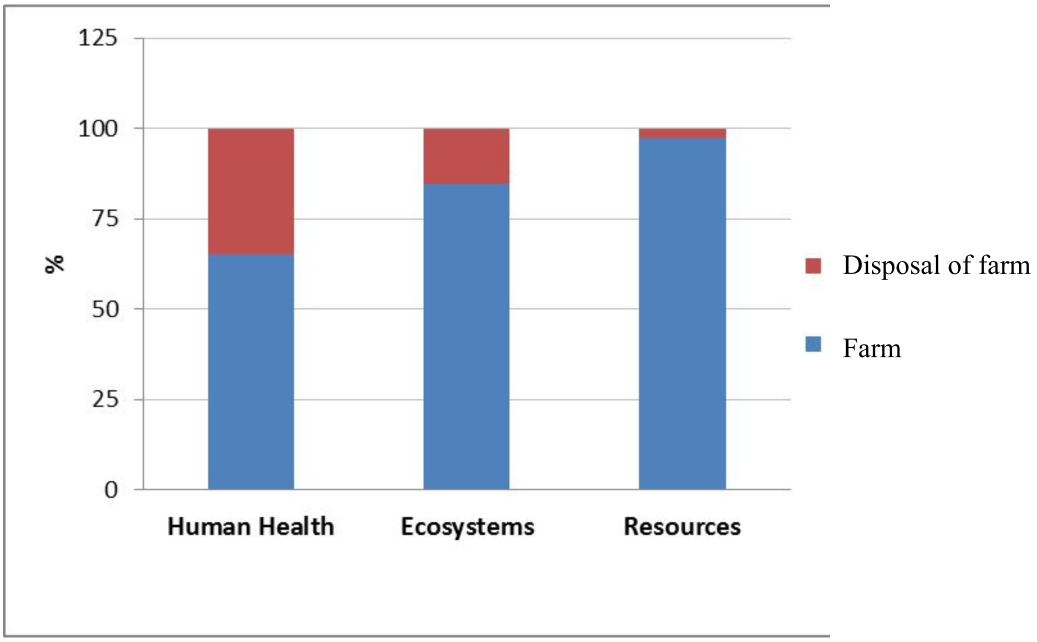


Figure 10.4 Damages at End-point level.

Figure , impacts are higher in midpoint level in climate change human health, climate change ecosystems, agricultural land occupation, and fossil depletion. Particularly, the disposal of farm contributes more in first three.

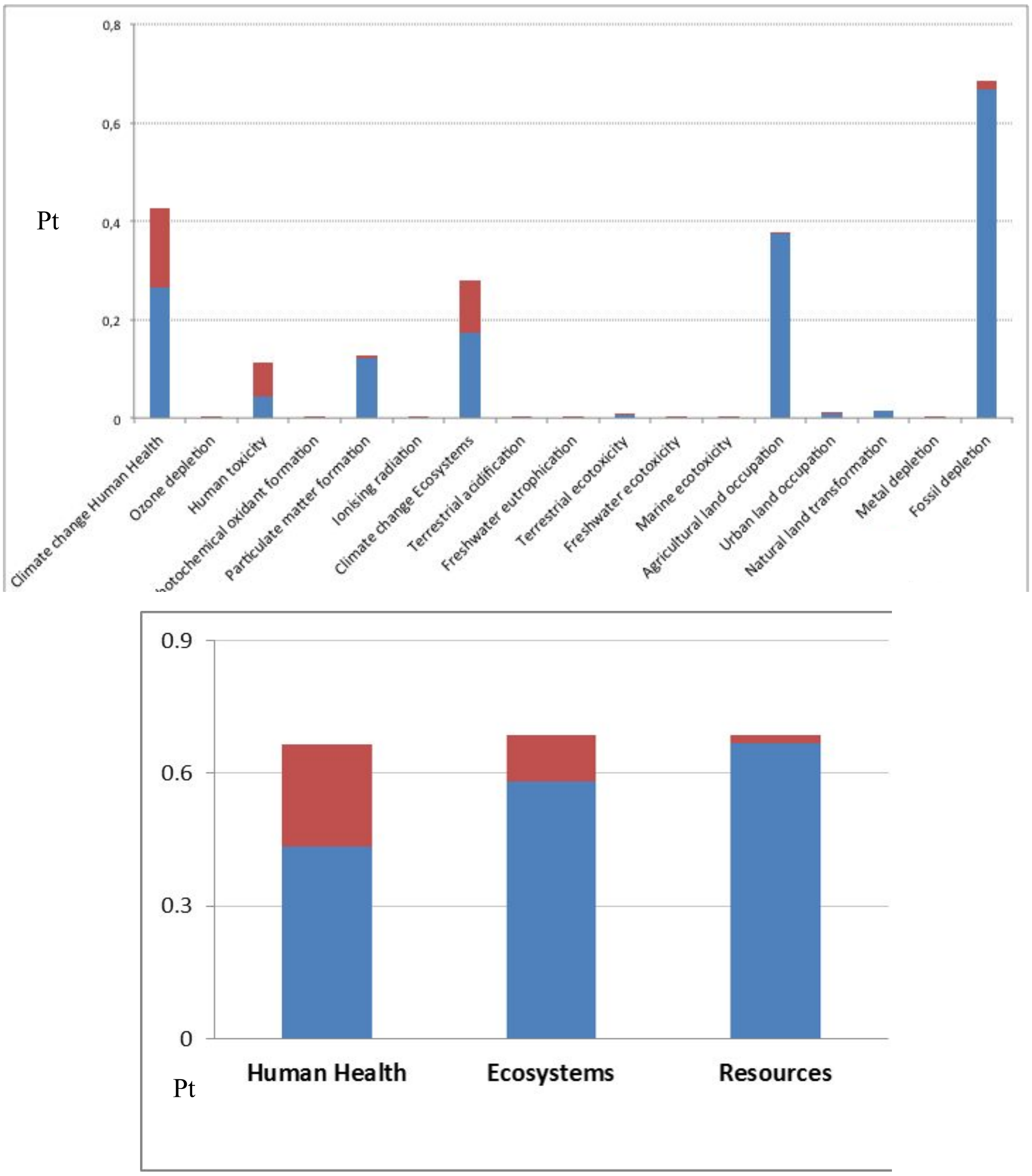


Figure 10.5 Impacts in midpoint and endpoint levels after normalisation.

Figure presents the results of weighting in midpoint and endpoint level. In the midpoint level, the impacts in four major categories previously highlighted are still high. Particularly, the impact of climate change human health becomes higher. In the endpoint level, the rate of impacts from disposal of farm regard to production and distribution is almost same, but the impact in resources is obviously decrease.

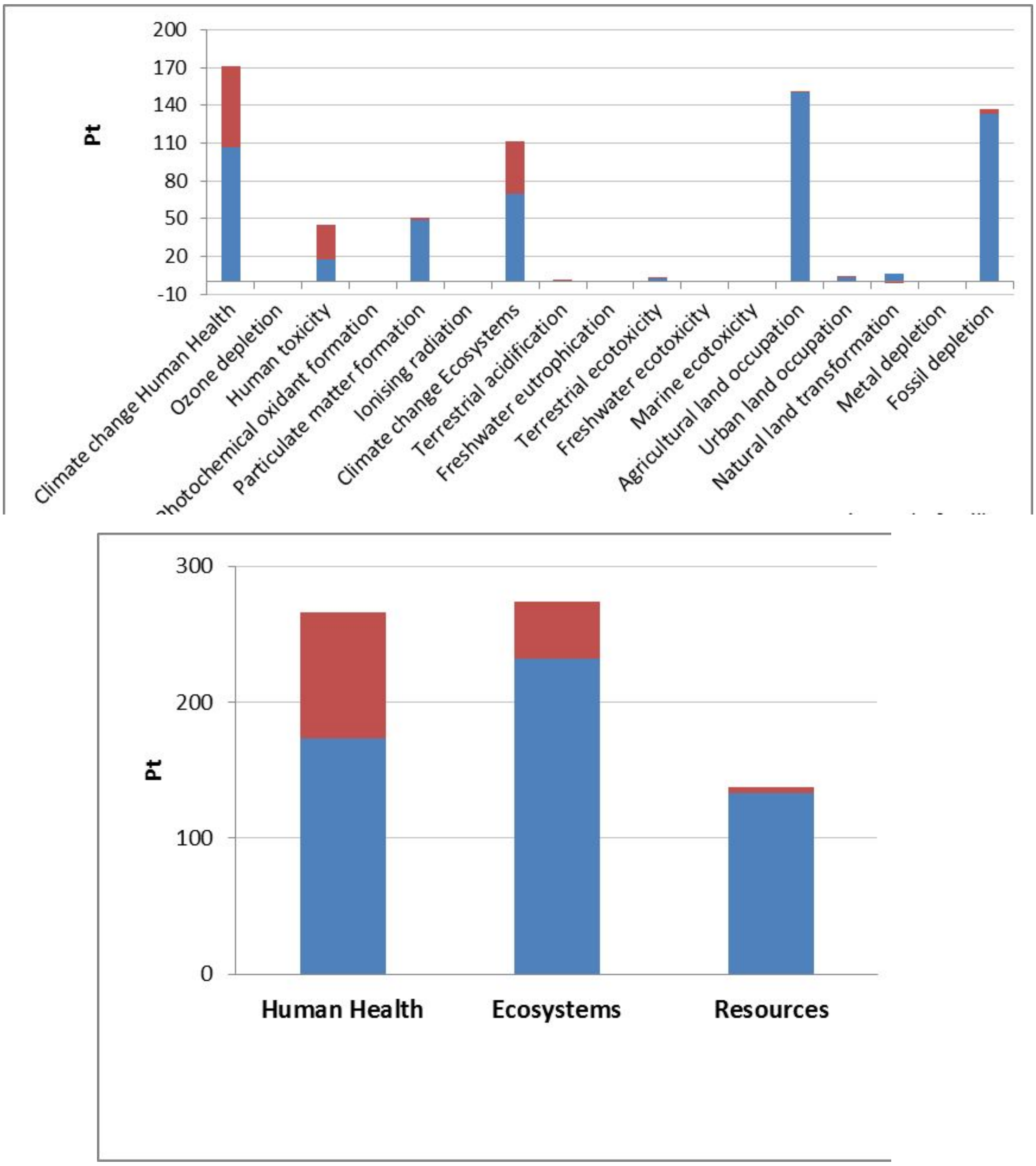


Figure 10.6 Impacts ad midpoint (above) and endpoint (bottom) levels after weighting.

Considering the significant impact of the disposal. A separate LCIA focused on production and distribution activities has been conducted for further details of the impact produced by these steps. Figure highlights following points:

- The impact of agricultural land occupation is mainly generated by actions to improve fertility, followed by materials used;
- Fossil depletion is mainly caused by fuel consumption in the farm

and distribution out of farm.

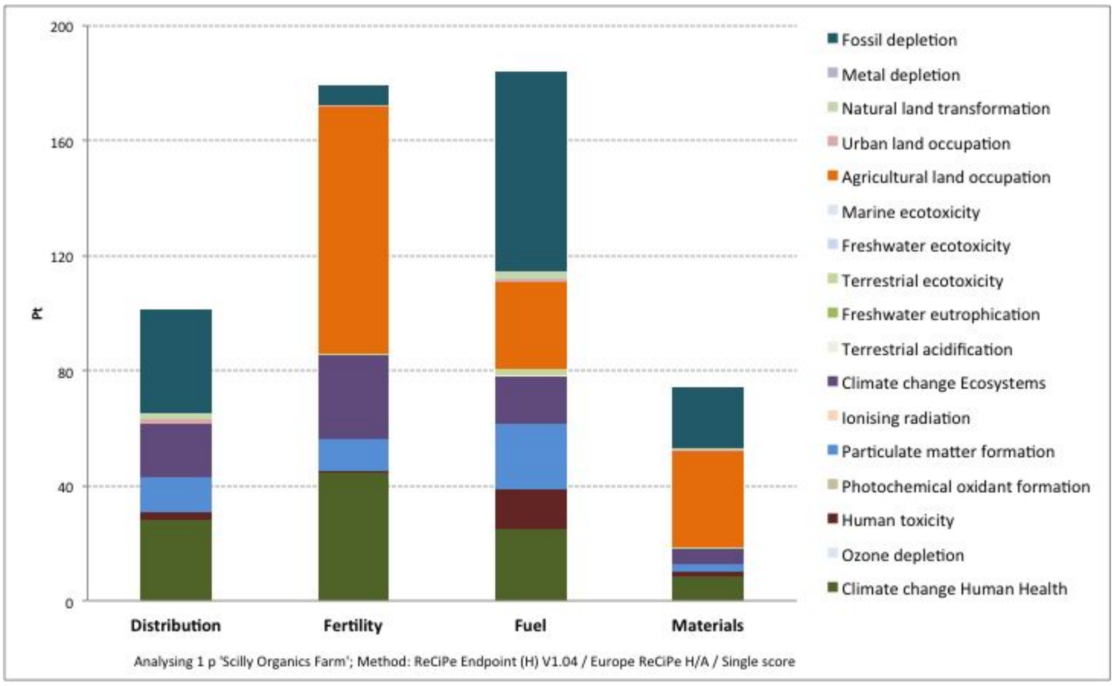


Figure 10.7 Single score of LCIA in midpoint level for production and distribution

10.2 Proposal of sustainable optimisation

Fuel consumption produces the most of impacts of the farm food. Green manures and compost production are the major sources for impact of fertility. Disposal of farm also need to be improved because it shares the largest contribution, 17%, in single score of processes. Therefore, following optimisation plans are proposed:

- To reduce the consumption of fuel in the farm or use more renewable energy such as hydropower, wind energy, solar energy.
- To collect air pollution, such as NH4, from green manure and compost and use them as energy sources. This treatment will reduce fuel consumption and impacts from fertility at the same time.
- To rearrange the disposal process of farm food. To reuse or recycle some by-product to decrease the impacts of disposal and material used. For instance, wood can be reuse as the material for construction of

shed.

The LCIA excludes the usage stage. In future work, activities of customer such as cooking should be considered into the LCIA.

10.3 Ontology modelling of farm food

The ontology model is case sensitive. For avoiding confusion during modelling and application of ontology, all names in ontology use lowercase. After domain research of farm food, all the classes, properties, and instances are modelled based on the life cycle of farm food as the figure shows below.

Classes are modelled based on life cycle stage such as production, distribution, disposal, and overhead, capital items. Optimisation plan is another small category of the ontology. Each stage has numbers of subclasses. For example, capital items include building and machinery, distribution includes destination and vehicle. Production is the largest subclass including four subclasses which are fertility, farm food, fuel, and usage. Object properties and data type properties are create according to ordinary logical relationship and potential data of classes. Some instances of these classes are created at the end.

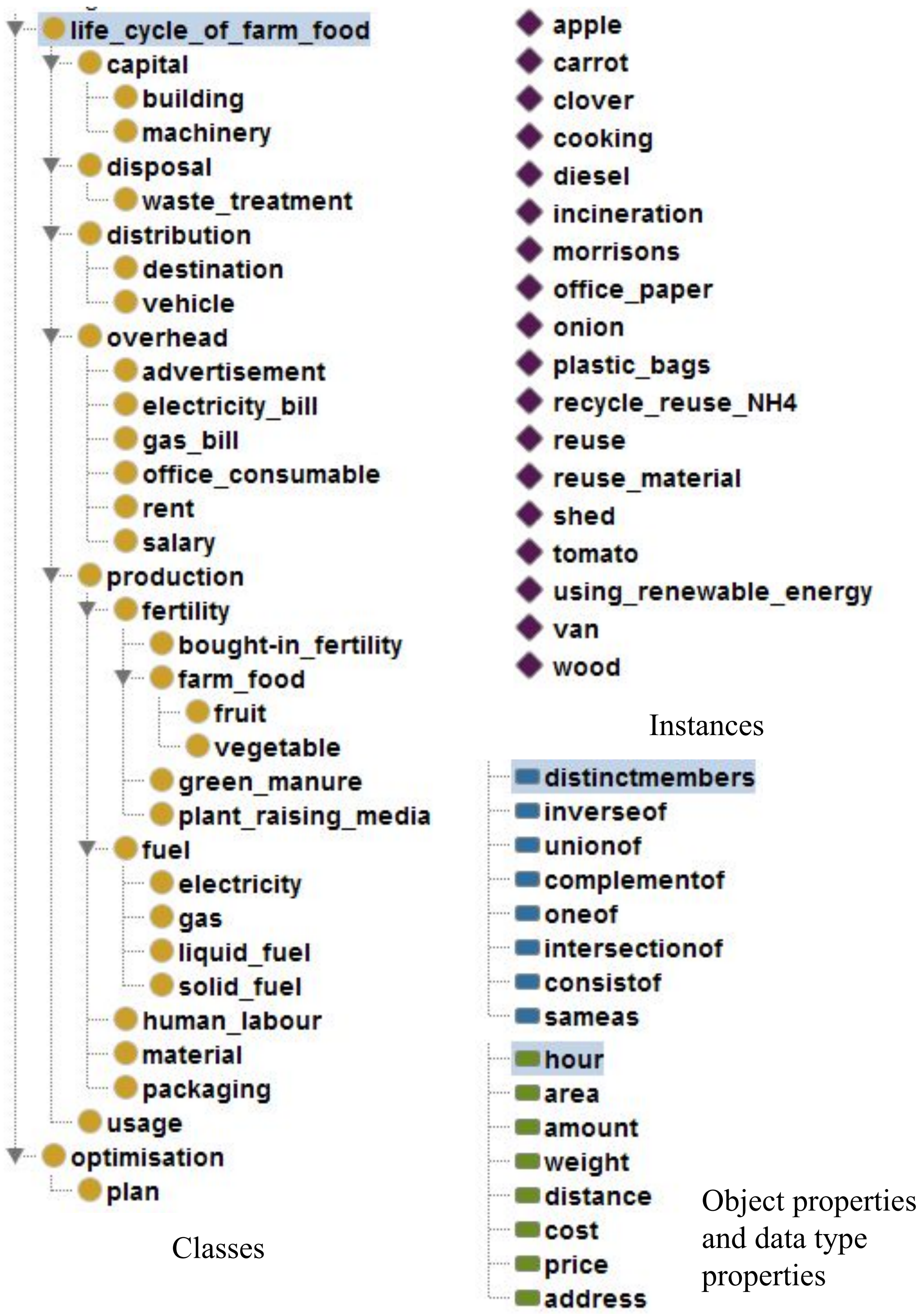


Figure 10.8 Ontology of farm food

10.4 Concluding remarks

This chapter presents results of life cycle impact assessment (LCIA) of farm food. The analysis of the results shows that there are numbers of potential optimisation plans. Three proposals of optimisation have been raised. Finally, ontology of the farm food is modelled as a database and a medium to communicate with other users in the life cycle.

Chapter 11 Conclusion and future work

This chapter presents the conclusion of the research based on aim and objectives stated in chapter 1. Novelty of the research and contribution to knowledge is followed. Finally, future work is proposed.

11.1 Conclusion

With completion of two case studies applying the sustainable design approach developed in the research, the aim of the research has been achieved. A sustainable design approach of mechanical product has been developed successfully.

Along the development of the approach, all of the objectives have been reached. The following specific conclusions are for each chapter in the research.

- Emerging technology and relative researches has been reviewed in chapter 2. The review comprises of a number of aspect including ecological indicators, product life cycle assessment, renewable energy and material selection, responsibilities of different users in the product life cycle. Application of ontology technique into data management of sustainability. Sustainable design and a clean development mechanism, and other methods, tools. The review extends the author's knowledge around the theme of the research and gives the author an opportunity to find the gap between existing research and future development in relative areas. Finally, the aim of the research, to develop a sustainable design approach of mechanical product underpinned with life cycle impact assessment, genetic algorithm, and ontology, has been confirmed.

- Five popular life cycle impact assessment software package, CES EduPack 2010 Eco audit tool, Solidworks 2010 Sustainability tool, Sustainable Minds, SimaPro 7.2, and Gabi 4 education, have been reviewed in chapter 3. The evaluation criteria used in the review includes function to define the product and its life cycle, LCIA methods employed in the software, accuracy of assessment and quantity of databases, availability for the user to modify the databases, presentation and layout of results, and detail information of results. Based on the comparison results which shows advantages and disadvantages of these software, guidelines are proposed for selection of the LCIA software tools for conducting sustainable product design. Furthermore, SimaPro comes out and becomes the most appropriate tool of the LCIA for this research because of its adaptable database, well integration with updated ReCiPe method and famous ecoinvent database, clear and intuitive presentation of LCIA result, powerful comparison function.
- A novel approach for sustainable design has been developed in chapter 4. Within the approach, a three-tier modelling method for life cycle impact assessment is developed. In the approach, a product is broken into three tiers: part, subassembly, and assembly. Each level has their ecological impact from manufacture, process, material, assembling, human labour, and other aspect. The upper level combines the ecological impact from lower level. At last, ecological impact of assembly goes into its upper level, the final level, and the product life cycle. And then the product life cycle impact assessment is completed. Secondly in the chapter 4, the human labour's ecological impact is proposed. And the method to calculate the ecological impact of human labour in per hour has been developed. The calculation method considered four aspects including food, drink, metabolism, transport.

The calculation method has been modelled into SimaPro database for future application or further improvement. As mentioned before, the software package, SimaPro, and the LCIA method, ReCiPe, are chosen as the tool and method to conduct the LCIA in the research. A shaft in industrial gearbox is taken as an instance to illustrate the method and procedure to assess the product life cycle using SimaPro and ReCiPe. The modelling of the shaft is parametric. The sustainable design approach, which considers human labour's ecological impact, uses product life cycle and three-tier method to model, and underpinned with SimaPro and ReCiPe, has been developed. In the end of the chapter, a representation layout, EI-COST is proposed. It is a spider net chart applied to present and evaluate the product specification or illustrate product properties including ecological and manufacture cost.

- An optimisation method for sustainable design using genetic algorithm is developed and presented in the chapter 5. The chapter starts from an introduction of optimisation, and genetic algorithm. Advantages of genetic algorithm are stated. After that, the methodology of optimisation and genetic algorithm are clarified. The optimisation consists of three essential elements, objective, constraint, variable. Three types of creating children include elite, crossover, and mutation. And stopping criteria of optimisation consists of generations, time limit, fitness limit, stall generations, stall time limit. Also, determination guidelines of stopping criteria are introduced. In the end, the procedure of sustainable product design underpinned by LCIA and design optimisation is presented. The procedure integrated previous researches into a complete flow, which is a systemic sustainable design approach.
- Start with introduction of current Web service and search engine system, the chapter 6 analyses some disadvantages and limitation of existing technology and reveals the definition and superiority of the ontology. Afterwards, an ontology modelling method of product life cycle is

described. After analysing the break down structure of ontology modelling, an example of ontology is presented. The modelling of ontology can be divided into three sections, class modelling, property modelling, and instance modelling. Class modelling comprises domain research and relationship analysis. Property modelling includes data type and object property modelling. The last step is to input instances of the classes to make the ontology operate normally. After that, an intermediary, a spread sheet, among SimaPro, MATLAB, and Protégé are proposed. The application of the spread sheet increases the compatibility of the whole approach and system. COM interface, Spread sheet link EX, and a plug-in for Protégé named spread sheet master can be used to exchange information between the spread sheet and these three software. With the help of the spread sheet, the scope of system integration is prospected in the end of the chapter. The system links all the users and their data together in the whole product life cycle. Through ontology, they can share their data with other users in the system or conduct the LCIA and optimisation together. There are numbers of potential application in future.

- For validation of the developed approach, a sustainable design of industrial gearbox is conduct in the chapter 7. After structure analysis of the gearbox, three-tier modelling method is used to model the life cycle of the gearbox in SimaPro. The ecological impact of human labour is also involved. The whole modelling is parametric to keep a potential for future application of the LCIA model. The three-tier modelling includes part modelling, subassembly modelling, and assembly modelling. After that, modelling of gearbox life cycle is presented. Based on the life cycle model of gearbox, an LCIA has been conducted using SimaPro with ReCiPe method. The results of LCIA consist of network, characterisation, damage assessment, normalisation, weighting, and single score. These figures comprehensively analyse the life cycle impact of gearbox. In additional, the ecological impact of human labour is also presented. Based on the analysis of results, optimisation plan is proposed.

- Three design optimisation plans are conducted in chapter 8. Plans include to extend the service life of gearbox, to increase the recycle rate of used material, and optimisation design using GA. They all successfully achieve the aim to decrease the ecological impact of gearbox life cycle. The optimisation result of increasing the recycle rate shows the ecological impact decreases around 70%. Moreover, the optimisation design using GA has two objective functions including ecological impact and manufacture cost of the gearbox life cycle. According to the comparison results of ecological impact between optimised and original design, the ecological has reduced 7%.
- Ontology modelling of gearbox life cycle is presented in chapter 9. Through class, property, and instance modelling, the ontology has been successfully constructed. In order to communicate with SimaPro, MATLAB, Protégé and present to other researcher who is not familiar with software interfaces, a spread sheet that contains all parameters and ecological impact calculation process and results has been created. It is a crucial component in the whole approach because it enhances the compatibility of the system.
- Chapter 10 present results of life cycle impact assessment (LCIA) of farm food. The analysis of the results shows there are numbers of potential optimisation plans. Three proposal of optimisation has been raised. To reduce the consumption of fuel in the farm or use more renewable energy; To collect air pollution, such as NH4, from green manure and compost and use them as energy sources; To rearrange the disposal process of farm food. To reuse or recycle some by-product to decrease the impacts of disposal and material used. Finally, ontology of the farm food is modelled as a database and a medium to communicate

with other users in the life cycle.

11.2 Novelty and contribution to knowledge

The novelty and contribution to knowledge of the research can be highlighted below

- A detailed review of five popular life cycle impact assessment software package, CES EduPack 2010 Eco audit tool, Solidworks 2010 Sustainability tool, Sustainable Minds, SimaPro 7.2, and Gabi 4 education, has been presented. Based on the comparison results which show advantages and disadvantages of these software in six evaluation criteria, guidelines are proposed for selection of the LCIA software tools for conducting sustainable product design. Furthermore, the analysis, and the comparison results can be used as a reference for researchers in LCIA or LCA area in future. The guideline can help user select suitable software to achieve their goals.

A number of novelties has been proposed and developed within the developed approach for sustainable design. These novelties are listed below:

- The three-tier method for modelling of product life cycle provides a progressive way to modelling the product life cycle and conducts the life cycle impact assessment. In the approach, a product is broken into three tiers: part, subassembly, and assembly. In the modelling of each tier, ecological impacts of different ecological impact elements in life cycle are considered. In the part tier, manufacture, material, process, supply, human labour, energy consumption, etc. are considered. In the subassembly tier, packaging, overhead, etc. are added into consideration. In the assembly tier, the ecological impact elements considered include transportation, packaging, product service life, design for disassembly, product re-use, recycling, and disposal.

- Ecological impact of human labour has taken into account in the LCIA as an input of product life cycle. In the existing literature, human labour has not been considered as an input for LCIA. Existing research often ignores the effect of human activities in the calculation of ecological impact of mechanical products. The research proposed consideration of human labour during the LCIA to restate the importance of human activities in society and natural environment. The modelling of human labour's ecological impact considers four aspects including food and drink, human metabolism, and transport between home and workplace. The first one is considered as input. The latter two are considered as output to the environment. The model of human labour's ecological impact is stored in the database of SimaPro. It can be used by other research directly or after minor modification. Also, yes_or_not factor of human labour has been created in SimaPro database. This factor can be modified to include or exclude the ecological impact of human labour in the LCIA. It also can be used to change the distribution of human labour in the product life cycle.
- Optimisation design with the objective of minimise ecological impact and manufacture cost using genetic algorithm. The optimisation design has considered ecological impact and manufacture cost at the same time. Also, it considered environment and economy simultaneously. Manufacturers always consider the economy. And consumers often consider environment. In that case, the optimisation design method can satisfy the requirement from two sides at the same time. The functions, variables, and constraints built in MATLAB can be used by future researcher. Or they can modify them to adapt their requirements.
- Procedure of sustainable product design underpinned by LCIA and design optimisation has been presented. Firstly, a new design produced based on the product specification and it will be modelled and conducted a LCIA in SimaPro to check the ecological impact. If the

results do not satisfied the requirement, the design goes into the optimisation and re-design stage. The optimisation uses genetic algorithm optimisation tool in MATLAB. And then, a LCIA of the optimised design will be conduct. The results of LCIA will be compared with the original design using the unique function of SimaPro to check the optimisation is successful or not. If user satisfied with the results, the design is finished.

- Ontology modelling of gearbox life cycle is present. The ontology has been successfully constructed and can be used to store data in the whole product life cycle. These data in the ontology can be retrieved by user in the life cycle. Also, they can shares data with other users through the ontology. The model of gearbox can be applied into industry such as gearbox manufacture. Or it can be used into other ontology research or collaboration manufacture by other researcher.
- EI-COST is a proposal representation layout, which is a spider net chart, applied to present and evaluate the product specification or illustrate product properties including ecological and manufacture cost. Therefore, the ecological impact has been introduced into product specification stage. Using the EI-COST, the designer will consider ecological impact as a criterion during design evaluation stage. It is also a decision-making tool for sustainable product design.
- Parametric modelling of gearbox life cycle has been modelled in SimaPro. These parameters can be modified by future users to adapt their requirement of application. Other gearbox or mechanical product can be easily modelled based on the parametric model. Manufacture also can use the model to check their product straightforward.
- Spread sheet for communication of software is created. The spread sheet includes the data form gearbox life cycle, LCIA data from SimaPro and ecoinvent database relating to the gearbox life cycle, and optimisation design. All the data needed in the approach is stored in the

spread sheet. It increases the compatibility of the approach. SimaPro, MATLAB, and other software can exchange data with it. It is the key of the whole integrated system of the developed approach. In another word, user can only use the spread sheet to do the LCIA of gearbox because it has all the data LCIA needs. If other potential user modifies the data of gearbox, they can also model their own gearbox in it and complete the LCIA directly.

- Farm food optimisation has been presented. And the ontology of farm food has the same potential usage as the one of gearbox. It is also an attempt to apply the developed approach into other area.

With these novelties, an approach for sustainable design has been developed.

11.3 Future work

There are still some limitation and possibility of the research. So a numbers of anticipated future work can be developed based on the research.

- **Conversion cost**

The author have attempted to consider the conversion cost into the life cycle impact assessment but there is still some researches in processing speed need to be further conducted.

Conversion cost is the expense of conversion from raw material to end product. It is consist of overhead cost, electricity cost for office facilities, machine depreciation, maintenance, and direct labour cost. Direct labour cost is the expense of hourly wage of workers. It can be obtained through calculation based on processing time, which is the quotient of processing material amount and processing speed. The hourly wage expressed by labour cost index, lc. (29) Overhead cost contains factory management cost, factory operation cost, factory workshop construction cost, and purchase of factory site and machine.

$$C_L = \frac{A_M}{v_P} \times w_h \quad (29)$$

C_L : cost of direct labour

A_M : Amount of material

v_P : processing speed

w_h : Hourly wage

Amount of material can be obtained through calculation based on drawing of part. Processing time can be worked out by amount of material and processing speed. Different processing machine has different processing speed. In this research, all of processing speed requires to be expressed as how many kilograms are cut per second to involve in calculation of objective function. All of the processing speed is estimated by experience.

- **Turning speed**

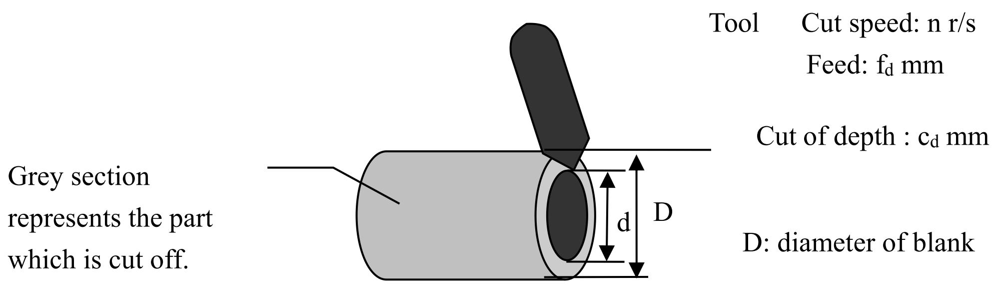


Figure 11.1 Sketch map of turning

Turning speed is related to cut speed, feed, cut of depth, and diameter of blank. It can be expressed as formation below. (30) Default values of these parameters are listed below as well. Companies can modify them depends on their needs and situation. Diameter of part and cutting time are assumed as 50 and 1 to represent most situations. Cutting linear velocity is 30-50m/min, 500-800mm/s. Circumference is Dπ, 157mm. So, range of cut speed is from 3.18 to 5r/s. estimated value is 4r/s.

$$v_t = f_d n\pi(D^2 - d^2)$$

$$v_t = f_d n\pi[(c_d + d)^2 - d^2]$$

$$v_t = f_d n\pi(c_d^2 + d^2 + 2dc_d - d^2)$$

$$v_t = f_d n\pi(c_d^2 + 2dc_d) \quad (30)$$

Table 11.1 Default values of parameters for turning speed calculation

Cut of depth : cd mm	1mm
D: diameter of blank	51mm
Cut speed: n r/s	4r/s
Feed: fd mm	0.2mm
d(diameter of part)=D-cd	50mm

Substituting these default value in formation (30), the turning speed is obtained, which is equal to 253.712mm3. Default density of material is 0.00000785 kg/mm3. So the turning speed in unit of mass per second is 0.0019916392kg/s.

- **Milling speed**

A list of processing speed of different machine and process shows below.

Table 11.2 Processing speed of different machine and process

Process	Processing speed
Milling	n/a
Drilling	n/a
Assembling	n/a
Turning	0.0019916392kg/s
Extrusion	n/a

➢ **Labour cost index and hourly wage**

In machinery factory, hourly wage for different types of work in production is varied. There are different wage standard for different companies. Here proposes an assumptive labour cost index number for calculation. In future work, anyone can modify it to adapt for wage standard of different companies. The labour cost index number is set as lc. Type of worker, works they do, and hourly wages for them are show in list below.

Table 11.3 Hourly wage with labour cost index for different machinery worker.

Type of worker	Work	Hourly wage
Miller	Milling	7lc
Fitter	Drilling, assembling	6lc
Lathe worker	Turning	6lc
Hammersmith	Extrusion	5lc

Because, standard and method to calculate overhead cost varied among different companies and factories. Overhead cost is out of consideration of calculation. And, which type and brand does the factory use is uncertain. So, electricity consumption, machine depreciation, and maintenance are unclear. For now, costs in green frame are considered. This means manufacture cost is the sum of material cost, direct labour cost, and transportation cost.

- **EI-COST for gearbox and farm food**

As mentioned before, EI-COST has been proposed. Due to the data of other criteria of gearbox and farm food are limited. The EI-COST of case studies are not presented in the research. If other data such as efficiency, price, usage of customer, can be obtained in future. EI-COST will be presented. In addition, cooking should be added as the elements of human labour's ecological impact.

- **Multi-objective optimisation in MATLAB.**

Because multi-objective optimisation function cannot use non-linear constraints as the constraint created in the research. So a method to solve it should be developed.

- **Improvement of case study of gearbox**

In SimaPro, it is difficult to input the calculation parameter, mog (mass of gearbox) which is involved in the optimisation design process in MATLAB. Because the formula is too long for the SimaPro. The calculation method of ecological impact should be redefined. Such as EI of disposal of gearbox, especially the waste scenario in England. There are still some potential possibilities of improvement. The data used in the research is secondary data. The mass of blank is related to the ecological impact of waste scenario in England. Further research should be conduct.

- **System integration**

Java program should be developed to link the ontology with excel because the plug-in named spread sheet master is not available now for the new version of Protégé. SimaEasy is a new online version of SimaPro, which may be easier to use in the approach for users. For now, it has not been published. Also, the spread sheet should be rearranged for user friendly.

- **Further consideration in LCIA of farm food**

As LCIA of farm food shows, the production, distribution and disposal of farm food life-cycle are mainly considered at current stage of research. Further consideration of other impacts such as impact of usage and activities of customer such as cooking, and recycle should be considered into the LCIA.

References

Alves, C., Ferrão, P.M.C., Freitas, M., Silva, A.J., Luz, S.M., and Alves, D.E., 2009. Sustainable design procedure: The role of composite materials to combine mechanical and environmental features for agricultural machines, *Materials and Design* 30 (2009) pp 4060–4068

Aoe, T., 2007. Eco-efficiency and ecodesign in electrical and electronic products, Journal of Cleaner Production 15 pp 1406-1414

Barth, M. and Boriboonsomsin, K., 2009. Energy and emissions impacts of a freeway-based dynamic eco-driving system, *Transportation Research*, Part D 14 (2009) pp 400–410

Blomqvist, E. and Ohgren, A., 2008. Constructing an enterprise ontology for an automotive supplier Engineering Applications of Artificial Intelligence 21, pp 386–397

Braungart, M., McDonough, W. and Bollinger, A., 2006. Cradle-to-cradle design: creating healthy emissions – a strategy for eco-effective product and system design, Journal of Cleaner Production 15 (2007) pp1337-1348

Burall, P., 1996. *Product development and the environment*, Gower Publishing Limited, Hampshire, pp 84-85

Byggeth, S., Broman, G. and Robert, K., 2006. A method for sustainable product development based on a modular system of guiding questions, *Journal of Cleaner Production* 15 (2007) pp 1-11

Cambridge dictionaries online, 2013. accessed on 17/09/2013, http://dictionary.cambridge.org/dictionary/british/research_1?q=research

Carrano, A.L., and Thorn, B.K., 2005. A Multidisciplinary Approach to Sustainable Product and Process Design, *Journal of Manufacturing Systems* Vol. 24, No. 3 pp 209-214

Casamayor, J. L. and Su, D., 2013. Integration of eco-design tools into the development of eco-lighting products, Journal of Cleaner Production, http://dx.doi.org/10.1016/j.jclepro.2013.02.011

Cerdan, C., Gazulla, C., Raugei, M., Martinez, E., and Fullana-i-Palmer, P., 2009. Proposal for new quantitative eco-design indicators: a first case study, Journal of Cleaner Production 17 (2009) pp1638–1643

Chamier-Gliszczynski, N., 2011. Sustainable operation of a transport system in cities, *Key Engineering Materials* Vols. 486 (2011) pp 175-178

Cha, K., Lim, S. and Hur, T., 2007. Eco-efficiency approach for global warming in the contect of Kyoto Mechanism, *Ecological economics* 67 pp 274-280

Chang, P. and Chang, H., 2009. Exploring senior officials' policy beliefs regarding sustainable transportation, *Transportation Research* Part D 14 (2009) pp 249–254

Dassault Systèmes, 2010, [accessed on 10 Aug 2010] http://www.solidworks.com/sw/183_ENU_HTML.htm

Davis, G. A. and Wilt., C. A., 1997. Extended Product Responsibility: A New Principle for Product-Oriented Pollution Prevention, U.S. Environmental Protection Agency, Office of Solid Waste, Washington, DC, 1997.

Defra, (2010), Survey of Commercial, 2010 Final Results, pp 4-5

Dehghanian, F. and Mansour, S., 2009. Designing sustainable recovery network of end-of-life products using genetic algorithm, *Resources, Conservation and Recycling* 53 (2009) pp 559–570

Donnelly, K., Beckett-Furnell, Z., Traeger, S., Okrasinski, T., and Holman, S., 2006. Eco-design implemented through a product-based environmental management system, *Journal of Cleaner Production* 14 (2006) pp1357-1367

Dori, D. and Shpitalni, M., 2007. Mapping Knowledge about Product Life cycle Engineering for Ontology Construction via Object-Process Methodology, doi:10.1016/S0007-8506(07)60063-8

EC-IPP, 2001. Green Paper on Integrated Product Policy, COM (2001) 68, 7/2/2001, Commission of the European Communities, Brussels, 2001

Edum-Fotwe, F. and Price, A., 2008. A social ontology for appraising sustainability of construction projects and developments, *International Journal of Project Management* 27 (2009) pp313–322

Giudice, F., Rosa, G. L., and Risitano, A., 2006. *Product Design for the Environment: A Life Cycle Approach*, CRC Press, Boca Raton, (2006) Fernandez, I. and Ruiz, M., 2008. Descriptive model and evaluation system to locate sustainable industrial areas, *Journal of Cleaner Production* 17 (2009) pp 87–100

Ferrer, G. and Swaminathan, J., 2009. Managing new and differentiated remanufactured products. *European Journal of Operational Research* (2009), doi:10.1016/j.ejor.2009.08.007

Gabi, 2013. http://www.gabi-software.com [accessed on 14 Jul 2013]

GDAs, 2011. http://gda.ciaa.eu/asp2/what_are_gdas.asp [accessed on 20 May 2011]

Gen, M. and Cheng R., Genetic Algorithms & Engineering Design, John wiley & sons, New York, 1997.

Giatrakos, G., Tsoutsos, T. and Zografakis, N., 2008. Sustainable power planning for the island of Crete, Energy Policy 37(2009) pp 1222–1238

Goedkoop, M. and Spriensma, R. 1999. The Eco-indicator 99. A damage oriented method for life cycle impact assessment. Methodology report and annex. Pré Consultants, Amersfoort, The Netherlands. http://www.pre.nl/eco-indicator99/ [accessed on 20 May 2011]

Goldberg, D., 1989. Genetic Algorithms in Search, Optimisation and Machine Learning, Addison-Wesley, Reading, MA, 1989.

Gong, G., Pan, P., Chen, X., and Yan, L., 1981. Illustrated catalogues of Mechanical Component Curriculum Design, Harbin Institute of Technology.

Granta Design, 2010. http://www.grantadesign.com/company/index.htm [accessed on 12 Sep 2010]

Gruber, T., 2001. "What is an Ontology?". Stanford University. http://www-ksl.stanford.edu/kst/what-is-an-ontology.html. Retrieved on Nov 9, 2009.

Guideline Daily Amounts, 2011. [accessed on 20 May 2011] http://www.gdalabel.org.uk/gda/gda_values.aspx#item2

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., Koning, A. de, Oers, L. van, Wegener Sleeswijk, A., Suh, S.,Udo de Haes, H.A., Bruijn, H. de, Duin, R. van, Huijbregts, M.A.J., 2001. LCA - An operational guide to the ISO-standards - Part 1: LCA in perspective (Final report, May 2001).

Harry Baayen, 2000. Eco-indicator 99, Manual for Designers, A damage oriented method for Life Cycle Impact Assessment,

Hauschild, M., Jeswiet, J. and Alting, L., 2007. From Life Cycle Assessment to Sustainable Production: Status and Perspectives, doi:10.1016/S0007-8506(07)60017-1

Himri, Y., Malik, Arif S., Boudghene Stambouli, A., Himri, S., Draoui, B., 2008. Review and use of the Algerian renewable energy for sustainable development, *Renewable and Sustainable Energy Reviews* 13 (2009) pp 1584–1591

Hitomi, K., 1996. *Manufacturing Systems Engineering*, 2nd ed., Taylor & Francis, London, 1996.

Houe, R. and Grabot, B., 2009. Assessing the compliance of a product with an eco-label: From standards to constraints, *Int. J.ProductionEconomics*121(2009) pp 21–38

Hu, X., Chang, S., Li, J., and Qin, Y., 2009. Energy for sustainable road transportation in China: Challenges, initiatives and policy implications, *Energy* (2009) pp 1–13

Hu, S., Su, L. Lee, K., Chen, J. and Huang, A., 2011. Using TRIZ Methods in Product Design and Improvement of a Presenter Mouse, *Key Engineering Materials* Vols. 486 (2011) pp 13-16

Hu, G. and Bidanda, B., 2009. Modeling sustainable product life cycle decision support systems, *Int. J.Production Economics* 122(2009) pp 366–375

Huang, Y., Bird, R. and Heidrich, O., 2008. Development of a life cycle assessment tool for construction and maintenance of asphalt pavements, *Journal of Cleaner Production* 17 (2009) pp 283–296

Huang, Y., Bird, R. and Bell, M., 2009. A comparative study of the emissions by road maintenance works and the disrupted traffic using life cycle assessment and micro-simulation, *Transportation Research* Part D 14 (2009) pp 197–204

Iberahim, F., Wahab, D., Nopiah, Z., and Abdullah, S., 2011. Establishment of Remanufacturing Index for Locally Manufactured Automotive Components, *Key Engineering Materials* Vols. 486 (2011) pp 77-80

IPCC (2007). 'Glossary J-P. In (book section): Annex I. In: *Climate Change* 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (B. Metz et al. Eds.). Cambridge University Press, Cambridge, U.K., and New York, NY, USA. Retrieved 2010-04-23.

ISO14040, (1997), Environmental Management — Life Cycle Assessment — Principles and Framework, ISO 14040:1997(E), International Organisation for Standardisation, Geneva, 1997.

ISO14062, (2002), Environmental Management — Integrating Environmental Aspects into Product Design and Development, ISO/TR 14062:2002(E), International Organisation for Standardisation, Geneva, 2002.

Schmidt, J., 2010. Documentation of the data consolidation and calibration exercise, and the scenario parameterisation, 2.-0 LCA consultants, 23rd February 2010.

Janssen, S., Ewert, F., Li, H., Athanasiadis, I.N., Wien, J.J.F., Thérond, O., Knapen, M.J.R., Bezlepkina, I., Alkan-Olsson, J., Rizzoli, A.E., Belhouchette, H., Svensson, M., van Ittersum, M.K., (2009), Defining assessment projects and scenarios for policy support: Use of ontology in Integrated Assessment and Modelling, *Environmental Modelling & Software* 24 (2009) pp 1491–1500

Jin, H., Xu, G., Han, W., Gao, L., and Li, Z., 2009. Sustainable development of energy systems for western China, *Energy* (2009) pp 1–6

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., and Rosenbaum, R., 2003. A user guide for the New Life Cycle Impact Assessment Methodology IMPACT 2002+, Industrial Ecology & Life Cycle Systems Group, GECOS, Swiss Federal Institute of Technology Lausanne (EPFL), CH-1015 Lausanne, Switzerland

Jones, E. and Harrison, D., 2001. Applying structured methods to Ecoinnovation. An evaluation of the Product Ideas Tree diagram, *Design Studies* Vol 22 No. 6 November 2001, pp 519-542

Joumard, R. and Nicolas, J., 2009. Transport project assessment methodology within the framework of sustainable development, *Ecol. Indicat*. (2009), doi:10.1016/j.ecolind.2009.04.002

Karakosta, C., Doukas, H. and Psarras, J., 2009. Directing clean development mechanism towards developing countries' sustainable development priorities, *Energy for Sustainable Development* 13 (2009) pp 77–84

Knight, P. and Jenkins, J., 2008. Adopting and applying eco-design techniques: a practitioners perspective, *Journal of Cleaner Production* 17 (2009) pp 549–558

Kothari, C.R., 2004. Research Methodology: Methods and Techniques, second edition, New Age International,

Kowalski, K., Stagl, S., Madlener, R., Omann, I., et al, 2008. Sustainable energy futures: Methodological challenges in combining scenarios and participatory multi-criteria analysis, *European Journal of Operational Research* 197 (2009) pp 1063–1074

Kwon, O. and Shin, M. K. 2008. LACO: A location-aware cooperative query system for securely personalized services Expert Systems with Applications 34, pp2966–2975

Kyoto Protocol, 1998. Kyoto protocol to the United Nations framework convention on climate change, Unite Nations

Labour Force Survey, 2011. Office for National Statistics, Released on Regional Trends Online, 3 March 2011,

Lauwers, L., 2008. Justifying the incorporation of the materials balance principle into frontier-based eco-efficiency models, *ECOLOGICAL ECONOMICS* 68 (2009) pp 1605–1614

Ljungberg, L., 2005. Materials selection and design for development of sustainable products, *Materials and Design* 28 (2007) pp 466–479

Li, L., Shi, Z., Yin, W., Zhu, D., Ng, S., Cai, C., and Lei, A., 2009. A fuzzy analytic hierarchy process (FAHP) approach to eco-environmental vulnerability assessment for the Danjiangkou reservoir area, China, *Ecological Modelling* 220 (2009) pp 3439–3447

Li, Z., Li, L., Zhou, J., and Liu, J., 2010. A determination Method of Product Design Parameters with Interval Constraint, *Key Engineering Materials* Vols. 419-420 (2010) pp 245-248.

Li, W., Feng, Z., and Zhao, D. 2007. Research on Ontology-based Description Model of Part Information, Computer Engineering, Apr. pp 250-252

Li, Y and Oberheitmann, A., 2008. Challenges of rapid economic growth in China: Reconciling sustainable energy use, environmental stewardship and social development, Energy Policy 37 (2009) pp 1412–1422

Liu, B., Xu, B., Yang, S., Shi, P., and Xue, S., 2010 A Research on the Concepts and Estimate Methods of Remanufacturing Rate of Engine, *Key Engineering Materials* Vols. 419-420 (2010) pp 253-256.

Macris, A. and Georgakellos, D., 2006. A new teaching tool in education for sustainable development: ontology-based knowledge networks for environmental training, *Journal of Cleaner Production* 14 (2006) pp 855-867

Marchand, A. and Walker, S., 2007. Product development and responsible consumption: designing alternatives for sustainable lifestyles, *Journal of Cleaner Production* 16 (2008) pp 1163-1169

MATLAB, 2011, http://www.mathworks.co.uk/products/MATLAB/

Matos, S. and Hall, J., 2007. Integrating sustainable development in the supply chain: The case of life cycle assessment in oil and gas and agricultural biotechnology, *Journal of Operations Management* 25 (2007) pp 1083–1102

Maxwell, D., Sheate, W. and Vorst, R., 2006. Functional and systems aspects of the sustainable product and service development approach for industry, *Journal of Cleaner Production* 14 (2006) pp 1466-1479

Meester, B., Dewulf, J.,Verbeke, S., Janssens, A., Van Langenhove, H. 2007. Exergetic life-cycle assessment(ELCA) for resource consumption evaluation in the built environment, *Building and Environment* 44 (2009) pp 11-17

Nes, N. and Cramer, J., 2005. Product lifetime optimization: a challenging strategy towards more sustainable consumption patterns, *Journal of Cleaner Production* 14 (2006) pp 1307-1318

Ortiz, O., Castells, F. and Sonnemann, G., 2008. Sustainability in the construction industry: A review of recent developments based on LCA, *Construction and Building Materials* 23 (2009) pp 28–39

Ostlin, J., Sundin, E. and Bjorkman, M., 2009. Product life-cycle implications for remanufacturing strategies, *Journal of Cleaner Production* 17 (2009) pp 999–1009

Oxford dictionaries, 2013, accessed on 17/09/2013 http://oxforddictionaries.com/definition/english/research?q=research

Park, P. and Tahara, K., 2006. Quantifying producer and consumer-based eco-efficiencies for the identification of key ecodesign issues, *Journal of Cleaner Production* 16 (2008) pp 95-104

PE-international, 2010, [accessed on 18 Sep 2010] http://www.pe-international.com/uk-ireland/company/contact/

PRé Consultants, 2011, http://www.pre-sustainability.com/content/about-pre [accessed on 20 Jul 2011]

Protégé, 2011, http://protege.stanford.edu/ [accessed on 20 Jul 2011]

Pusavec, F., Krajnik, P. and Kopac, J., 2009. Transitioning to sustainable production – Part I: application on machining technologies, *J Clean Prod* (2009), doi:10.1016/j.jclepro.2009.08.010

Qu, Z, Zhang, F., Li Y, and Zhang, Y. 2008. Weather Query System of Strong Convection Based on Ontology. Lanzhou University. Lanzhou, China

Road traffic and speeds statistics, 2010. Department of Transport, 4 November, 2010

ReCiPe Mid/Endpoint method, version January 2010, http://sites.google.com/site/lciarecipe/project-definition [accessed 12th June 2011]

Saboohi, Y. and Farzaneh, H., 2008. Model for developing an eco-driving strategy of a passenger vehicle based on the least fuel consumption, *Applied Energy* 86 (2009) pp 1925–1932

Shangguan, J., Yan, Y., Liu, H., Wang, G., and Zhao, B., (2009), Role Assignment and Cooperation of Ontology and Object-Oriented Principle in Construction of Digital Product Model, *TSINGHUA SCIENCE AND TECHNOLOGY* ISSN 1007-0214 12/38 pp71-76 Volume 14, Number S1, June 2009

Sherwani, A., Usmani, J. and Varun, 2009. Life cycle assessment of solar PV based electricity generation systems, *Renewable and Sustainable Energy Reviews* 14 (2010) pp 540-544

Singh, N., 1996. Systems Approach to Computer-Intefrated Design and Manufacturing, John Wiley & Sons, New York, 1996.

SM 2011 Impact Assessment Methodology, [accessed on 15 Jan 2010] http://www.sustainableminds.com/software/methodology

Steen, B., 1992. AFR-REPORT nr 11. ISSN 1102-6944. ISRN AFR-R-11-SE, Swedish Environmental Research Institute.

Stoeglehner, G. and Narodoslawsky, M., 2009. How sustainable are biofuels? Answers and further questions arising from an ecological footprint perspective, Bioresource Technology 100 (2009) pp 3825–3830

Su, D. and Ren, Z., 2011. Ecological impact assessment and Eco-design of industrial gearboxes, *Key Engineering Materials*. vol 486, pp. 197-200

Sun, J., Han, B., Ekwaro-Osire, S., and Zhang, H., 2003. Design for environment: Methodologies, tools, and implementation, Journal of Integrated Design and Process Science, 7(1), pp 59-75, 2003.

Sustainable minds, (2012), http://www.sustainableminds.com/ [accessed on 30 Jan 2012]

Teng, X., Kong, F., and Zhang, J., 2010. An Approach for Module Partition of Product, Key Engineering Materials Vols. 419-420 (2010) pp257-260

Teng, X., Kong, F., and Zhang, J., 2011. The Evaluation Method for Module Partition Schemes of Complex Product Systems, Key Engineering Materials Vols. 486 (2011) pp 37-40

TRACI, 2007. http://www.epa.gov/nrmrl/std/sab/traci/ [accessed on 27 Oct 2011]

Tsai M., 2010. A Knowledge-based System for Product Design with Modules. *Key Engineering Materials* Vols. 419-420 (2010) pp553-556.

Tseng, M., Divinagracia, L. and Divinagracia, R., 2009. Evaluating firm's sustainable production indicators in uncertainty. *Computers & Industrial Engineering* (2009), doi:10.1016/j.cie.2009.07.009

Tserng, H., Yin, S., Dzeng, R.J., Wou, B., Tsai, M.D., and Chen, W.Y., 2009. A study of ontology-based risk management framework of construction projects through project life cycle, *Automation in Construction*

18 (2009) pp 994–1008

Wang, H., Xiang, D., and Duan, G., 2010. Design for Saving Energy Based On Energy Flow Analysis Method and CAE Technology, *Key Engineering Materials* Vols. 419-420 (2010) pp 329-332.

Wang, J., Jing, Y., Zhang, C., and Zhao, J., 2009. Review on multi-criteria decision analysis aid in sustainable energy decision-making, *Renewable and Sustainable Energy Reviews* 13 (2009) pp 2263–2278

WCED, (1987), World Commission on Environment and Development, *Our Common Future*, Oxford University Press, New York, 1987.

Yan, W., Chen, C. and Chang, W., 2008. An investigation into sustainable product conceptualization using a design knowledge hierarchy and Hopfield network, *Computers & Industrial Engineering* 56 (2009) pp 1617–1626

Yan, J., Ye, K., Wang, H., and Hua, Z., 2009. Ontology of collaborative manufacturing: Alignment of service-oriented framework with service-dominant logic, *Expert Systems with Applications* (2009), doi:10.1016/j.eswa.2009.07.051

Yao, X., Watanabe, C. and Li, Y., 2008. Institutional structure of sustainable development in BRICs: Focusing on ICT utilization, *Technology in Society* 31 (2009) pp 9–28

Yuksel, I., 2009. Hydropower for sustainable water and energy development, *Renewable and Sustainable Energy Reviews* 14 (2010) pp 462–469

Zah, R., Faist, M., Reinhard, J., and Birchmeier, D., 2009. Standardized and simplified life-cycle assessment (LCA) as a driver for more sustainable biofuels, *Journal of Cleaner Production* 17 (2009) S102-S105

Zeng, Q., Liu, Z., Wan, L., and Zhao, Y., 2010. Research on Workflow Management of Multi-Disciplinary Collaborative Design based on Ontology, *Key Engineering Materials* Vols. 419-420 (2010) pp 757-760

Zhong, Y., Wu, C., and Tang, Z., 2001. Mechanical design, Huazhong University of Science & Technology Press.

Zhou, C., Yin, G. and Hu, X., (2008) Multi-objective optimization of material selection for sustainable products: Artificial neural networks and genetic algorithm approach, *Materials and Design* 30 (2009) pp 1209–1215

Appendix

A. Calculation of ecological impact of human labour

Food Standards Agency

The Food Standards Agency is an independent Government department set up by an Act of Parliament in 2000 to protect the public's health and consumer interests in relation to food.

Guideline Daily Amount Values			
Typical values	**Women**	**Men**	**Children (5-10 years)**
Calories	2,000 kcal	2,500 kcal	1,800 kcal
Protein	45 g	55 g	24 g
Carbohydrate	230 g	300g	220 g
Sugars	90 g	120 g	85 g
Fat	70 g	95 g	70 g
Saturates	20 g	30 g	20 g
Fibre	24 g	24 g	15 g
Salt	6 g	6 g	4 g

Standards & Targets - Adults 19-74 years

	Standard	Target	Target- b'fast	Target-l/eve	Target - snacks
Energy	2225 kcals	2225	445	667	445
Protein	50g	50g	10g	15g	10g
Carbohydrate	297g	297g	59g	89g	59g
NMES	65g	63.7g	13g	18.8g	13g
Total fat	87g	85.3g	17.4g	25.2g	17.4g
Saturated fat	27g	26.5g	5.4g	7.8g	5.4g
Fibre	18g	18g	3.6g	5.4g	3.6g
Sodium	2400mg	2352mg	480mg	696mg	480mg
Salt	6g	5.88g	1.2g	1.74g	1.2g
Potassium	3500mg	>3500mg	700mg	1400mg	-
Iron	14.8mg	>14.8mg	3mg	5.9mg	-
Riboflavin	1.3mg	>1.3mg	0.26mg	0.52mg	-

Example Menu for Adults 19-74

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Early Morning	Tea / Coffee / Water	Tea / Coffee / Water	Tea / Coffee / Water	Tea / Coffee / Water	Tea / Coffee / Water	Tea / Coffee / Water	Tea / Coffee / Water
Breakfast	Fruit / Fruit Juice Cereals / Porridge Sausage & Tomato Yoghurt / Parfait Toast with butter / spread Preserves Tea or Coffee Water	Fruit / Fruit Juice Cereals / Porridge Poached Egg Yoghurt / Parfait Toast with butter / spread Preserves Tea or Coffee / Water	Fruit / Fruit Juice Cereals / Porridge Bacon & Mushroom Yoghurt / Parfait Toast with butter / spread Preserves Tea or Coffee / Water	Fruit / Fruit Juice Cereals / Porridge Cottage Cheese & Tomato Yoghurt / Parfait Toast with butter / spread Preserves Tea or Coffee / Water	Fruit / Fruit Juice Cereals / Porridge Baked Beans Yoghurt / Parfait Toast with butter / spread Preserves Tea or Coffee / Water	Fruit / Fruit Juice Cereals / Porodge Bacon & Tomato Yoghurt / Parfait Toast with butter / spread Preserves Tea or Coffee / Water	Fruit / Fruit Juice Cereals / Porridge Boiled Egg Yoghurt / Parfaits Toast with butter / spread Preserves Tea or Coffee / Water
Mid Morning Snack	Tea / Coffee / Water	Tea / Coffee / Water	Tea / Coffee / Water	Tea / Coffee / Water	Tea / Coffee / Water	Tea / Coffee / Water	Tea / Coffee / Water
Lunch	Carrot & coriander Soup Beef Goulash Vegeburger & gravy Jacket Potato & Cheese Egg Mayonnaise Sandwich Ham Salad Boiled New Potatoes / Rice Carrots/Green Beans/Salad Apple Crumble & Custard Fruit/Yoghurt/Ice-Cream	Mushroom Soup Grilled Salmon Vegetable Moussaka Jacket Potato & Beef Chilli Turkey Salad Sandwich Vegetable Samosa & Salad RoastPotato/ Smashed Potato Broccoli/MixedVegetables/Salad Chocolate Gateau Fruit/Yoghurt/Ice-Cream	Vegetable Soup Cottage Pie Tofu/Cashew StirFry &Noodles Jacket Potato & Tuna Pate & Tomato Sandwich Egg & Bean Salad Peas / Leeks / Salad Plum Sponge & Custard Fruit/Yoghurt/Ice-Cream	Tomato Soup Roast Turkey Cheese & Tomato Pizza JacketPotato,Ratatouille,Cheese Beef Salad Sandwich Sardine Salad Roast Potato/Mashed Potato Spinach /Broad Beans/ Salad Fruit Pie & Custard Fruit/Yoghurt/Ice-Cream	Leek & Potato Soup Fried Haddock Pasta & Tomato Sauce Jacket Potato &Baked Beans Cheese & Pickle Sandwich Corned Beef Salad Chips / Mashed Potato Peas / Sweetcorn / Salad Banana Custard Fruit/Yoghurt/Ice-Cream	Minestrone Soup Chicken Tikka Masala & Rice Chicken Liver & Onions Vegetarian Quiche Jacket Potato&Vegetable Chilli Sardine & Salad Sandwich Mozzarella & Tomato Salad Smashed New Potatoes GreenBeans/Courgettes/Salad Rice Pudding & DriedApricots Fruit/Yoghurt/Ice-Cream	Pea Soup Roast Lamb Vegetable Curry & Rice Jacket Potato&Cottage Cheese Ham & Cheese Sandwich Chicken Salad Roast Potato/Mashed Potato Broccoli / Parsnip Rhubarb Pie & Custard Fruit/Yoghurt/Ice-Cream
Afternoon Tea & Nightime Snack*	Tea / Coffee / Water & snack	Tea / Coffee / Water & snack	Tea / Coffee / Water & snack	Tea / Coffee / Water & snack	Tea / Coffee / Water & snack	Tea / Coffee / Water & snack	Tea / Coffee / Water & snack

Evening Meal	Fish Pie Vegetable Lasagne Jacket Potato & Tuna Beef Sandwich Pate & Salad Peas / Spinach ChocGinger&Apricot Mousse Fruit/Yoghurt/Ice-Cream	Lamb Casserole Mushroom Risotto JacketPotato&Cottage Cheese Prawn Sandwich Ham & Cheese Salad Boiled Potatoes Broad Beans / Ratatouille Prune & Hazelnut Cream Fruit/Yoghurt/Cheese &Biscuits	Sausage & Tomato Nut Roast Jacket Potato & Cheese Chicken Cranberry Sandwich Smoked Mackerel Salad Smashed Potatoes Carrots /Baked Beans/ Salad Fruit & Cereal Yoghurt Fruit/Yoghurt/Ice-Cream	Spaghetti Bolognaise Vegetarian Sausages Jacket Potato &Beef Chilli Egg Mayonnaise Sandwich Chicken Salad Boiled New Potatoes Sweetcorn / Swede / Salad Fruit Mousse & Flapjack Fruit/Yoghurt/Ice-Cream	Stir Fry Pork & Rice Vegetarian Shepherds Pie Jacket Potato&Cottage Cheese Humus & Pitta Bread Tuna Salad Broccoli / Spinach / Salad Banana Bread & Apricots Fruit/Yoghurt/Ice-Cream	Braised Steak Vegetarian Ravioli Jacket Potato & Tuna Turkey Sandwich Ham Salad Roast Potatoes Broad Beans/ Carrots / Salad Black Forest Gateaux Fruit/Yoghurt/Ice-Cream	Grilled Chicken Breast Cauliflower Cheese Jacket Potato&Baked Beans Beef Sandwich Prawn Salad Smashed New Potatoes Sweetcorn/Spinach/Salad Trifle Fruit/Yoghurt/Ice-Cream
Daily Snacks	Currant Bun Fruit/Nuts/Biscuits/Cereal Bar Cheese&Crackers/Yoghurt Chocolate/Crisps Beverages	Scone & Jam Fruit/Nuts/Biscuits/Cereal Bar Cheese&Crackers/Yoghurt Chocolate/Crisps Beverages	Chocolate Swiss Roll Fruit/Nuts/Biscuits/Cereal Bar Cheese&Crackers/Yoghurt Chocolate/Crisps Beverages	Malt Loaf Fruit/Nuts/Biscuits/Cereal Bar Cheese&Crackers/Yoghurt Chocolate/Crisps Beverages	Toasted Tea Cake Fruit/Nuts/Biscuits/Cereal Bar Cheese&Crackers/Yoghurt Chocolate/Crisps Beverages	Carrot Cake Fruit/Nuts/Biscuits/Cereal Bar Cheese&Crackers/Yoghurt Chocolate/Crisps Beverages	Chocolate Krispie Cakes Fruit/Nuts/Biscuits/Cereal Bar Cheese&Crackers/Yoghurt Chocolate/Crisps Beverages

EU & DK Input Output Database

Human metabolism (per person year)	DM (kg)
Inputs	
Food	202.2
Body growth	0.55
Total	**202.7**
Outputs	
Urine (CH_4ON_2)	27.4
Faeces (C_2H_4O)	13.7
Respiration: C in CO_2	71.2
Respiration: CH_4	0.083
Respiration: H_2O	89.9
Total	**202.2**
Balance (input - output)	**0.5**

Table 3.1: Carbon and dry mass balance for human metabolism for one person in one year.

EMPLOYMENT AND JOBS

7 Actual weekly hours worked

United Kingdom (hours worked by people aged 16 and over), seasonally adjusted

	Total weekly hours (millions)[1 2]	Average (mean) actual weekly hours worked			
		All workers[1]	Full-time workers[3]	Part-time workers[3]	Second Jobs
People	YBUS	YBUV	YBUY	YBVB	YBVE
Dec-Feb 2009	923.3	31.6	36.8	15.4	9.7
Dec-Feb 2010	913.6	31.7	37.1	15.5	9.5
Mar-May 2010	911.4	31.5	36.9	15.6	9.5
Jun-Aug 2010	918.8	31.6	36.9	15.7	9.6
Sep-Nov 2010	918.4	31.6	37.1	15.7	9.5
Dec-Feb 2011	**929.4**	**31.8**	**37.5**	**15.6**	**9.6**
Change on quarter	*11.0*	*0.2*	*0.4*	*-0.1*	*0.1*
Change %	*1.2*	*0.7*	*1.1*	*-0.5*	*1.3*
Change on year	*15.8*	*0.1*	*0.3*	*0.1*	*0.1*
Change %	*1.7*	*0.4*	*0.9*	*0.5*	*0.8*

7(1) Usual weekly hours of work[1]

United Kingdom, seasonally adjusted

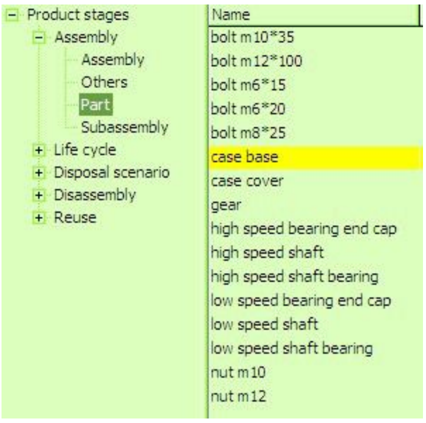
	All in Employment (%)			Employees (%)			Self-Employed (%)		
	People	Men	Women	People	Men	Women	People	Men	Women
Dec-Feb 2010									
Less than 6 Hours	1.5	0.8	2.2	1.2	0.6	1.7	3.0	1.3	7.0
6 up to 15 hours	7.0	3.6	11.0	6.8	3.4	10.3	8.1	4.2	17.6
16 up to 30 hours	19.2	9.0	30.7	19.1	7.9	30.6	19.4	14.3	31.7
31 up to 45 hours	53.1	58.8	46.5	55.4	62.2	48.5	38.3	42.9	27.1
Over 45 hours	19.3	27.8	9.6	17.6	26.0	8.9	31.2	37.2	16.6
Total (thousands)	28,843	15,368	13,476	24,761	12,531	12,230	3,873	2,736	1,137
Sep-Nov 2010									
Less than 6 Hours	1.6	1.0	2.3	1.2	0.8	1.7	3.3	1.6	7.3
6 up to 15 hours	6.9	3.6	10.7	6.6	3.3	9.9	8.7	4.6	18.5
16 up to 30 hours	19.8	9.6	31.6	19.9	8.5	31.7	19.2	14.3	31.2
31 up to 45 hours	52.5	58.5	45.6	54.9	62.0	47.4	38.1	43.0	26.3
Over 45 hours	19.2	27.3	9.8	17.5	25.4	9.2	30.7	36.5	16.8
Total (thousands)	29,089	15,601	13,489	24,878	12,671	12,207	3,980	2,810	1,170
Dec-Feb 2011									
Less than 6 Hours	1.6	1.0	2.4	1.3	0.8	1.8	3.4	1.7	7.2
6 up to 15 hours	6.8	3.4	10.6	6.4	3.1	9.9	8.5	4.7	17.3
16 up to 30 hours	19.9	9.7	31.8	19.8	8.4	31.7	20.9	15.7	33.1
31 up to 45 hours	52.4	58.3	45.6	54.9	61.8	47.6	37.1	42.1	25.5
Over 45 hours	19.3	27.6	9.7	17.7	26.0	9.0	30.1	35.8	16.9
Total (thousands)	29,233	15,663	13,570	25,018	12,760	12,258	3,993	2,794	1,199

1. Total usual weekly hours worked by people aged 16 and over in main job including paid and unpaid overtime.

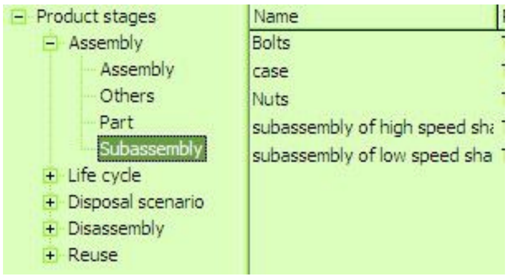
Source: Labour Force Survey
Labour market statistics enquiries: labour.market@ons.gov.uk

(Schmidt, 2010)

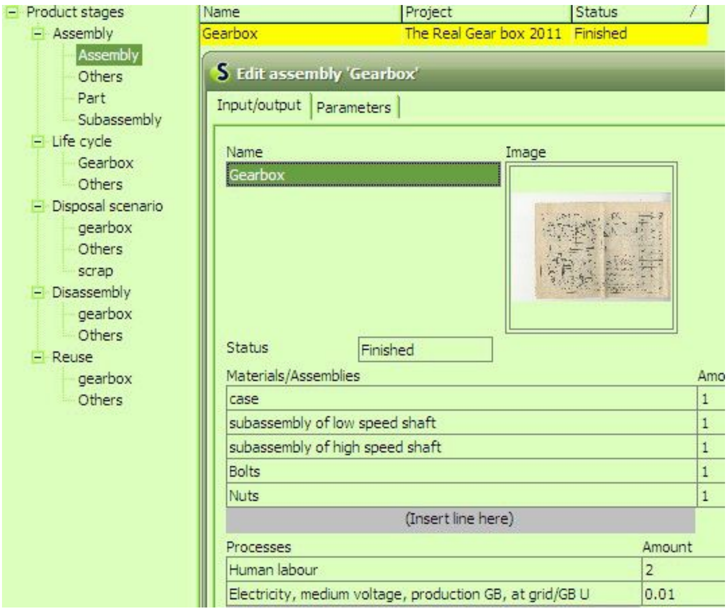
B. Calculation of ecological impact of gearbox in SimaPro



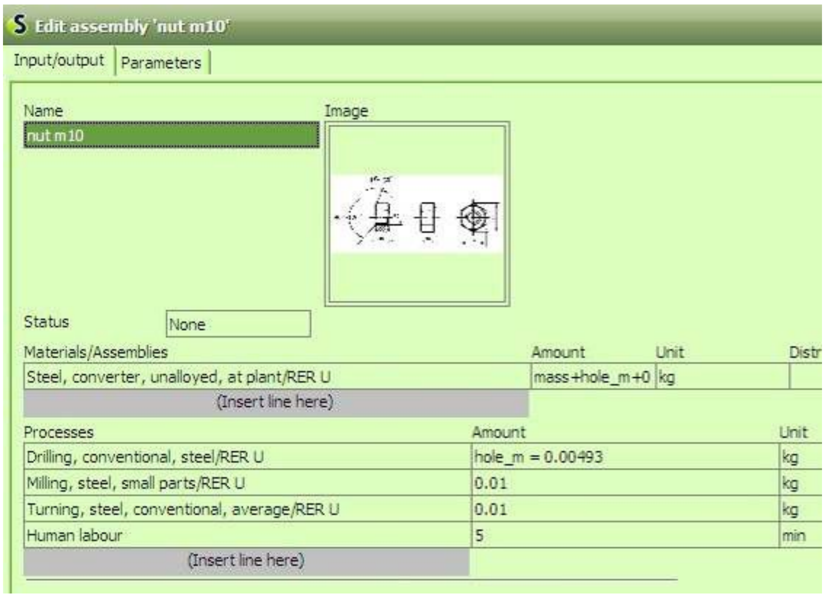
Components list

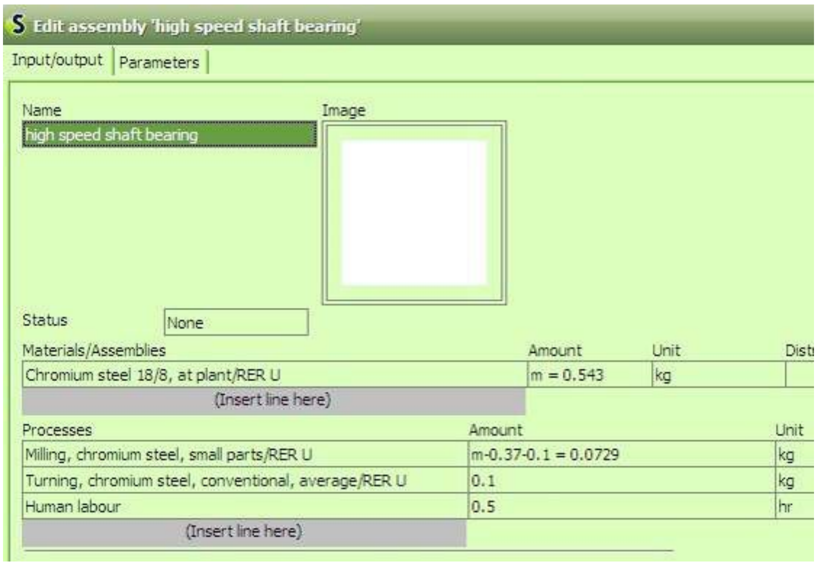


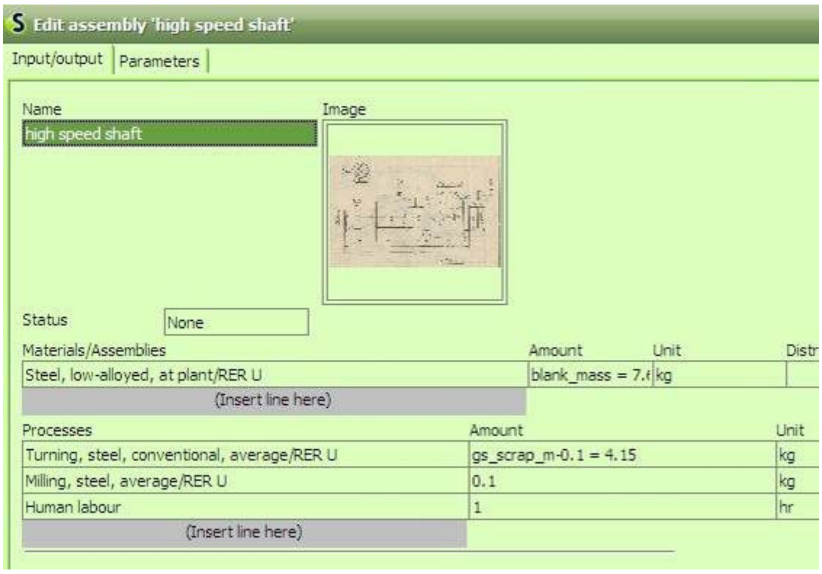
Subassembly list

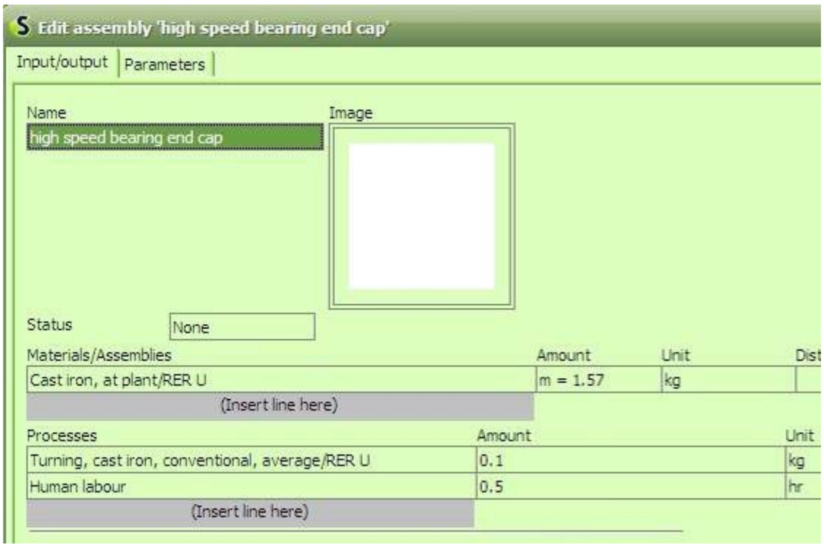


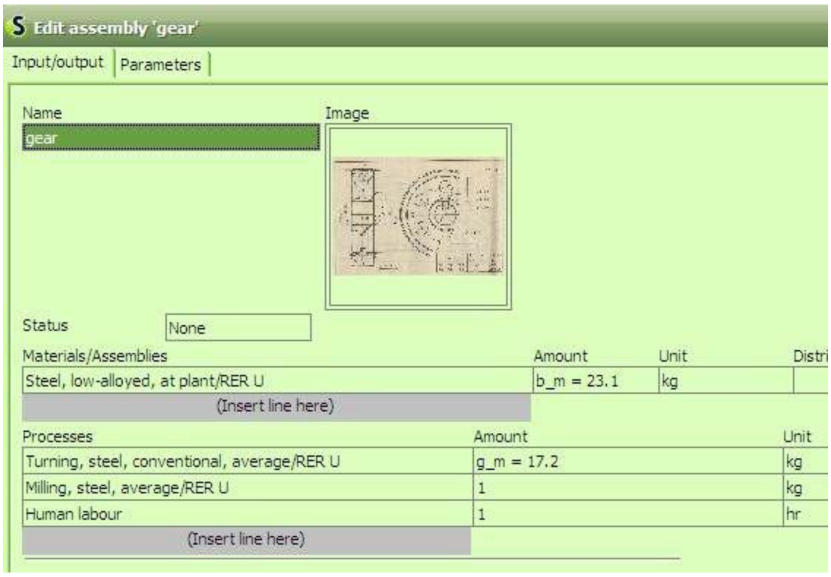
Assembly of gearbox and product stages list.

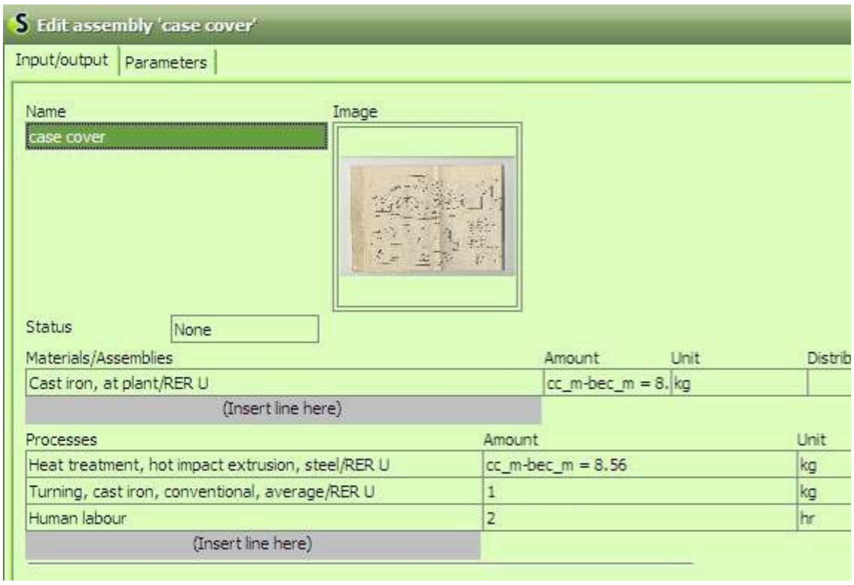

Edit assembly 'nut m10'
Input/output
Parameters
Name
nut m10
Image
Status
None
Materials/Assemblies
Amount
Unit
Distr
Steel, converter, unalloyed, at plant/RER U
mass+hole_m+0
kg
(Insert line here)
Processes
Amount
Unit
Drilling, conventional, steel/RER U
hole_m = 0.00493
kg
Milling, steel, small parts/RER U
0.01
kg
Turning, steel, conventional, average/RER U
0.01
kg
Human labour
5
min
(Insert line here)

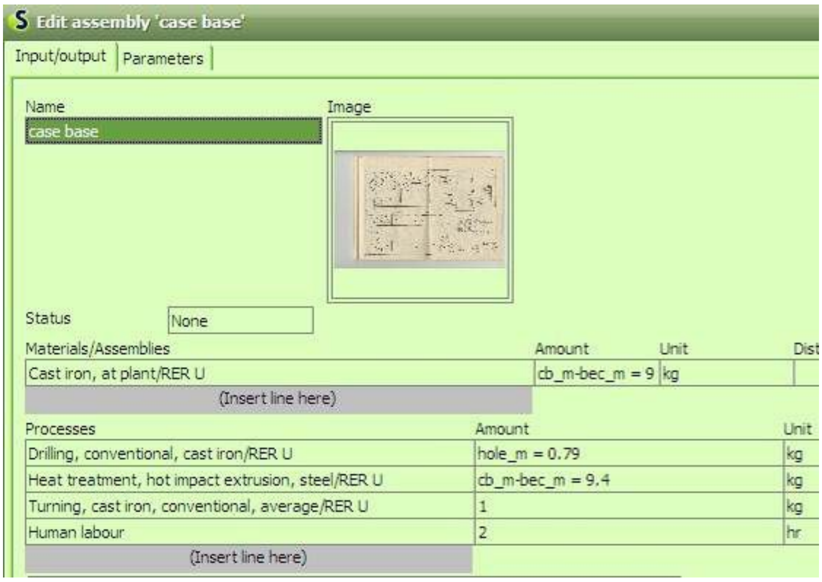

Edit assembly 'high speed shaft bearing'
Input/output
Parameters
Name
high speed shaft bearing
Image
Status
None
Materials/Assemblies
Amount
Unit
Dist
Chromium steel 18/8, at plant/RER U
m = 0.543
kg
(Insert line here)
Processes
Amount
Unit
Milling, chromium steel, small parts/RER U
m-0.37-0.1 = 0.0729
kg
Turning, chromium steel, conventional, average/RER U
0.1
kg
Human labour
0.5
hr
(Insert line here)


Edit assembly 'high speed shaft'
Input/output
Parameters
Name
high speed shaft
Image
Status
None
Materials/Assemblies
Amount
Unit
Distr
Steel, low-alloyed, at plant/RER U
blank_mass = 7.
kg
(Insert line here)
Processes
Amount
Unit
Turning, steel, conventional, average/RER U
gs_scrap_m-0.1 = 4.15
kg
Milling, steel, average/RER U
0.1
kg
Human labour
1
hr
(Insert line here)


Edit assembly 'high speed bearing end cap'
Input/output
Parameters
Name
high speed bearing end cap
Image
Status
None
Materials/Assemblies
Amount
Unit
Dist
Cast iron, at plant/RER U
m = 1.57
kg
(Insert line here)
Processes
Amount
Unit
Turning, cast iron, conventional, average/RER U
0.1
kg
Human labour
0.5
hr
(Insert line here)


Edit assembly 'gear'
Input/output
Parameters
Name
gear
Image
Status
None
Materials/Assemblies
Amount
Unit
Distri
Steel, low-alloyed, at plant/RER U
b_m = 23.1
kg
(Insert line here)
Processes
Amount
Unit
Turning, steel, conventional, average/RER U
g_m = 17.2
kg
Milling, steel, average/RER U
1
kg
Human labour
1
hr
(Insert line here)


Edit assembly 'case cover'
Input/output
Parameters
Name
case cover
Image
Status
None
Materials/Assemblies
Amount
Unit
Distrib
Cast iron, at plant/RER U
cc_m-bec_m = 8.
kg
(Insert line here)
Processes
Amount
Unit
Heat treatment, hot impact extrusion, steel/RER U
cc_m-bec_m = 8.56
kg
Turning, cast iron, conventional, average/RER U
1
kg
Human labour
2
hr
(Insert line here)



Edit assembly 'case base'

Input/output | Parameters

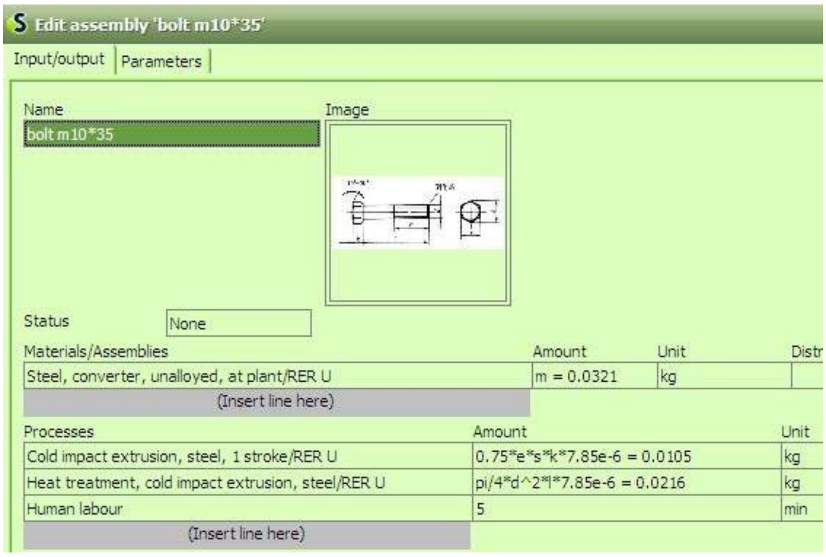
Name: case base

Image

Status: None

Materials/Assemblies	Amount	Unit	Dist
Cast iron, at plant/RER U	cb_m-bec_m = 9	kg	
(Insert line here)			

Processes	Amount	Unit
Drilling, conventional, cast iron/RER U	hole_m = 0.79	kg
Heat treatment, hot impact extrusion, steel/RER U	cb_m-bec_m = 9.4	kg
Turning, cast iron, conventional, average/RER U	1	kg
Human labour	2	hr
(Insert line here)		



Edit assembly 'bolt m10*35'

Input/output | Parameters

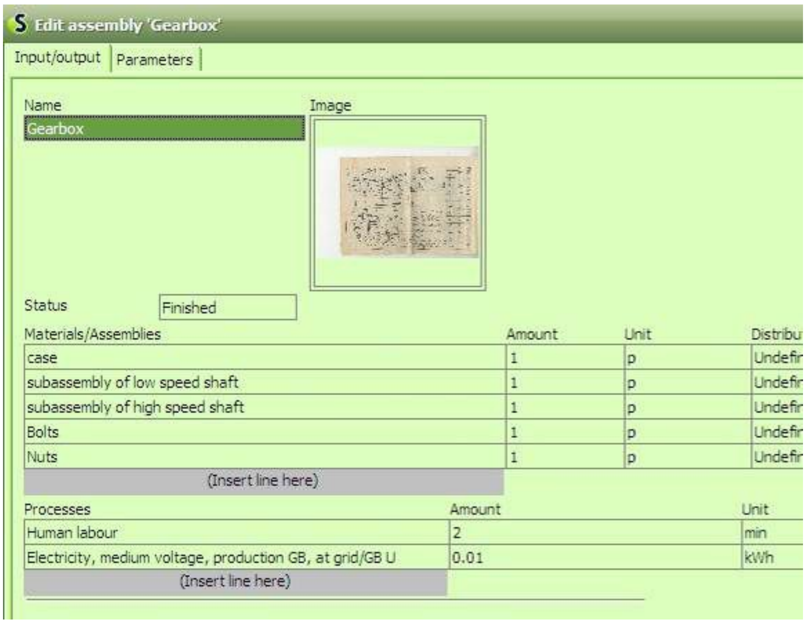
Name: bolt m10*35

Image

Status: None

Materials/Assemblies	Amount	Unit	Distr
Steel, converter, unalloyed, at plant/RER U	m = 0.0321	kg	
(Insert line here)			

Processes	Amount	Unit
Cold impact extrusion, steel, 1 stroke/RER U	0.75*e*s*k*7.85e-6 = 0.0105	kg
Heat treatment, cold impact extrusion, steel/RER U	pi/4*d^2*l*7.85e-6 = 0.0216	kg
Human labour	5	min
(Insert line here)		



Edit assembly 'Gearbox'

Input/output | Parameters

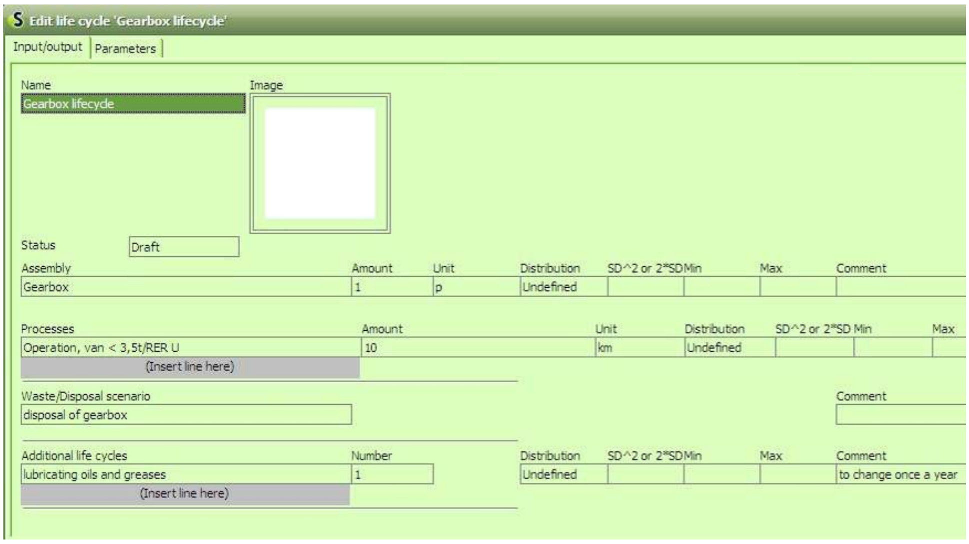
Name: Gearbox

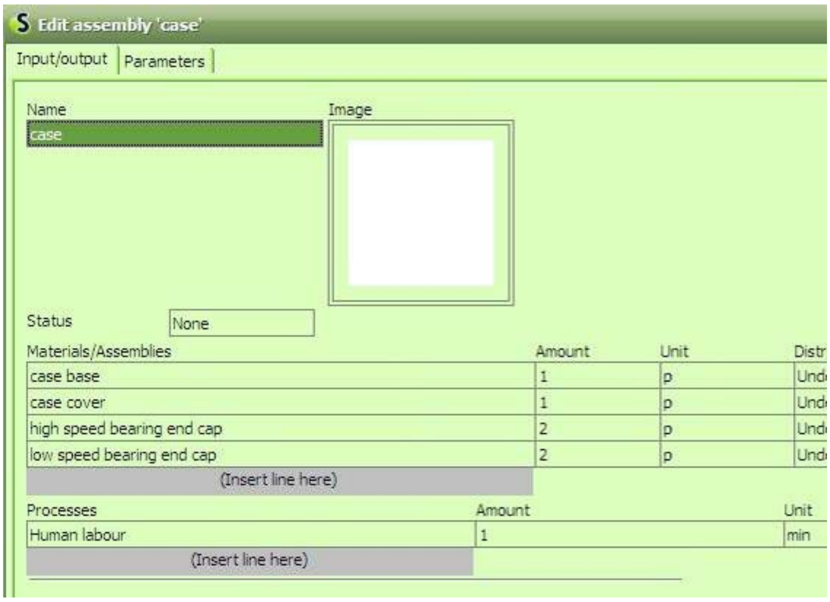
Image

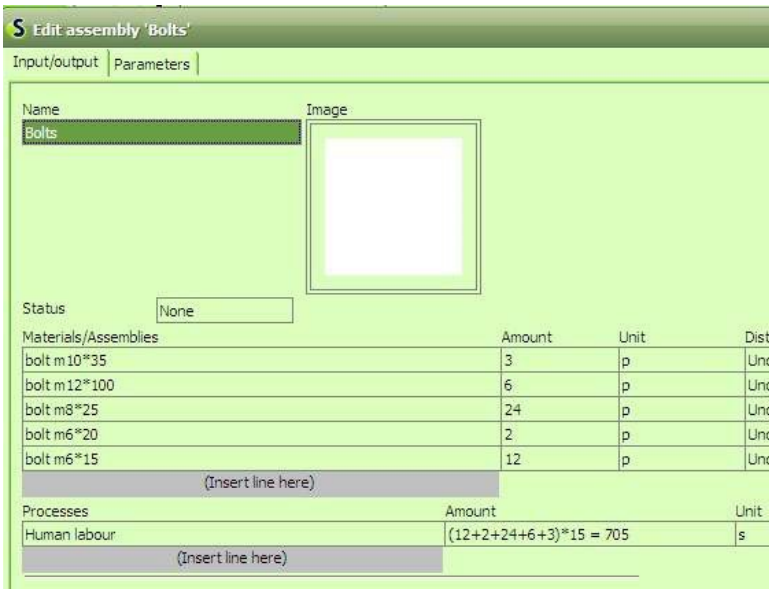
Status: Finished

Materials/Assemblies	Amount	Unit	Distribu
case	1	p	Undefir
subassembly of low speed shaft	1	p	Undefir
subassembly of high speed shaft	1	p	Undefir
Bolts	1	p	Undefir
Nuts	1	p	Undefir
(Insert line here)			

Processes	Amount	Unit
Human labour	2	min
Electricity, medium voltage, production GB, at grid/GB U	0.01	kWh
(Insert line here)		


Edit life cycle 'Gearbox lifecycle'
Input/output
Parameters
Name
Gearbox lifecycle
Image
Status
Draft
Assembly
Amount
Unit
Distribution
SD^2 or 2*SD
Min
Max
Comment
Gearbox
1
p
Undefined
Processes
Amount
Unit
Distribution
SD^2 or 2*SD
Min
Max
Operation, van < 3,5t/RER U
10
km
Undefined
(Insert line here)
Waste/Disposal scenario
Comment
disposal of gearbox
Additional life cycles
Number
Distribution
SD^2 or 2*SD
Min
Max
Comment
lubricating oils and greases
1
Undefined
to change once a year
(Insert line here)


Edit assembly 'case'
Input/output
Parameters
Name
case
Image
Status
None
Materials/Assemblies
Amount
Unit
Distr
case base
1
p
Und
case cover
1
p
Und
high speed bearing end cap
2
p
Und
low speed bearing end cap
2
p
Und
(Insert line here)
Processes
Amount
Unit
Human labour
1
min
(Insert line here)


Edit assembly 'Bolts'
Input/output
Parameters
Name
Bolts
Image
Status
None
Materials/Assemblies
Amount
Unit
Dist
bolt m10*35
3
p
Unc
bolt m12*100
6
p
Unc
bolt m8*25
24
p
Unc
bolt m6*20
2
p
Unc
bolt m6*15
12
p
Unc
(Insert line here)
Processes
Amount
Unit
Human labour
(12+2+24+6+3)*15 = 705
s
(Insert line here)

Edit assembly 'nut m10'

Input/output | Parameters

Input parameters

Name	Value	Distribution	SD^2 or 2*SD	Min	Max	Hide	Comment
d	10	Undefined				☐	
e	18	Undefined				☐	
s	16	Undefined				☐	
m	8	Undefined				☐	
(Insert line here)							

Calculated parameters

Name	Expression	Comment
v	(0.75*e*s-pi/4*d^2)*m = 1.1E3	mm^3
mass	v*7.85e-6 = 0.00863	density 7.85e-6 kg/mm^3
hole_m	pi/4*d^2*m*7.85e-6 = 0.00493	
(Insert line here)		

Edit assembly 'high speed shaft bearing'

Input/output | Parameters

Input parameters

Name	Value	Distribution	SD^2 or 2*SD	Min	Max	Hide	Comment
d	40	Undefined				☐	
d2	52.8	Undefined				☐	
cd	80	Undefined				☐	
cd2	67.2	Undefined				☐	
b	18	Undefined				☐	
(Insert line here)							

Calculated parameters

Name	Expression	Comment
v	pi/4*b*(cd^2-d^2) = 6.79E4	mm^3
m	v*8e-6 = 0.543	AISI H12 density 7.93e3-8.09e3 kg/m^3
(Insert line here)		

Edit assembly 'high speed shaft'

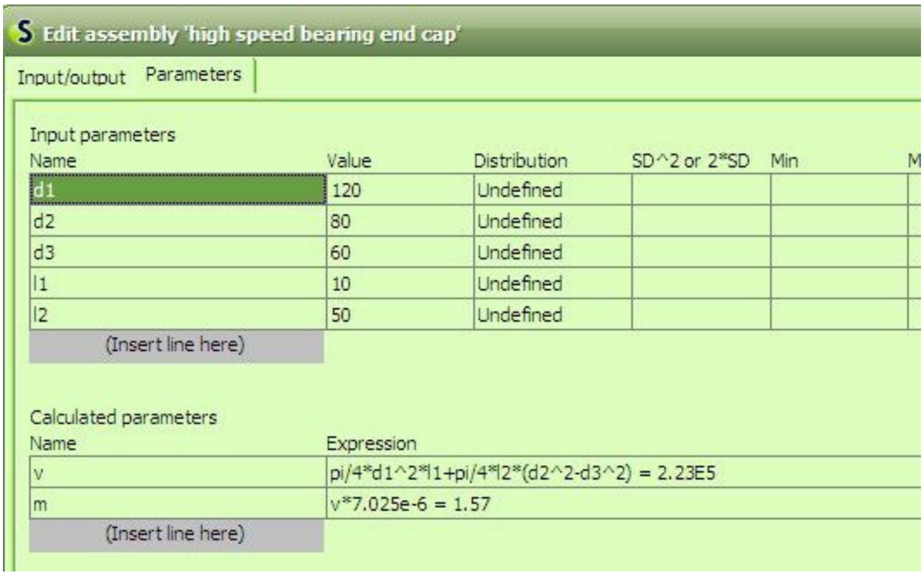
Input/output | Parameters

Input parameters

Name	Value	Distribution	SD^2 or 2*SD	Min	Max	Hide	Comment
blank_length	253	Undefined				☐	mm
blank_diameter	70	Undefined				☐	
gs_L1	60	Undefined				☐	gearshaft_length1
gs_L2	70	Undefined				☐	
gs_L3	38	Undefined				☐	
gs_L4	20	Undefined				☐	
gs_L5	65	Undefined				☐	
gs_d1	30	Undefined				☐	
gs_d2	38	Undefined				☐	
gs_d3	40	Undefined				☐	
gs_d4	48	Undefined				☐	
gs_d5	66.6	Undefined				☐	
(Insert line here)							

Calculated parameters

Name	Expression	Comment
blank_volume	pi/4*blank_diameter^2*blank_length = 9.74E5	mm^3
gearshaft_volume	pi/4*(gs_d1^2*gs_l1+gs_d2^2*gs_l2+gs_d3^2*gs_l3+gs_d4^2*gs_l4+gs_d5^2*gs_l5) = 4	mm^3
gs_scrap_v	blank_volume-gearshaft_volume = 5.41E5	
blank_mass	blank_volume*7.85e-6 = 7.64	Density of AISI1040 is 7.8e3-7.9e3 kg/m^3 =7.85e-6
gs_scrap_m	gs_scrap_v*7.85e-6 = 4.25	
(Insert line here)		



Edit assembly 'high speed bearing end cap'

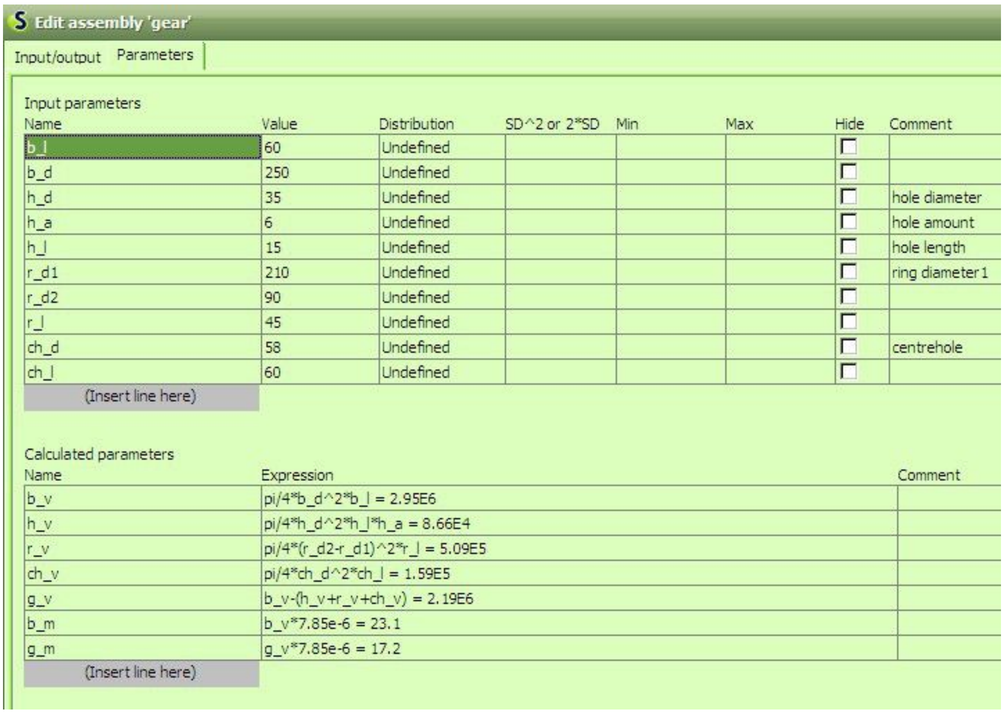
Input/output | Parameters

Input parameters

Name	Value	Distribution	SD^2 or 2*SD	Min	M
d1	120	Undefined			
d2	80	Undefined			
d3	60	Undefined			
l1	10	Undefined			
l2	50	Undefined			
(Insert line here)					

Calculated parameters

Name	Expression
v	pi/4*d1^2*l1+pi/4*l2*(d2^2-d3^2) = 2.23E5
m	v*7.025e-6 = 1.57
(Insert line here)	



Edit assembly 'gear'

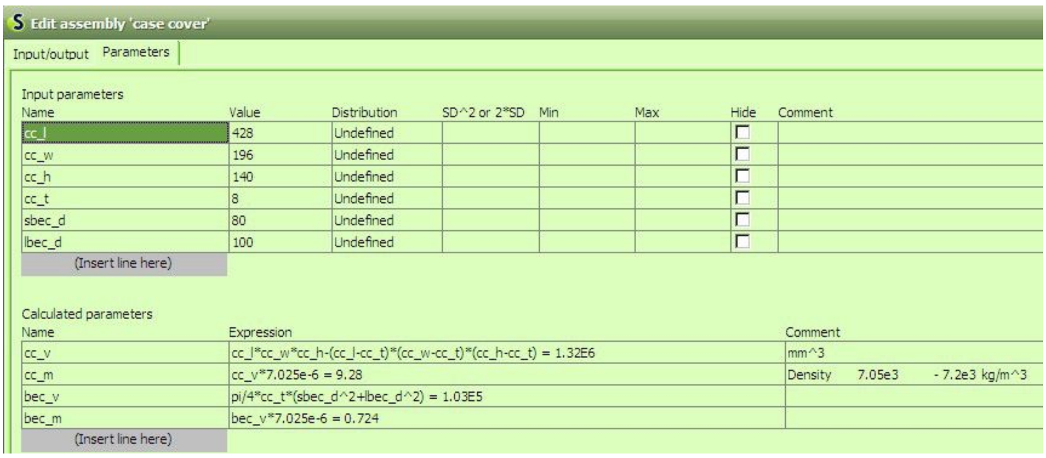
Input/output | Parameters

Input parameters

Name	Value	Distribution	SD^2 or 2*SD	Min	Max	Hide	Comment
b_l	60	Undefined				☐	
b_d	250	Undefined				☐	
h_d	35	Undefined				☐	hole diameter
h_a	6	Undefined				☐	hole amount
h_l	15	Undefined				☐	hole length
r_d1	210	Undefined				☐	ring diameter1
r_d2	90	Undefined				☐	
r_l	45	Undefined				☐	
ch_d	58	Undefined				☐	centrehole
ch_l	60	Undefined				☐	
(Insert line here)							

Calculated parameters

Name	Expression	Comment
b_v	pi/4*b_d^2*b_l = 2.95E6	
h_v	pi/4*h_d^2*h_l*h_a = 8.66E4	
r_v	pi/4*(r_d2-r_d1)^2*r_l = 5.09E5	
ch_v	pi/4*ch_d^2*ch_l = 1.59E5	
g_v	b_v-(h_v+r_v+ch_v) = 2.19E6	
b_m	b_v*7.85e-6 = 23.1	
g_m	g_v*7.85e-6 = 17.2	
(Insert line here)		



Edit assembly 'case cover'

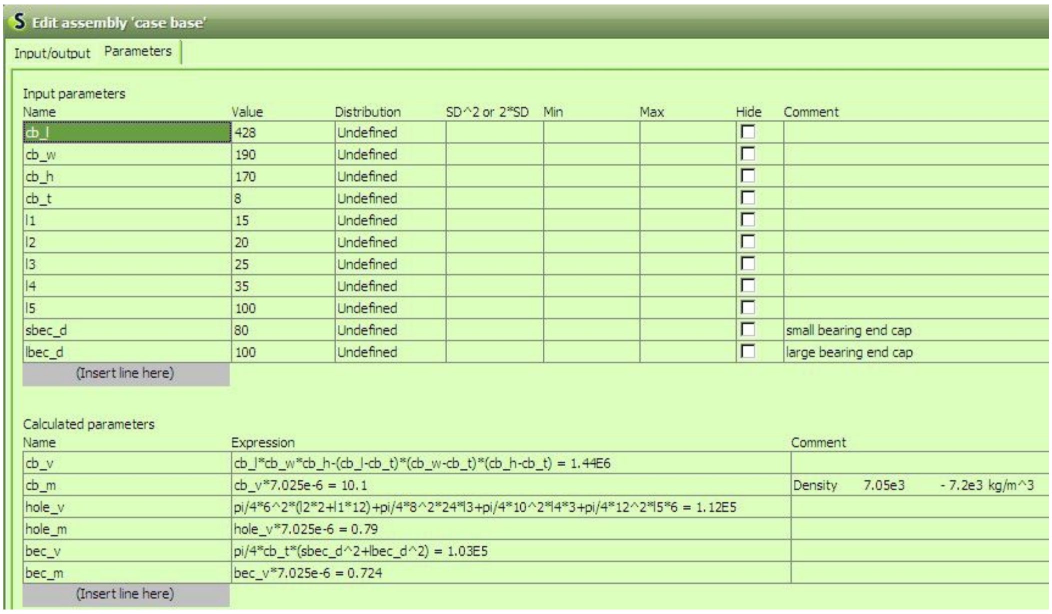
Input/output | Parameters

Input parameters

Name	Value	Distribution	SD^2 or 2*SD	Min	Max	Hide	Comment
cc_l	428	Undefined				☐	
cc_w	196	Undefined				☐	
cc_h	140	Undefined				☐	
cc_t	8	Undefined				☐	
sbec_d	80	Undefined				☐	
lbec_d	100	Undefined				☐	
(Insert line here)							

Calculated parameters

Name	Expression	Comment
cc_v	cc_l*cc_w*cc_h-(cc_l-cc_t)*(cc_w-cc_t)*(cc_h-cc_t) = 1.32E6	mm^3
cc_m	cc_v*7.025e-6 = 9.28	Density 7.05e3 - 7.2e3 kg/m^3
bec_v	pi/4*cc_t*(sbec_d^2+lbec_d^2) = 1.03E5	
bec_m	bec_v*7.025e-6 = 0.724	
(Insert line here)		



Edit assembly 'case base'

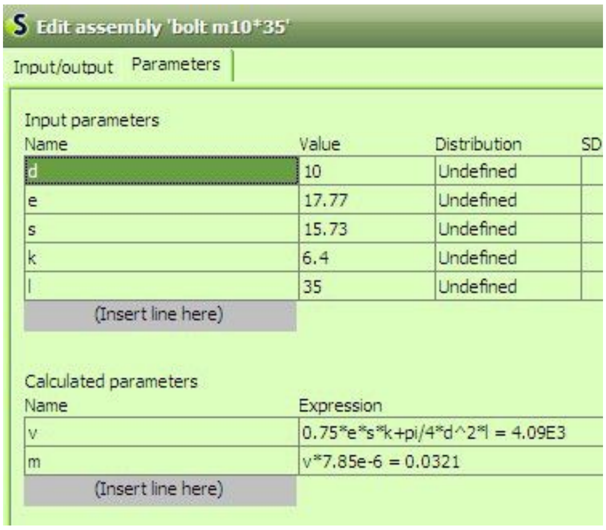
Input/output | Parameters

Input parameters

Name	Value	Distribution	SD^2 or 2*SD	Min	Max	Hide	Comment
cb_l	428	Undefined				☐	
cb_w	190	Undefined				☐	
cb_h	170	Undefined				☐	
cb_t	8	Undefined				☐	
l1	15	Undefined				☐	
l2	20	Undefined				☐	
l3	25	Undefined				☐	
l4	35	Undefined				☐	
l5	100	Undefined				☐	
sbec_d	80	Undefined				☐	small bearing end cap
lbec_d	100	Undefined				☐	large bearing end cap
(Insert line here)							

Calculated parameters

Name	Expression	Comment
cb_v	cb_l*cb_w*cb_h-(cb_l-cb_t)*(cb_w-cb_t)*(cb_h-cb_t) = 1.44E6	
cb_m	cb_v*7.025e-6 = 10.1	Density 7.05e3 - 7.2e3 kg/m^3
hole_v	pi/4*6^2*(l2*2+l1*12)+pi/4*8^2*24*l3+pi/4*10^2*l4*3+pi/4*12^2*l5*6 = 1.12E5	
hole_m	hole_v*7.025e-6 = 0.79	
bec_v	pi/4*cb_t*(sbec_d^2+lbec_d^2) = 1.03E5	
bec_m	bec_v*7.025e-6 = 0.724	
(Insert line here)		



Edit assembly 'bolt m10*35'

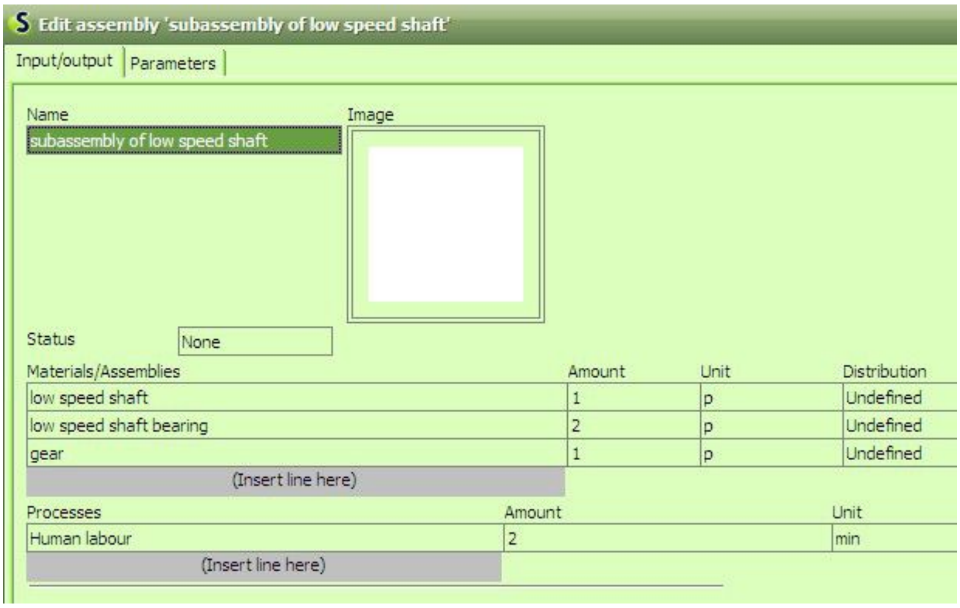
Input/output | Parameters

Input parameters

Name	Value	Distribution	SD
d	10	Undefined	
e	17.77	Undefined	
s	15.73	Undefined	
k	6.4	Undefined	
l	35	Undefined	
(Insert line here)			

Calculated parameters

Name	Expression
v	0.75*e*s*k+pi/4*d^2*l = 4.09E3
m	v*7.85e-6 = 0.0321
(Insert line here)	



Edit assembly 'subassembly of low speed shaft'

Input/output | Parameters

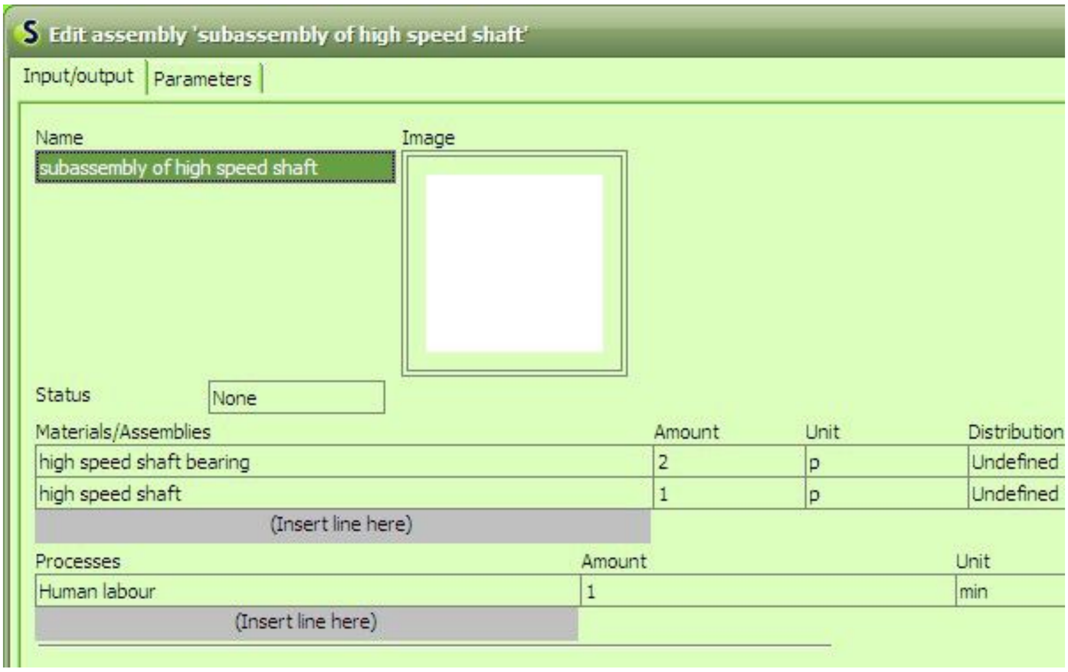
Name: subassembly of low speed shaft

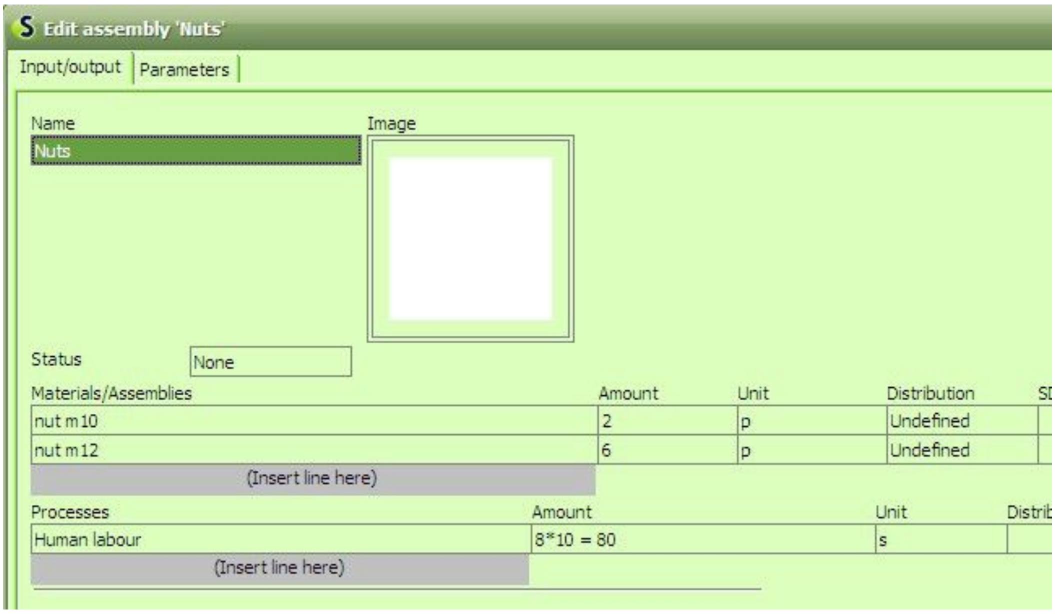
Image

Status: None

Materials/Assemblies	Amount	Unit	Distribution
low speed shaft	1	p	Undefined
low speed shaft bearing	2	p	Undefined
gear	1	p	Undefined
(Insert line here)			

Processes	Amount	Unit
Human labour	2	min
(Insert line here)		


Edit assembly 'subassembly of high speed shaft'
Input/output
Parameters
Name
Image
subassembly of high speed shaft
Status
None
Materials/Assemblies
Amount
Unit
Distribution
high speed shaft bearing
2
p
Undefined
high speed shaft
1
p
Undefined
(Insert line here)
Processes
Amount
Unit
Human labour
1
min
(Insert line here)


Edit assembly 'Nuts'
Input/output
Parameters
Name
Image
Nuts
Status
None
Materials/Assemblies
Amount
Unit
Distribution
nut m10
2
p
Undefined
nut m12
6
p
Undefined
(Insert line here)
Processes
Amount
Unit
Human labour
8*10 = 80
s
(Insert line here)

C. Optimisation design: Objectives

```matlab
function g = EI(x)

global pi b1_d b1_e b1_s b1_k b1_l hl_b b2_d b2_e b2_s b2_k b2_l b3_d b3_e
b3_s b3_k b3_l b4_d b4_e b4_s b4_k b4_l b5_d b5_e b5_s b5_k b5_l
n1_d n1_e n1_s n1_m n2_d n2_e n2_s n2_m hl_n hsb_d hsb_cd hsb_b
hl_hsb hl_lsb lsb_d lsb_cd lsb_b g_h_d g_h_a g_h_l g_r_d1
g_r_d2 g_r_l g_ch_d g_ch_l hl_g s_blank_l s_blank_d s_l1 s_l2 s_l3 s_l4
s_l5 s_d1 s_d2 s_d3 s_d4 s_d5 hl_lss hl_hss gs_blank_l gs_l1 gs_l2 gs_l3
gs_l4 gs_d1 gs_d2 gs_d3 gs_d4 hl_s_b hl_s_n hl_s_hss hl_s_lss hl_a_g e_a_g
dis hl_dispo_g hl_disa
load('E:\Program Files\MATLAB\R2011b\bin\My settings\my variables test.mat')

g = hl_s_b*0.0362+3*((0.75*b1_e*b1_s*b1_k+pi/4*b1_d^2*b1_l)*0.00000785*0.208 +
0.75*b1_e*b1_s*b1_k*7.85e-6*0.0921 + pi/4*b1_d^2*b1_l*7.85e-6*0.0192 +
hl_b*0.0362)+6*((0.75*b2_e*b2_s*b2_k+pi/4*b2_d^2*b2_l)*0.00000785*0.208 +
0.75*b2_e*b2_s*b2_k*7.85e-6*0.0921 + pi/4*b2_d^2*b2_l*7.85e-6*0.0192 +
hl_b*0.0362)+24*((0.75*b5_e*b5_s*b5_k+pi/4*b5_d^2*b5_l)*0.00000785*0.208 +
0.75*b5_e*b5_s*b5_k*7.85e-6*0.0921 + pi/4*b5_d^2*b5_l*7.85e-6*0.0192 +
hl_b*0.0362)+2*((0.75*b4_e*b4_s*b4_k+pi/4*b4_d^2*b4_l)*0.00000785*0.208 +
0.75*b4_e*b4_s*b4_k*7.85e-6*0.0921 + pi/4*b4_d^2*b4_l*7.85e-6*0.0192 +
hl_b*0.0362)+12*((0.75*b3_e*b3_s*b3_k+pi/4*b3_d^2*b3_l)*0.00000785*0.208 +
0.75*b3_e*b3_s*b3_k*7.85e-6*0.0921 + pi/4*b3_d^2*b3_l*7.85e-6*0.0192 + hl_b*0.0362) +
hl_s_n*0.0362+6*((0.75*n2_e*n2_s*n2_m*0.00000785+0.02)*0.208 +
pi/4*n2_d^2*n2_m*0.00000785*0.386+0.01*0.547+0.01*0.397+0.0362*hl_n)+2*((0.75*n1_e*n1_s*n1_m*0.00000785+
0.02)*0.208 + pi/4*n1_d^2*n1_m*0.00000785*0.386+0.01*0.547+0.01*0.397+0.0362*hl_n) +
((cb_l*cb_w*cb_h-(cb_l-cb_t)*(cb_w-cb_t)*(cb_h-cb_t)) - (pi/4*cb_t*(sbec_d^2+lbec_d^2))) * 0.000007125 *(0.226 +
0.00184)+1*0.374+hl_cb*0.0362 +
(pi/4*6^2*(cb_l2*2+cb_l1*12)+pi/4*8^2*24*cb_l3+pi/4*10^2*cb_l4*3+pi/4*12^2*cb_l5*6) * 0.000007125 * 0.363 +
(cc_l*cc_w*cc_h-(cc_l-cc_t)*(cc_w-cc_t)*(cc_h-cc_t)-
pi/4*cc_t*(sbec_d^2+lbec_d^2))*0.000007125*(0.226+0.00184)+1*0.374+hl_cc*0.0362 +
2*((pi/4*hsbec_d1^2*hsbec_l1+pi/4*hsbec_l2*(hsbec_d2^2-hsbec_d3^2))*0.226*0.000007125+
0.1*0.374+hl_hsbec*0.0362) +
2*((pi/4*lsbec_d1^2*lsbec_l1+pi/4*lsbec_l2*(lsbec_d2^2-lsbec_d3^2))*0.000007125*0.226+0.1*0.374+hl_lsbec*0.0362)
+hl_c*0.0362 +
2*(pi/4*hsb_b*(hsb_cd^2-hsb_d^2)*0.000008*0.644+0.0362*hl_hsb+0.81*0.1+1.01*(pi/4*hsb_b*(hsb_cd^2-hsb_d^2)*0.
000008-0.37-0.1))+ (pi/4*(x(1)*20+10)^2*gs_blank_l*0.00000785*0.24 +
((pi/4*(x(1)*20+10)^2*gs_blank_l-pi/4*(gs_d1^2*gs_l1+gs_d2^2*gs_l2+gs_d3^2*gs_l3+gs_d4^2*gs_l4+(x(1)*20+5)^2*
(x(3))))*0.00000785-0.1)*0.397+0.1*0.425+hl_hss*0.0362) + hl_s_hss*0.0362 +
2*(pi/4*lsb_b*(lsb_cd^2-lsb_d^2)*0.000008*0.644+0.0362*hl_lsb+0.81*0.2+1.01*(pi/4*lsb_b*(lsb_cd^2-lsb_d^2)*0.000
008-0.61-0.2)) + pi/4*s_blank_d^2*s_blank_l*0.00000785*0.24 +
((pi/4*s_blank_d^2*s_blank_l-pi/4*(s_d1^2*s_l1+s_d2^2*s_l2+s_d3^2*s_l3+s_d4^2*s_l4+s_d5^2*s_l5))*0.00000785-0.
```

```
1)*0.397 +0.1*0.425+hl_lss*0.0362 + pi/4*(x(1)*x(2))^2*(x(3)-5)*0.00000785*0.24+ ((pi/4*g_h_d^2*g_h_l*g_h_a + pi/4*(g_r_d2-g_r_d1)^2*g_r_l + pi/4*g_ch_d^2*g_ch_l)*0.00000785-1)*0.397 + 1*0.425 + hl_g*0.0362+
hl_s_lss*0.0362 +
hl_a_g*0.0362+e_a_g*0.0639+0.0362*(hl_dispo_g+hl_disa)+0.622+dis*0.000223*((cb_l*cb_w*cb_h-(cb_l-cb_t)*(cb_w-cb_t)*(cb_h-cb_t) - pi/4*cb_t*(sbec_d^2+lbec_d^2) -
(pi/4*6^2*(cb_l2*2+cb_l1*12)+pi/4*8^2*24*cb_l3+pi/4*10^2*cb_l4*3+pi/4*12^2*cb_l5*6)) *
0.000007125+(cc_l*cc_w*cc_h-(cc_l-cc_t)*(cc_w-cc_t)*(cc_h-cc_t)-
pi/4*cc_t*(sbec_d^2+lbec_d^2))*0.000007125+2*((pi/4*hsbec_d1^2*hsbec_l1+pi/4*hsbec_l2*(hsbec_d2^2-hsbec_d3^2))*0.000007125)+2*((pi/4*lsbec_d1^2*lsbec_l1+pi/4*lsbec_l2*(lsbec_d2^2-lsbec_d3^2))*0.000007125)+3*((0.75*b1_e*b1_s*b1_k+pi/4*b1_d^2*b1_l)*0.00000785)+6*((0.75*b2_e*b2_s*b2_k+pi/4*b2_d^2*b2_l)*0.00000785)+12*((0.75*b3_e*b3_s*b3_k+pi/4*b3_d^2*b3_l)*0.00000785)+2*((0.75*b4_e*b4_s*b4_k+pi/4*b4_d^2*b4_l)*0.00000785)+24*((0.75*b5_e*b5_s*b5_k+pi/4*b5_d^2*b5_l)*0.00000785)+2*( (0.75*n1_e*n1_s-pi/4*n1_d^2)*n1_m*0.00000785)+6*( (0.75*n2_e*n2_s-pi/4*n2_d^2)*n2_m*0.00000785)+2*(pi/4*hsb_b*(hsb_cd^2-hsb_d^2)*0.000008)+2*(pi/4*lsb_b*(lsb_cd^2-lsb_d^2)*0.000008)+(pi/4*(x(1)*x(2))^2*(x(3)-5)- (pi/4*g_h_d^2*g_h_l*g_h_a + pi/4*(g_r_d2-g_r_d1)^2*g_r_l +
pi/4*g_ch_d^2*g_ch_l))*0.00000785+pi/4*(s_d1^2*s_l1+s_d2^2*s_l2+s_d3^2*s_l3+s_d4^2*s_l4+s_d5^2*s_l5)*0.00000785+pi/4*(gs_d1^2*gs_l1+gs_d2^2*gs_l2+gs_d3^2*gs_l3+gs_d4^2*gs_l4+(x(1)*20+5)^2*(x(3)))*0.00000785)+0.344;

function r =COST(x)

global cb_l cb_w cb_h cb_t sbec_d lbec_d hl_cb pi cc_l cc_w cc_h cc_t hl_cc hl_hsbec hsbec_d1 hsbec_d2 hsbec_d3 hsbec_l1 hsbec_l2 lsbec_d1 lsbec_d2 lsbec_d3 lsbec_l1 lsbec_l2 hl_lsbec b1_d b1_e b1_s b1_k b1_l hl_b b2_d b2_e b2_s b2_k b2_l b3_d b3_e b3_s b3_k b3_l b4_d b4_e b4_s b4_k b4_l b5_d b5_e b5_s b5_k b5_l n1_e n1_s n1_m n2_e n2_s n2_m hl_n hsb_d hsb_cd hsb_b hl_hsb hl_lsb lsb_d lsb_cd lsb_b hl_g s_blank_l s_blank_d hl_lss hl_hss gs_blank_l hl_s_b hl_s_n hl_c hl_s_hss hl_s_lss hl_a_g hl_re hl_dispo_g hl_disa
load('E:\Program Files\MATLAB\R2011b\bin\My settings\my variables test.mat')

r = (((cb_l*cb_w*cb_h-(cb_l-cb_t)*(cb_w-cb_t)*(cb_h-cb_t)) -
(pi/4*cb_t*(sbec_d^2+lbec_d^2)))+(cc_l*cc_w*cc_h-(cc_l-cc_t)*(cc_w-cc_t)*(cc_h-cc_t)-
pi/4*cc_t*(sbec_d^2+lbec_d^2))+(pi/4*hsbec_d1^2*hsbec_l1+pi/4*hsbec_l2*(hsbec_d2^2-hsbec_d3^2))+(pi/4*lsbec_d1^2*lsbec_l1+pi/4*lsbec_l2*(lsbec_d2^2-lsbec_d3^2)))*0.000007125*0.376 +
(pi/4*hsb_b*(hsb_cd^2-hsb_d^2)+pi/4*lsb_b*(lsb_cd^2-lsb_d^2))*0.000008*2.72 +
((0.75*b1_e*b1_s*b1_k+pi/4*b1_d^2*b1_l)+(0.75*b2_e*b2_s*b2_k+pi/4*b2_d^2*b2_l)+(0.75*b3_e*b3_s*b3_k+pi/4*b3_d^2*b3_l)+(0.75*b4_e*b4_s*b4_k+pi/4*b4_d^2*b4_l)+(0.75*b5_e*b5_s*b5_k+pi/4*b5_d^2*b5_l)+(0.75*n1_e*n1_s*n1_m)+(0.75*n2_e*n2_s*n2_m))*0.00000785*0.3965
+(pi/4*(x(1)*x(2))^2*(x(3)-5)+pi/4*s_blank_d^2*s_blank_l+pi/4*(x(1)*20+10)^2*gs_blank_l)*0.00000785*0.416 +
10*0.001*1.38*((cb_l*cb_w*cb_h-(cb_l-cb_t)*(cb_w-cb_t)*(cb_h-cb_t) - pi/4*cb_t*(sbec_d^2+lbec_d^2) -
(pi/4*6^2*(cb_l2*2+cb_l1*12)+pi/4*8^2*24*cb_l3+pi/4*10^2*cb_l4*3+pi/4*12^2*cb_l5*6)) *
0.000007125+(cc_l*cc_w*cc_h-(cc_l-cc_t)*(cc_w-cc_t)*(cc_h-cc_t)-
pi/4*cc_t*(sbec_d^2+lbec_d^2))*0.000007125+2*((pi/4*hsbec_d1^2*hsbec_l1+pi/4*hsbec_l2*(hsbec_d2^2-hsbec_d3^2))*0.000007125)+2*((pi/4*lsbec_d1^2*lsbec_l1+pi/4*lsbec_l2*(lsbec_d2^2-lsbec_d3^2))*0.000007125)+3*((0.75*b1_e*b1_s*b1_k+pi/4*b1_d^2*b1_l)*0.00000785)+6*((0.75*b2_e*b2_s*b2_k+pi/4*b2_d^2*b2_l)*0.00000785)+12*((0.75*b3_e
```

*b3_s*b3_k+pi/4*b3_d^2*b3_l)*0.00000785)+2*((0.75*b4_e*b4_s*b4_k+pi/4*b4_d^2*b4_l)*0.00000785)+24*((0.75*b5_e*b5_s*b5_k+pi/4*b5_d^2*b5_l)*0.00000785)+2*((0.75*n1_e*n1_s-pi/4*n1_d^2)*n1_m*0.00000785)+6*((0.75*n2_e*n2_s-pi/4*n2_d^2)*n2_m*0.00000785)+2*(pi/4*hsb_b*(hsb_cd^2-hsb_d^2)*0.000008)+2*(pi/4*lsb_b*(lsb_cd^2-lsb_d^2)*0.000008)+(pi/4*(x(1)*x(2))^2*(x(3)-5)- (pi/4*g_h_d^2*g_h_l*g_h_a + pi/4*(g_r_d2-g_r_d1)^2*g_r_l + pi/4*g_ch_d^2*g_ch_l))*0.00000785+pi/4*(s_d1^2*s_l1+s_d2^2*s_l2+s_d3^2*s_l3+s_d4^2*s_l4+s_d5^2*s_l5)*0.00000785+pi/4*(gs_d1^2*gs_l1+gs_d2^2*gs_l2+gs_d3^2*gs_l3+gs_d4^2*gs_l4+(x(1)*20+5)^2*x(3))*0.00000785) + (hl_g+hl_lss+hl_hss+hl_cb+hl_cc+hl_hsbec+hl_lsbec+hl_b+hl_n+hl_hsb+hl_lsb+hl_s_b+hl_s_n+hl_c+hl_s_lss+hl_s_hss+hl_a_g+hl_re+hl_dispo_g+hl_disa)*11.08;

Constraints

```
function [c,ceq]=constraints(x)

global t z1 ka kv kbeta sigmahp ze sigmafp yfa ysa l_crankle a sigma_1b
load('E:\Program Files\MATLAB\R2011b\bin\My settings\my variables test.mat')

c(1) = 220- x(1)*x(2);
c(2) = x(1)*x(2)-500;
c(3) = ze*(ka*kv*kbeta*2*t /(x(1)*x(2)+5)*(x(2)/z1+1)/x(2)/z1/x(3)/(x(1)*x(2)+5))^2 - sigmahp;
c(4) = ka*kv*kbeta*2*t /(x(1)*x(2)+5)*ysa*yfa/x(3)/x(1) - sigmafp;
c(5) = 1.03*((2*(2*t /(x(1)*x(2)+5)*tand(20))*l_crankle/2)^2+(a*t)^2)^(-1/2)/0.1/(x(1)*x(2)+5)^3 - sigma_1b;
c(6) = 1.03*((2*(2*t /(x(1)*x(2)+5)*tand(20))*l_crankle/2)^2+(a*t)^2)^(-1/2)/0.1/s_d4^3 - sigma_1b;
%c(7) = x(1)^2 - x(2) - 1;
ceq = [];
End
```

Parameters

Name	abbreviation	default value
case base	**parameter**	
case base length	cb_l	428
case base width	cb_w	190
case base height	cb_h	170
case base thickness	cb_t	8
length 1	cb_l1	15
length 2	cb_l2	20
length 3	cb_l3	25
length 4	cb_l4	35
length 5	cb_l5	100
diameter of hole for high speed (small) bearing end cap	sbec_d	80
diameter of hole for low	lbec_d	100

speed (large) bearing end cap		
case cover	**Parameter**	
case cover length	cc_l	428
case cover width	cc_w	196
case cover height	cc_h	140
case cover thickness	cc_t	8
diameter of hole for small bearing end cap	sbec_d	80
diameter of hole for large bearing end cap	lbec_d	100
High speed bearing end cap(small)	**Parameter**	
diameter 1	hsbec_d1	120
diameter 2	hsbec_d2	80
diameter 3	hsbec_d3	60
length 1	hsbec_l1	10
length 2	hsbec_l2	50
low speed bearing end cap(large)	**Parameter**	
diameter 1	lsbec_d1	140
diameter 2	lsbec_d2	100
diameter 3	lsbec_d3	80
length 1	lsbec_l1	10
length 2	lsbec_l2	50
bolt m10*35	**Parameter**	
diameter	b1_d	10
	b1_e	17.77
	b1_s	15.73
	b1_k	6.4
	b1_l	35
bolt m12*100	**Parameter**	
diameter	b2_d	12
	b2_e	20.03
	b2_s	17.73
	b2_k	7.5
	b2_l	100
bolt m6*15	**Parameter**	
diameter	b3_d	6
	b3_e	11.05
	b3_s	10

	b3_k	4
	b3_l	15
bolt m6*20	**Parameter**	
diameter	b4_d	6
	b4_e	11.05
	b4_s	10
	b4_k	4
	b4_l	20
bolt m8*25	**Parameter**	
diameter	b5_d	8
	b5_e	14.38
	b5_s	12.73
	b5_k	5.3
	b5_l	25
nut m10	**Parameter**	
diameter	n1_d	10
	n1_e	18
	n1_s	16
	n1_m	8
nut m12	**Parameter**	
diameter	n2_d	12
	n2_e	20.03
	n2_s	18
	n2_m	10
high speed shaft bearing	**Parameter**	
diameter	hsb_d	40
	d2	52.8
diameter of cap	hsb_cd	80
	cd2	67.2
	hsb_b	18
low speed shaft bearing	**Parameter**	
diameter	lsb_d	55
diameter of cap	lsb_cd	100
	lsb_b	21
gear	**Parameter**	
blank length	g_b_l	60
blank diameter	g_b_d	237
hole diameter	g_h_d	35
hole amount	g_h_a	6

hole length	g_h_l	15
ring diameter 1	g_r_d1	210
ring diameter 2	g_r_d2	90
ring length	g_r_l	45
centrehole diameter	g_ch_d	58
centrehole length	g_ch_l	60
low speed shaft	**Parameter**	
blank length	s_blank_l	255
blank diameter	s_blank_d	65
shaft length 1	s_l1	62
shaft length 2	s_l2	67
shaft length 3	s_l3	57
shaft length 4	s_l4	57
shaft length 5	s_l5	12
shaft diameter 1	s_d1	45
shaft diameter 2	s_d2	52
shaft diameter 3	s_d3	55
shaft diameter 4	s_d4	58
shaft diameter 5	s_d5	65
high speed shaft	**Parameter**	
blank length	gs_blank_l	253
blank diameter	gs_blank_d	70
gear shaft length 1	gs_l1	60
gear shaft length 2	gs_l2	70
gear shaft length 3	gs_l3	38
gear shaft length 4	gs_l4	20
gear shaft length 5	gs_l5	65
gear shaft diameter 1	gs_d1	30
gear shaft diameter 2	gs_d2	38
gear shaft diameter 3	gs_d3	40
gear shaft diameter 4	gs_d4	48
gear shaft diameter 5	gs_d5	65
human labour for gear manufacture	hl_g	1
human labour for low speed shaft	hl_lss	1
human labour for high speed shaft	hl_hss	1
human labour for case base	hl_cb	2
human labour for case	hl_cc	2

cover		
human labour for high speed bearing end cap	hl_hsbec	0.5
human labour for low speed bearing end cap	hl_lsbec	0.5
human labour for bolts	hl_b	0.083333333
human labour for nuts	hl_n	0.083333333
human labour for high speed bearing	hl_hsb	0.5
human labour for low speed bearing	hl_lsb	0.5
human labour for subassembly of bolts	hl_s_b	0.195833333
human labour for subassembly of nuts	hl_s_n	0.022222222
human labour for subassembly of case	hl_c	0.016666667
human labour for subassembly of low speed shaft	hl_s_lss	0.033333333
human labour for subassembly of high speed shaft	hl_s_hss	0.016666667
human labour for assembly of gearbox	hl_a_g	0.033333333
electricity consumption of assembly of gearbox	e_a_g	0.01
transport distance	dis	10
human labour for reuse	hl_re	2
human labour for disposal of gearbox	hl_dispo_g	2
human labour for disposal of bolts, nuts, subassembly of high&low speed shaft	hl_dispo_other	2