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Comparison of sealed and open roller bearings using an environmental life cycle perspective

Study including a life cycle assessment for a specific application and development of a life cycle based tool

Master of Science Thesis in Industrial Ecology, Mechanical Engineering

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Abstract

Spherical roller bearings are a large product group at SKF which can be produced with or without an integrated bearing seal. In the study described in this report, the environmental aspects of integrated seals are evaluated.

The evaluation is done in three steps; the first step is the identification of the significant parameters affecting environmental performance of bearings, the second part is a life cycle assessment (LCA) for spherical roller bearings used in a continuous caster and the third part is the development of a life cycle based tool for comparison between the global warming potential when using sealed and open bearings.

The parameters that have been identified as affecting the difference in environmental performance between sealed and open bearings are:

- Grease leakage affecting:
    - grease consumption;
    - electricity consumption in re-lubrication pumps or peak friction due to re-lubrication;
    - amount of grease in waste water system;
    - amount of grease sent for destruction as hazardous waste.
- Wear on bearings affecting:
    - bearing service life;
    - maintenance intervals.
- Seal friction causing reduced energy efficiency.

The purpose of the LCA was to assess the environmental performance of sealed and open bearings used in a continuous caster, and in particular address the knowledge gap on the effects of reduced grease in waste water treatment system. This was done mainly through re-use of data from former LCA studies but also through a site visit and discussions with experts. The main result from the LCA is that the potential environmental impact when using sealed bearings is lower than when using open bearings. It is also concluded that the effects of reduced grease in waste water are minor.

The results from the LCA were used as the input for the development of the life cycle based tool. The LCA results were complimented with friction models and generalized. During the tool development discussions were held with two potential user groups: engineers working with product development and engineers working with market communications. The tool has been claimed to be useful from potential users in both user groups. The tool also contains cost calculations. However, these are not considered to be sufficiently accurate and since better tools for cost calculations exist, it is recommended to use those instead.

The main conclusion that can be drawn from the tool development is that the difference in global warming potential between sealed and open bearings strongly depends on the running conditions in the assessed application.

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I would also like to thank all the people at the Development Center at SKF in Göteborg for all fun and interesting discussions during the coffee breaks.

Karin Agestam
Göteborg, 2011

Abbreviations

Abbreviation	*Explanation*
LCA	Life cycle assessment
SRB	Spherical roller bearing
IM & PD	Department for industrial marketing and product development at SKF
FU	Functional unit
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
GWP	Global warming potential according to CML 2001 over 100 years
eq	Equivalents

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1 Introduction

In today's society the importance of environmental matters increases for each day that passes. On one hand, there's concern for the effects of global warming, depleted resources and an unsustainable way of living. On the other hand, there's the search for solutions in terms of new "green" technologies or environmental improvements of existing technologies.

But how and by whom can the solutions be found? Where are the economic resources and the commitment to achieve the goal of sustainability?

In 2001, out of the 100 largest economies in the world, 51 were companies and 49 were countries (GlobalPublicationsFoundation, 2001). This means that since the companies control the economic resources they also have a good chance to make a contribution to the work towards a more sustainable society. Some companies actually take that chance and develop it even further. Some companies actually start to see a business potential in being green.

When working with environmental issues, a systems perspective is essential. For a product this means that one needs to consider the whole life cycle, seeing the environmental impact from the product, not only as the manufacturing or the usage, but as the sum of raw material acquisition, production, use phase and end of life treatment. To facilitate the consideration of the whole life cycle when assessing a product's potential environmental impact, one can use a methodology called life cycle assessment (LCA). LCA allows you to follow a certain work path to find out for example which of the life cycle phases contributes most to the potential environmental impact and helps to reach decisions that make a difference.

An important part of companies' environmental work is within communication. Not only to get good attention and sell more but also to spread information along the product's supply chain, both to customers and to suppliers. Sometimes, how a user operates the product can influence the potential environmental impact significantly, and then informing the user about the effect of its behavior is essential towards a reduced life cycle impact.

This report describes the study of a product's environmental impact from a life cycle perspective which is a part of a company's environmental work. It also describes the development and the potential usage of a life cycle based tool which can be used for communication with users helping them make aware selections.

1.1 Background

The assessed product is a spherical roller bearing and the company producing it is SKF. Their bearings are used in thousands of applications all over the world. This means that an improvement with positive environmental effects during the use-phase of those bearings can make a significant contribution towards a more sustainable society. For example, many of these applications use energy and the amount of energy is often dependent on the efficiency of the components used. This means that more efficient bearings create more efficient applications and help to create a more energy efficient society.

However, it is not only the energy efficiency in terms of low friction in the bearing that matters during the use-phase. The environmental performance of a bearing during its use-phase depends for example on:

- wear on bearing affecting the service life;
- grease consumption;
- friction

An integrated bearing seal can be added to the bearing construction and that can affect the environmental performance of the bearing in different ways. The seal can reduce both grease leakage and wear, but causes additional friction. This means that there is a trade-off in environmental performance. The trade-off varies between different working conditions and is affected by aspects such as the size of the bearing, the load it is exposed to and how sensitive the surrounding is to grease leakage. SKF have performed several studies to evaluate the trade-offs in specific applications. However, there are still knowledge-gaps, for example the effects of the grease load on waste water treatment systems is not well understood. In addition how applicable the conclusions of the studies are for other applications is unknown. A general model of how the differences in the environmental performance of sealed and open bearings are influenced by the operating conditions would be highly valuable for SKF.

Assessing this issue and presenting the results in a useful way can lead to potential environmental improvements in many industrial bearing applications.

The discussed aspects also affect the cost for the customer, which is most often the decisive parameter in purchasing decisions. If it is possible to show that economic and environmental benefits correlate to each other, this can be a significant marketing advantage for a product.

1.2 Purpose

The purpose of this study is to evaluate and quantify the environmental pros and cons of seals integrated in a spherical roller bearing (SRB), from a life cycle perspective. A LCA of a SRB, used in a continuous casting process, will be conducted with the aim to close the knowledge gap in waste water treatment. It will also include a generalization of the LCA results in order to make them useful for further cases in different applications. This will be done through development of a life cycle based tool for market communication and product development. The tool will enable the user to compare differences in CO_2-emissions and costs, of sealed and open SRBs used in different applications.

One goal is to supply SKF with knowledge about their products. The knowledge may be used for future product development, sales, marketing and strategic decisions.

The purpose is further described in Section *3 Purpose.*

2 Background information

In the following sections, background information is presented including a presentation of SKF, its environmental work, an introduction to LCA and marketing, a resume of previous LCA studies at SKF and a description of the technological system for the study. The description of the technological system includes the studied products, SRB, and the application in which the LCA study takes place.

2.1 SKF

SKF was founded in 1907 by the engineer Sven Wingquist who invented the self-aligning ball bearing. In 1918 SKF had 12 factories, 12 000 employees and sales representatives in 100 countries. The year 1918 was also when the spherical roller bearing was invented by SKF. Today the company has almost 45 000 employees throughout the world (SKF, 2004).

SKF takes its environmental challenges seriously. The environmental strategy is integrated in the business strategy and is supported by top management. The environmental strategy has a large focus on life cycle thinking. This involves understanding and learning about the products' environmental impacts from cradle to grave. One example of this is that all major SKF suppliers have to implement an environmental management system certified to ISO14001 standards (SKF, 2010).

Life cycle thinking is integrated into the product development process at SKF. Over the past years this has included performing a number of LCAs on products, processes and solutions. Tools have been developed for use in the product development process and are now under implementation (SKF, 2010).

2.1.1 BeyondZero

The concept of BeyondZero was introduced at SKF as an overall environmental strategy in 2005. It aims to define the company's environmental work where the goal is for SKF to have a "*net positive contribution to the environment*" (SKF, 2010).

BeyondZero can be divided into two parts. On one hand it includes minimizing the environmental impact from all operations within SKF. On the other hand it includes developing "market offers" that give customers better environmental performance when using SKF's products compared to competitive products. The intention of this concept is to take SKF "beyond zero" and create a positive environmental impact. SKF aims to use the engineering knowledge in the company to help customers to address the increasing demand on improved environmental performance (SKF, 2010).

A part of SKF's environmental strategy can be denoted as product differentiation which is further described in Section *2*.2.1 LCA for marketing in environmental management. They sell high quality products to knowledgeable customers.

2.2 Applications for LCA

LCA work can have different applications. A part of the project has been the development of a life cycle based tool for comparison between sealed and open bearings. In the following sections, descriptions of how LCA can be applied in different ways are presented.

2.2.1 LCA for marketing in environmental management

LCA can be used as a research tool for preparing environmental marketing and understanding the impact of solutions. The life cycle based tool can be used for marketing and communication with customers. In order to understand the importance and potential usage of LCA within this area, this section summarizes the combination of LCA and marketing and how that can be a part of a firm's environmental management strategy.

Marketing business to business is different from marketing business to consumers. Since SKF have most of its customers in the industry, only business to business marketing is considered in this report. Business to business marketing is characterized by long-time relationships and personal communication. Significant time and knowledge transfer can be spent on each customer. The information can therefore be detailed and technical (Baumann and Tillman, 2004).

The relationship between marketing and LCA was already present during the development of LCA. Companies have used LCA results to market their products as better alternatives from an environmental perspective, but contradictions between different companies' LCA results for the same products occurred. The differences depended to a large extent to dissimilar system boundaries. That raised the discussion about consistency and in this way marketing has strongly influenced and pushed the standardization of LCA. In order to use LCA results when communicating with a market, consistency between different studies is essential (Baumann and Tillman, 2004).

The risk with all kinds of environmental marketing, including communicating LCA work, is that it has sometimes been abused, resulting in "greenwash". The concept of greenwash means that companies publish false or misleading green initiatives (ecomii, 2011). According to Case (Case, 2010), a product can have a good environmental performance and be innovative, but still be abused as greenwash if exaggerated claims are made in the marketing. Green marketing is difficult and it should be about making correct claims, to avoid greenwash, in order to reach fair communication. One has to expect tough examination from conscious customers and organizations. One also has to be able to answer questions about the claims (Case, 2010).

From an environmental point of view, a systems perspective is always necessary and LCA and LCA-based tools can be important instruments to broaden the horizon. Companies need to change focus from its products to the whole supply chain. This is highly important when more and more operations are outsourced (Welford, 2003).

Differentiation is an environmental management strategy which aims to differentiate products in, for example, an environmentally sound way. In this way a firm creates additional value for their customers making them accepting a higher price. Differentiation is not about cost reduction but creating competitive advantage and customer loyalty (Hart, 1995). Differentiation acquires a company to improve the environmental and social performance along the supply chain, develop sustainable trading strategies and communicate their work to stakeholders (Welford, 2003).

When applying differentiation as environmental management strategy, the firm has the possibility to take the environmental work to a high strategic level. Welford states that "*The environment and the concept of sustainable development should be at the forefront of competitiveness strategy, driving environmental, social and economic performance in positive directions and communicating that to increasingly receptive customer*" (Welford, 2003).

2.2.2 LCA and product development

Another application for the life cycle based tool is product development. Product development is the LCA application that has the longest history. The connection between LCA and product development is logical since the focus is a product in both cases (Baumann and Tillman, 2004).

In product development, tradeoffs between different preferences usually have to be made. Along with the environmental preferences, several other aspects such as technical, economic and aesthetic have to be taken into consideration during the process (Baumann and Tillman, 2004).

Several tools exist to facilitate the integration of a life cycle approach in product development. The tool developed in this study can be classified as "Dedicated LCA software" which, according to Baumann and Tillman (2004), can be used during the following product development stages:

- **planning** where it is used for analysis of reference product;
- **conceptual design** where it is used for environmental evaluation of concepts; and
- **embodiment and detailed design** where it is used for environmental evaluation of components and details.

A product's environmental performance is to a large extent decided during the development phase when selecting materials and design. Great environmental achievements can therefore be reached if the environmental aspects are integrated in an early stage. If LCA is used for learning in an early stage one knows what to focus on when reducing the life cycle impact. For example, the life cycle phase that contributes most to the potential environmental impact can be observed (Baumann and Tillman, 2004).

2.3 Previous LCA studies

Several LCA studies have been performed by SKF and since a part of the study includes generalization, those are part of the base line. Conclusions drawn in two previous studies connected to this study are presented here.

One general conclusion that is possible to draw from previous studies is that the GWP from bearing manufacturing, including material processing and production, is almost linearly dependant of the bearing weight. This is due to the large impact from steel processing and production (Fors, 2011).

2.3.1 Life cycle assessment of SKF's spherical roller bearing

The aim of the study called "Life cycle assessment of SKF's spherical roller bearing" by Ekdahl (2001) was to investigate the environmental properties of SRB 24024 and identify parameters and processes that cause major potential environmental impact. It was a cradle to gate LCA including a case study for the use-phase in continuous casting. This study is used as a reference for the description of bearing manufacturing processes described in Section *4.2.8.1 Bearing manufacturing*, but the data from the study is not used since more recent data exists. The study suggests further LCA studies should be conducted to increase knowledge in certain areas, for example a comparison between sealed and open SRB (Ekdahl, 2001).

2.3.2 LCA based solution selection

The purpose of the study called LCA based solution selection by Häggström and Berg (2002) was to compare the environmental impact during the whole life cycle between NoWear™ coated bearings and non-coated bearings. The NoWear™ coat has positive environmental effects for example in terms of increased service life and reduced grease consumption. In the study, one case with NoWear™ coated bearings was compared to another case with non-coated bearings used in paper mills (Häggström and Berg, 2002).

The result showed that, in terms of global warming potential[1], it was beneficial to use coated bearings, even though the extended life length and the reduced grease consumption were not completely utilized. Two fictive cases were set up, one were double service life were assumed for coated bearings and one were coated bearings were assumed to consume 100 times less lubricants (Häggström and Berg, 2002).

The result from the case study was only presented in weighted terms. Weighting is not used in this study, but since the relationship between the weighted results roughly corresponds to the relationship for global warming potential they are of interest anyway. The results show that the increased service life of the bearings is the parameter that affects the results most since the impact from the production gives the largest contribution to the potential environmental impact.

2.4 Spherical roller bearings

Spherical roller bearings (see Figure 1) are self-aligning and they can carry high radial and axial loads in both directions. The robust construction allows usage in a wide range of applications (SKF, 2011c).

Figure 1 Spherical roller bearing (Photo courtesy of SKF)

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[1] Abiotic resource depletion was not included in the study but eutrophication and acidification was included.

2.4.1 Lubricants

Lubricants are used in bearings to prevent metal to metal contact, reduce wear and protect from corrosion. The lubricant quality is degraded by mechanical work, aging and contamination (SKF, 2004).

2.4.2 Sealed bearings

Bearings can have an integrated seal in order to keep the grease in the bearing and protect it against contamination. The integrated seals are made of high tech rubber and steel. In some applications the bearings are greased for life, but in other applications re-lubrication is needed. If that is the case, the amount of grease for re-lubrication is significantly smaller than for open bearings (SKF, 2011e).

The seal protects the inner parts of the bearing from contamination. That gives increased service life, longer maintenance intervals, a more reliable system, and unplanned and expensive production stops can be avoided. The seal also reduces grease leakage to the surroundings. Depending on the application and the surroundings the effect of this will vary. In outdoor applications it might result in less grease leakage to the ground and in the case of continuous casting machine it can reduce the amount of grease sent for destruction as hazardous waste (Agnemar and Manne, 2009).

Sealed SRB's are especially suitable for applications with high load and low speed in harsh environments. They have been successfully implemented in a wide range of applications. Some of the applications are industrial robots, rope ways and continuous casters (SKF, 2000).

2.5 Steel industry and continuous casting

The application for the LCA part of the study is a continuous caster, the principles of the application are therefore described in this section.

Steel can be produced from either iron ore or scrap. The primary raw materials in the ore based steel production are iron ore and coal. The coal is converted to coke and mixed with the iron ore in the sintering process which is sent to the blast furnace. The blast furnace produces liquid pig iron which is pre-treated before it is refined to steel. The steel passes the secondary refining before it reaches the continuous caster (Jernkontoret, 2004).

The continuous casting process is illustrated in Figure 2. The molten steel is poured through the ladle (1) and the tundish (3) reaching the mold (5). By intensive cooling of the mold the steel is now hardening creating a shell around the still liquid core (10). The steel passes the top roll support area (6) and the bow zone (7) while it's solidification continuously. In this part most of the secondary cooling take place, cooling water is sprayed on the ingot. The finished steel leaving the caster can take the form of slabs, billets, blooms etc (12).

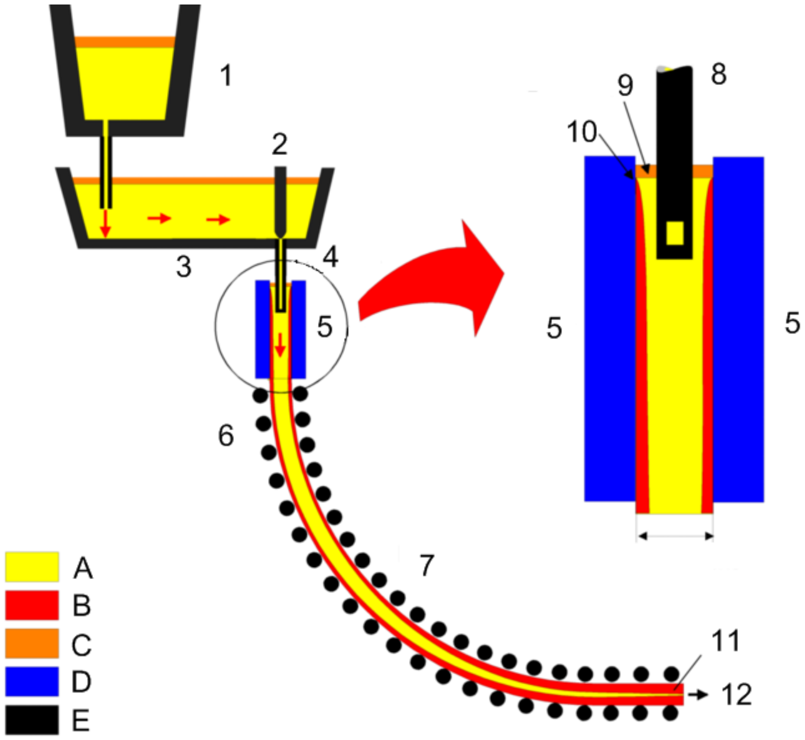

Figure 2 Illustration of continuous casting. The parts are ladle (1), stopper (2), tundish (3), shroud (4), mold (5), roll support (6), bow zone (7), shroud (8), bath level (9), meniscus (10), withdrawal unit (11) and finished steel (12). The colors denote liquid metal (A), solidified metal (B), slag (C), water-cooled copper plates (D) and refractory material (E) (Javurek, 2008).

The operating conditions in the caster are characterized by high load, low speed, high and varying temperature and steam. Problems are for example corroded and contaminated bearings causing short bearing service life and high grease consumption causing severe environmental problems (SKF, 2004).

The studied bearings are mounted in a roll unit which is located in the straightener segment of the continuous caster which is in the end of the bending curve where the horizontal part starts. The roll unit consists of roller segments, called mantles and bearings mounted on a shaft and the bearings are kept in housings. A lubrication system is connected to the unit as well as a water cooling system (Rodriguez, 2011).

3 Purpose

As stated in Section *1.2 Purpose*, the purpose of the study is to evaluate and quantify the potential environmental impact when using sealed or open SRB. A more detailed description of the purpose is stated below.

The study includes:

- identification of parameters affected by seals in SRB;
- a LCA of a SRB used in continuous casting and;
- development of a tool for comparison between sealed and open SRB of different bearing sizes and working under different conditions.

The methodology for the implementation is described in section *4 Method* and the research questions that are intended to be answered by the study are:

1. What are the differences in potential environmental impact when using a sealed SRB compared to an open one in a continuous casting process? The focus will be on the use-phase.
    a. How is the waste water system in the continuous caster affected through reduced grease consumption?
2. Which parameters affect the differences in environmental performance between sealed and open SRB and how are the parameters affected by bearing size and operating conditions?
    a. How can these impacts be related to costs from a customer's perspective?
3. What is the potential usage of a tool for comparison between sealed and open bearings?

4 Method

The methodology used for assessment and comparison of potential environmental impact and the affected costs when using sealed or open bearings can be divided into three parts.

1. **Identification of significant parameters** – The parameters that affect the environmental and economic performance of bearings will be identified.
2. **LCA of the bearing's environmental performance in continuous casting** – The LCA will not consider the economic effects.
3. **Development of a LCA-based tool for comparison between open and sealed bearings** –The life cycle flow chart created in the LCA will be the basis for the life cycle in the model and some results, and data from the LCA will be used as input-data. The tool will include environmental and economic assessment of the bearings.

The methodologies for the identification of parameters, the LCA and the tool development are described in Sections 4.1, 4.2 and 4.3 respectively.

4.1 Identification of parameters

The environmental parameters that are affected by seals are identified through:

- discussions with people at SKF;
- reports from previous studies and various applications for SRB and;
- site visit at one of SKF's customers in the steel industry.

The parameters that are studied are presented in Table 1 where they also are connected to potential environmental and economic effects.

Table 1 Parameters affecting the difference between sealed and open bearings in potential environmental impact.

	Parameter	Environmental aspect	Economic aspect
Grease leakage	Grease consumption (production of new grease)	Abiotic resource depletion Energy use	Cost of purchasing new grease
	Usage of re-lubrication pumps	Energy use	Cost of energy
	Peak friction due to re-lubrication	*System efficiency* Energy use	*Revenue loss* Cost of energy
	Amount of grease in waste water treatment system	Energy use	Cost of energy
	Amount of grease sent for destruction	Grease waste handling	Cost for sending grease to disposal
Wear on bearings	Service life (production of new bearings)	Abiotic resource depletion Energy use	Cost of bearings
	Maintenance intervals	*Plant efficiency*	*Revenue loss*
Friction	Seal friction	*System efficiency* Energy use	*Revenue loss* Cost of energy

4.2 LCA methodology

The main parts of LCA methodology are goal and scope definition, inventory analysis, and life cycle impact assessment. The complete LCA methodology is described in Appendix I.

4.2.1 Goal definition

The goal of the LCA is to assess and compare the potential environmental impact of using either an open or a sealed SRB in a continuous caster, using specific impact categories and focusing on global warming potential. The assessment will be done based on an existing application of the bearings, which has been decided as the continuous casting process in the steel industry (see Section *4.2.2.1 Options to model*).

The environmental aspects that the study focuses on are presented in the previous Section 4.1 Identification of parameters.

4.2.2 Scope and modeling requirements

In the following section, important decisions for the LCA are presented.

4.2.2.1 Options to model

The LCA will be performed for two different SRBs produced by SKF and used in a continuous casting process. One of the SRBs will have an integrated seal while the other one will be open. They will fill the same function in the process in order to be comparable.

The chosen application for the use-phase in the LCA is continuous casting. A pre-study was made in order to underpin the application selection. The criteria set up in order to find a proper application were:

- open and sealed bearings fulfilling comparable functions;
- grease leak to waste water treatment system;
- occurrence of seal friction in the application; and
- interested customers exist in the industry that have or have had both sealed and open bearings installed.

The alternative applications that were evaluated and the reasons why those not were chosen are:

- Conveyer system:
  - no waste water treatment system present;
  - in conveyor systems, the leaked grease is difficult to collect and the grease flow is therefore difficult to model. It is thus also difficult to assess the effects of it
- Paper industry:
  - sealed bearings have only recently been launched for the market and data availability might therefore become a problem

The continuous casting process in the steel industry was chosen since it fulfills all criteria except the one regarding friction. Continuous casting is also preferable since a previous study has been performed by SKF for a similar system and data can be reused. Another advantage is that all of the grease in the waste water can be allocated to come from the bearings.

Reasons for modeling the chosen system are:

- As far as known, no LCA has been performed with the same scope and the same system boundaries, but a similar study has been made but with different scope. The study will thus address a knowledge-gap, especially within the area of waste water treatment.

- It is an application, where both sealed and open bearings have been used and interested customers exist.

4.2.2.2 Initial flowchart

Figure 3 shows the flow chart for the life cycle of an SRB with the use-phase in a continuous casting process.

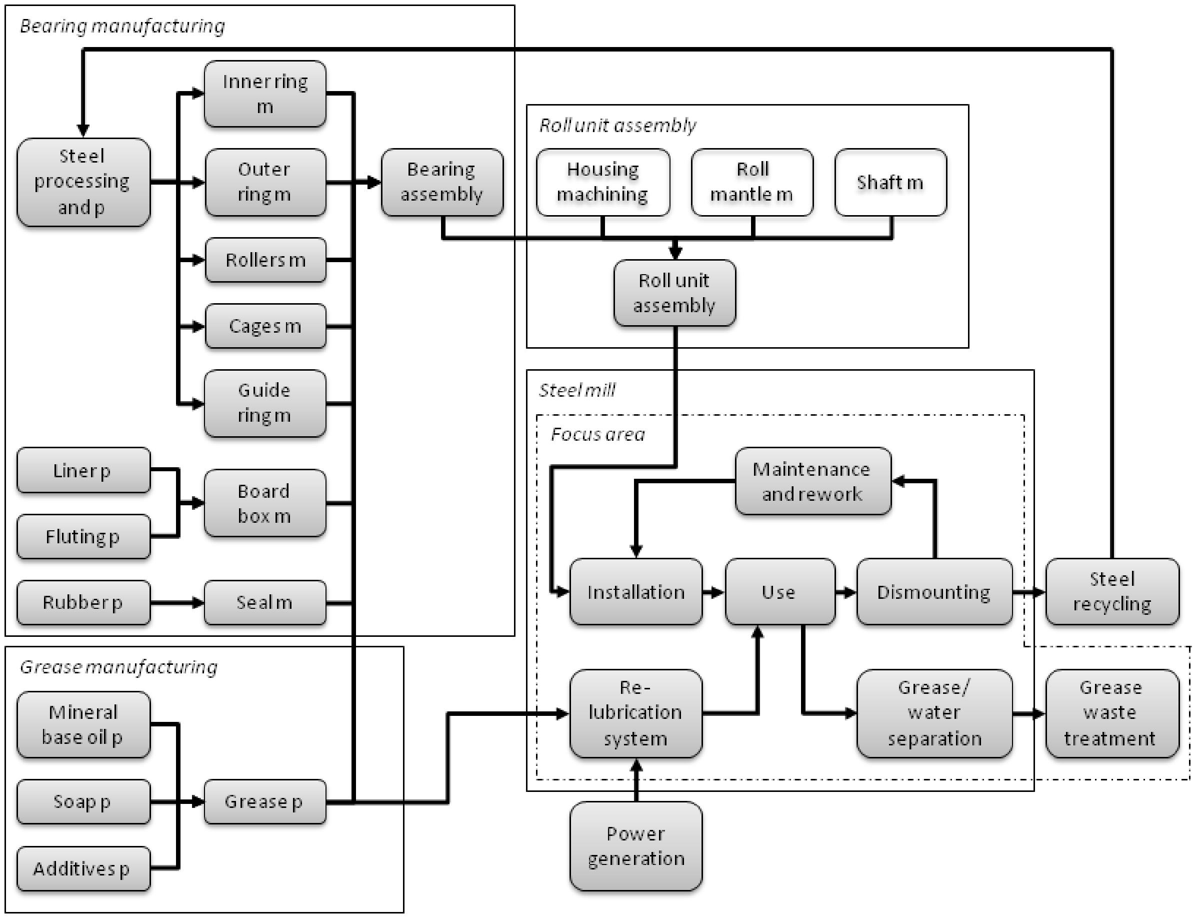

Figure 3 Initial flowchart for the SRB life cycle. Note that transports not are shown. The dashed line indicates the focus area for the study. P=Production M=Manufacturing

4.2.2.3 Functional unit and reference flow

The functional unit (FU) used in the study is the *use of one bearing in a continuous casting roll line, straightener segment, for one year.* This is the unit that all flows are related to.

The functional unit is chosen with respect to comparability. The data is collected for a continuous casting line that previously had open bearings but is now changed to sealed bearings. This means that data for the present situation will be used for the sealed bearings, but data for the previous situation is used for the open bearings. When changing from open to sealed bearings, the annual average production went from 1.4 to 1.9 Mtons of steel, but the production increase is not possible to allocate only to the change of bearings, since other technical changes were made as well.

4.2.3 Impact categories and method of impact assessment

The focus among impact categories will be on 100 years global warming potential measured in CO_2-equivalents. Potential environmental impact from abiotic resource depletion, eutrophication, acidification and ozone depletion, will be presented but not further analyzed.

Classification and characterization will be done with the method CML2001-Nov.09 included in the software GaBi. No weighting will be performed in the study.

4.2.4 Type of LCA

An LCA study can be either accounting or change oriented, depending on whether it evaluates the total environmental impact of a product, or if it aims to evaluate the consequence of a change in the system. In this case, the LCA will be accounting and thus evaluate the total difference environmental impact in the two cases.

4.2.5 System boundaries

The LCA is a cradle to grave study and therefore evaluates the impact during the bearing's whole life cycle but the focus is on the use-phase. The system boundaries in relation to nature and within the technical system are illustrated in the initial flow chart shown in Figure 3. They could further be described as:

- the bearing manufacturing will take place at one of SKF's production sites;
- average data will be used for grease manufacturing;
- the steel mill will be a customer of SKF; and
- grease waste treatment and bearing waste treatment will be included in the study

Geographical system boundaries depend on the location of the different activities within the system.

The aim is to use data representing the present system since the environmental performance of the product in today's system is evaluated. Retrospective data will be used if data for the present system not is available.

The primary method for handling allocation problems is system expansion. System expansion is be made for grease waste treatment where it is assumed that the grease is energy recovered through incineration. System expansion is made for steel recycling as well, further described in Section *4.2.8.5.1 Steel recycling*.

The background system, including for example electricity production, represents European average. The foreground system is subdivided into the life cycle phases.

4.2.6 Data quality requirements

There are several requirements of data used in LCA; the data needs to be relevant, reliable and accessible. Due to time limits in the project, most of the data will not be collected but reused from previous LCA studies at SKF. This might in some cases compromise the data quality.

Since the LCA is accounting, average data is used. Use of average data is in line with SKF's policy and gives the study uniform system boundaries with other studies at SKF; in this way the study becomes more comparable to those.

Data for the processes in the system will be collected as follows:

- Data for production of bearings and grease will be found in previous LCA studies by SKF.
- Site specific data will be used for the use-phase. This data was collected for another LCA study by SKF with different system boundaries. It is re-calculated to the system boundaries of this study.
- For grease and bearing waste treatment European average data is used collected by PE International.
- For electricity use and heat production average data for Europe is used collected by PE International.

4.2.7 Assumptions and limitations

- Transportation is not included due to lack of data. It has been shown in previous LCA's that the contribution to the potential environmental impact from transportation over the life cycle is minor, approximately less than 1% (Häggström and Berg, 2002).
- Seal friction is not included. The friction caused by the seal is low for slow rotating speed and since the rotating speed is less than two revolutions per minute in continuous casting, the potential environmental impact from the seal friction is considered to be minor.
- Maintenance is not included even though it is noted that maintenance in continuous casting can be reduced when changing from sealed to open bearings.
- There are uncertainties in the data for grease manufacturing.

4.2.8 Life cycle inventory for the LCA

In the following parts the included processes and data are described.

4.2.8.1 Bearing manufacturing

Since the focus of the study is on the use-phase, the model for the bearing manufacturing will be taken from a previous LCA-study at SKF, which was for the medium sized deep groove ball bearing 6310. This data is used since it is considered to be the most reliable and updated study at SKF for the moment.

There are differences between the studied bearing and 6310. The main differences are presented in Table 2.

Table 2 Differences between the studied bearing and the bearing that the data was collected for. In the right column, solutions for the potential problems are presented

Difference and potential problem	Solution
The weight of 6310 is 1.05 kg and the weight of the studied bearing is 13 kg.	Mass will be used as allocation factor to compensate for the differences in material consumption.
The studied bearing is a spherical roller bearing but 6310 is a ball bearing. This might cause differences in material losses and production methods.	Mass allocation for each part solves this partly but it might be a source of errors.
Energy use for production per kg bearing differs between small and large sizes.	Previous studies have shown that the main impact from production comes from material usage and not the production processes. This is therefore considered a negligible error.

The processes included in bearing manufacturing are described below, the descriptions in Sections 4.2.8.1.1.-4.2.8.1.7 comes from the Master thesis "Life cycle assessment on SKF's Spherical Roller Bearing" (Ekdahl, 2001) unless otherwise is stated. The bearing manufacturing process consists of several steps that might vary but this description is considered representative for a general case (Berglund, 2011).

4.2.8.1.1 Steel processing and production

The steel is produced from iron ore and steel scrap. In the model, 75% of the steel is assumed to come from steel scrap which is in line with a study by the European Environment Agency (Moll et al., 2005). The steel is melted in a furnace and hot rolled to billets. Billets are the raw material for bearing rings and rollers.

4.2.8.1.2 Inner and outer ring manufacturing

The methods for manufacturing of the inner and outer rings are similar to each other. The first step is to check the billets for cracks and other material defects. Then the process consists of several steps, including hot shearing, forging, rolling, cutting and piercing. The pieces are turned into the final shape and heat treated to achieve the correct metal properties. Finally the surfaces are treated through grinding and honing.

4.2.8.1.3 Rollers manufacturing

The rollers originate from square billets which are hot rolled to wire rod and then peeled and drawn to surface removed wire. The rollers are then manufactured from the bar through cutting and pressing, finally they are heat treated and finally grinded and polished.

4.2.8.1.4 Cages manufacturing

The cages for SKF's SRB are made of steel billets with a quality especially developed for this purpose. The billets are hot rolled and then pickled in acid bath in order to remove oxide. The steel sheet is cut, pressed, turned and blasted into the correct dimension and surface properties.

4.2.8.1.5 Guide ring manufacturing

The guide ring is made of steel powder produced from crushed sponge iron. The iron powder is sintered under high temperature into guide rings.

4.2.8.1.6 Board box manufacturing

The board box is made of a material called miniwell, which is made of Kraftliner, fluting and polymer. The board box is used for packaging of the bearing.

4.2.8.1.7 Seal production

The seal is made of metal and rubber, the metal part corresponds to over 99% of the weight.

4.2.8.2 Grease manufacturing

Bearing grease normally consists of mineral base oil, around 80%, soap and additives. There are large uncertainties about the impact from grease manufacturing due to limited data availability in this study.

4.2.8.3 Roll unit assembly

A complete roll unit in continuous casting at the studied customer consists of four bearings, four housings, three roll mantles, one shaft, seals and grease. Only the bearings are supplied by SKF and the unit is mounted at the plant. Only the bearings are assessed in the LCA.

4.2.8.4 Steel mill

The following processes take place at the steel mill.

4.2.8.4.1 Use

As described in Section *4.1 Identification of parameters* the differences in potential environmental impacts between sealed and open bearings is affected by grease leakage, wear on bearings and friction.

The amount of grease that is added to the system is for the studied case about three times higher for the open bearing. The system is cooled with a high flow of water. It is assumed that all grease ends up in the waste water, which is reasonable according to maintenance manager at the visited plant.

The service life of the bearings is affected by the wear which decreases with sealed bearings. For the studied case, no re-work or maintenance is performed on the bearings but they are changed by a certain interval. The service life of sealed bearings is approximately 50% longer than for the open bearings in the studied case.

The seal causes friction in the contact surfaces. This friction is low for low rotating speed and since this is the case in continuous casting it is excluded from the LCA. However, it is included in the LCA based tool and further described under 4.3.4.3 Seal friction.

4.2.8.4.2 Maintenance and rework

Maintenance and rework is performed on the parts in the roll unit. No impact from this is included in the LCA study even though it is noted that it is affected when changing from open to sealed bearings.

4.2.8.4.3 Re-lubrication system

A re-lubrication system is used in the caster that continuously pumps grease into the bearings. Electricity consumption for pumps is included in the model.

Re-lubrication causes increased friction during a period of time. This friction is excluded from the LCA since the rotating speed is slow in the caster.

4.2.8.4.4 Grease water separation

One of the major knowledge gaps that the study aims to address is the effects of reduced grease in the waste water treatment process. This section is therefore more detailed than the sections about the other processes.

Waste-water from steel plants is characterized by high concentrations of metals, large water usage in processes for cooling and high rate of recirculation. The waste water system is generally built up by several steps fulfilling different functions, like separation of particles or grease (Sivard, 2010).

Due to the large differences in technologies for waste water treatment between plants it is difficult to give a general model. A description follows of the waste water treatment at a continuous casting plant.

Water is sprayed on the steel for cooling. It then needs to be cleaned from contaminants such as mill scale, grease, oil and suspended substances. The cleaning is done through dewatering, sedimentation, thickener and sand filters. There are several sand filters in which the sand is changed once a year. Lye and flocculent is added during the process. The major part of the water is re-circulated while a small part goes to a dam with industrial water. The process is schematically illustrated in Figure 4. Most of the grease is separated in the sedimentation basin where the water stays in basins. The grease ascends to the surface and is removed with scrapers (SSABOxelösund, 2006).

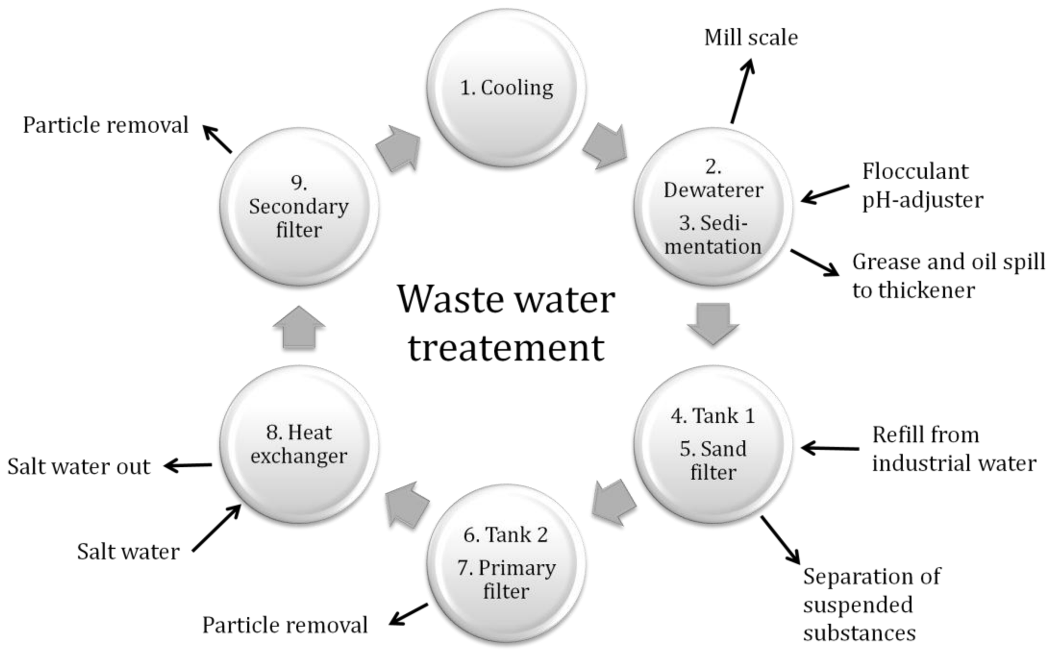

Figure 4 Schematic illustration of the waste water treatment for a continuous casting plant

The grease is mixed with mill scale in the process, which means that when the grease is separated it is not pure grease but grease mixed with mill scale. The grease and scale are not separated at the plant so the amount of hazardous waste sent for destruction at the studied plant is larger than the amount of grease that was added in the re-lubrication system.

After discussions with experts it is concluded that the waste water treatment system probably wouldn't be changed even though the grease was significantly reduced. Only if no grease at all leaked from the caster, could it perhaps be possible to change the waste water treatment system. Insufficiently cleaned water might cause large problems; it can for example lead to insufficient cooling of the slab resulting in defects on the steel. The economic risks with inadequately cleaned water are too high. Due to this fact, the difference in potential environmental impact when reducing the grease consumption is considered negligible. Therefore, no impact from waste water treatment is included in the LCA (Tennander, 2011).

If the aim of the LCA was to evaluate the total environmental impact of a bearing, it would not have been suitable to exclude the waste water treatment without further investigations, but since the primary aim is to evaluate the difference between sealed and open bearings it is considered appropriate.

4.2.8.5 Additional processes

The additional processes in the life cycle are described in the following sections.

4.2.8.5.1 Steel recycling

According to the European Topic Centre on Waste and Material Flows, 75% of the steel in Europe is recycled (Moll et al., 2005). The recycling is assumed to take place at the same plant, i.e. no transport is included for the steel scrap. The steel recycling is accounted for as a credit, i.e. a process with negative impact in the LCA.

4.2.8.5.2 Grease waste treatment

Used lubricating oils can be re-refined or re-used in other ways. It is stated that proper waste management of those oils is important because large amounts are generated globally, they have a strong potential for re-use or regeneration, and there are potential environmental effects if they are not handled properly (UNEP, 1995).

Used grease is treated as hazardous waste and the material is either recycled or its energy content recycled. The possibility of material recycling depends on the chemical composition and the market demand. When the energy content is recovered, the grease is incinerated at high temperature (1200°C), which breaks down most molecules. The flue gas is filtered so that no hazardous substances from for example additives are emitted. The generated energy is used for either district heating, electricity or industrial heat water depending on the local conditions (Holmquist, 2011).

It is assumed that 80% of the grease in the studied system undergoes energy recovery to be used as industrial heat. A low heating value is used for grease incineration, the reason for this is that average European values are used and the demand for heat does not exist everywhere. The low heating value is a compensation for this (Rinde, 2011).

4.2.8.5.3 Power generation

Electric power is used in the re-lubrication pumps and European average values are used.

4.2.9 Life cycle impact assessment

Life cycle impact assessment (LCIA) aims at converting the environmental loads into potential environmental impacts. The methodology used for LCIA is CML2001 – Nov. 09. The assessed impact categories in the study are global warming potential, expressed in CO_2-equivalents with 100 years perspective, and abiotic resource depletion, expressed in Sb-equivalents. Since further impact categories are included in the used data sets and generated by GaBi, further results are presented but not analyzed. The results from the LCIA are presented in Section *5.2 LCA result*.

4.3 Methodology for development of LCA-based tool

The purpose is to develop a LCA based tool to assess and visualize the differences in potential environmental impacts and costs, when using sealed or open SRB's, in different applications and of different sizes. In the tool, the results from the LCA are generalized and complemented with more factors, for example the friction which was excluded from the LCA since it was assumed to not affect the result due to the slow rotating speed in the continuous caster.

The environmental impact is expressed in CO_2-equivalents for global warming potential during 100 years, according to CML2001–Nov. 09. Impacts for the whole life cycle are included. The cost is the life cycle cost from the customer's perspective.

The results from the identification of parameters and the LCA are the main input to the tool. It has been analyzed how the parameters vary between different bearing sizes and different applications. During the tool development, a dialogue has been held with potential users and they have had the possibility to give feedback and development suggestions.

The main purpose with the tool development is to create a tool which can visualize the differences in different applications and not to investigate whether sealed or open bearings have lower potential environmental impact. However, discussions are held about which factors that contributes most to the potential environmental impact.

4.3.1 Tool requirements

The tool has two main user categories; application engineers and product developers. The application engineers work with customers in different industries and the aim is that they should be able to use the tool together with customers when discussing bearing selection. Product developers should be able to set up different scenarios to identify what environmental effects a selection might have, or to motivate decisions.

The two different usage areas set different requirements on the tool. The different requirements might contradict. But in order to minimize the trade offs, the tool is created to be easy to understand and use but complex enough to cover all of the factors that have large impacts.

Requirements for the tool are set up in the list below.

- To enable usage for people working with customers, the tool has to be easy to use and possible to understand fast.
- If the tool will be used for external communication, the credibility and transparency of the tool are of highest importance. The limitations of the tool are stated whenever relevant to avoid improper usage of result causing misleading communication.
- Product developers might be interested in setting up different cases and use the result as a part of a reference for example when selecting concept. It therefore needs to be possible to understand the calculations to facilitate changing for example formulas.
- If for example more certain data or better calculation models become available, the tool needs to be able to update without too great effort. Comments and explanations can facilitate this.

4.3.2 Tool layout

The tool is developed in Microsoft Excel where tabs are used to sort the content. It includes one tab with background information where the user can learn about the issues around sealed bearings and how the tool can be used. The bearing's life cycle is illustrated and the affected parameters are explained. The limitations with the tool are also stated. Under the next tab, the user can set parameters that depend on the application and affect the result. Explanations are written for each parameter.

The next three tabs contain various graphs showing the results. After that, one tab with typical parameter values for three bearing applications is presented. The remaining tabs in the tool are hidden and contain for example calculations and impact factors for emissions, the user can choose to unhide those tabs to get further understanding about the model and make changes to it.

The input to the model is a set of parameters, for example load ratio and grease consumption, for a specific case and a specific bearing size. The parameters are recalculated to hold for seven SRB sizes with inner diameter from 25 mm to 360 mm. Data for those seven bearings are the basis for the generalization or scaling of the impacts. Depending on the characteristics of the impact, different scaling factors are used, for example bearing weight or bearing inner diameter.

When selecting bearing, the user can choose between either specifying the bearing properties for any bearing, or selecting a pre defined bearing from the seven sizes included in the model.

4.3.3 Impact factors

All impact factors included in the tool are described here. Those are used for translating the impact parameters into potential environmental impacts in GWP.

4.3.3.1 Grease

The assessment of potential environmental impact grease production and end of life scenario is modeled in the same way as for the LCA described in Sections *4.2.8.2 Grease manufacturing* and 4.2.8.5.2 Grease waste treatment. The impact from grease is expressed in kg CO_2-equivalents per kg of grease, including production and end of life.

The cost factor includes cost of grease for a customer and cost of end of life treatment. The grease cost is estimated by application engineers at SKF. The cost for the end of life treatment for grease is estimated based on the cost a customer pays for grease waste destruction and the amount of grease they use per year. It is thus not the actual price per kg grease.

4.3.3.2 Electricity

The user can select between different geographical regions for CO_2-emissions from electricity consumption. The emissions for each continent are shown in Table 3 below. The CO_2-emissions are extracted from the LCA software GaBi, where the regions' electricity mixes and grid losses are taken into account. The data was compiled by PE international. The cost for electricity represent European average and comes from Europe's Energy Portal representing industry average 2011 with a consumption level of 20 GWh/yr (EuropesEnergyPortal, 2011). The cost factor is 0.01 €/kWh. It is not possible to select continent for the electricity cost since representative sources are lacking.

Table 3 CO_2-emissions from electricity for different geographic regions, expressed in CO_2-equivalents with 100 years potential.

Continent	**Emissions [kgCO_2/kWh]**
Global	0,8
China	1,2
Australia	1,2
Europe	0,5
US	0,8
India	1,6

4.3.3.3 Bearings

The values for CO_2-emissions from bearing consumption include production and end of life, excluding transportation. The data for production was collected in an earlier LCA study by SKF for a medium sized deep groove ball bearing called 6310. Data from this study is used since it is considered as the most reliable and updated of the bearing LCAs performed at SKF. For the end of life scenario 75% recycling of the steel is assumed.

The GaBi software was used to set up models for production of four of the bearing sizes included in the model. When comparing the CO_2-emissions per kg bearing of the four bearing sizes, it is seen that the CO2-emissions from bearing production is almost linearly dependant on the weight of the bearing, which is also confirmed by other sources (Fors, 2011). Therefore an average value is used in the tool and scaled after the bearing weight.

Bearing prizes are based on catalogue values from 2011 for the seven bearings included in the model (SKF, 2011g). Since the price should represent a bearing size and not the specific bearing, the prices were adjusted to fit a smoother line. This was done through fitting a power function to the prices with the bearing inner diameter as variable.

4.3.4 Impact parameters

Below follows a description of the parameters included in the tool and how the impact is calculated and scaled.

4.3.4.1 Grease consumption

Grease consumption for re-lubrication is input as kg grease per year used in one specific open bearing, the user can then select if the sealed bearing is re-lubricated and in that case how much the grease is reduced. Since the grease amount depends on the free volume in the bearing, the outer diameter and width are used for scaling the grease consumption.

4.3.4.2 Re-lubrication

The effect of bearing re-lubrication depends on whether the re-lubrication is done manually or with an automatic re-lubrication system. The user can therefore select between those two options in a drop-down menu. If the re-lubrication is done manually, a friction peak occurs in the bearing due to a temporarily higher viscosity of the grease. This effect is considered negligible if the re-lubrication is automatic, but in that case, pumps are used for the re-lubrication causing electricity consumption.

4.3.4.2.1 Re-lubrication friction

When re-lubricating bearings manually a friction peak occurs. The peak lasts for 4-24 hours and is assumed to be a multiple from one to four of the friction that always exists in the bearing (Lindsten, 2011). According to SKF general catalogue, the equations for the friction are:

Bearing friction torque (SKF, 2008):
$T_{bearing} = 0,5*0,018*C*d*1000/(C/P)$ (1)
Where
C = Dynamic basic load rating for the bearing
d = Bearing inner diameter
C/P = Load ratio for the specific case

This gives re-lubrication friction torque as (Lindsten, 2011):
$T_{re\text{-}lube} = T_{bearing}*f*t*x$ (2)
f = Re-lubrication frequency
t = Time for friction peak duration
x = Multiple of the bearing friction

In the tool, the input for re-lubrication friction is C/P and f. C and d are specified for the seven bearing sizes in the tool. Default values are set for t and x but those are possible to change by the user.

The power loss due to the friction can be calculated with equation 3 below where s is the speed in revolutions per minute.

$P_{loss} = T*s/9550$ (3)

Input for the speed is rpm and inner and outer diameter. The speed is scaled using the dimensionless parameter nd_m, according to equation 4 below. nd_m is constant for all bearing sizes.

nd_m=rpm*(inner diameter+outer diameter)/2 (4)

The friction power loss is translated into CO_2-emissions and costs through the corresponding electricity consumption during one year.

4.3.4.2.2 Automatic re-lubrication

Electricity for pumps in an automatic re-lubrication system can be included. The input is the installed power in the pumps, the load factor that the pumps run with and the number of bearings that the pumps re-lubricate. The grease consumption is the scaling factor for the re-lubrication system.

4.3.4.3 Seal friction

The equation for seal friction is found on page 90 in SKF general catalogue (SKF, 2008), as $T=K_{S1}*d_s^{\beta}+K_{S2}$. In equation 5, the relevant constants are inserted.

$T_{seal\ friction} = 0,057*d_2+50$ (5)

P_{loss} is calculated with equation 3 and is translated into CO_2-emissions and costs through the corresponding electricity consumption during one year.

4.3.4.4 Bearing consumption

The bearing consumption is based on the service life of the bearing, which can be affected by the seal. The input is the service life of sealed and open bearings in the application. The service life is recalculated to how many bearings that are needed during one year. This is multiplied with the impact factors described under 4.3.3 Impact factors.

4.3.4.5 Maintenance

Maintenance can in some applications be affected by the seal. If the user can estimate a value for reduced maintenance cost, he can do so, otherwise it will be excluded. The environmental effects of maintenance are excluded since they are assumed to be too difficult to estimate. It is though stated clearly, on several places, that this is a limitation with the tool.

4.3.4.6 External seal friction

In some applications there are external seals for the bearing housing. If the integrated bearing seal can replace one of the external seals, it can be of interest to compare the sealed bearing with an open bearing with an external seal. In that case the user can select to include an external seal for the open bearing in the model. The friction torque (T_{ref}) in the external seal has to be estimated. The external seal is assumed to have its contact surface on the same position as the inner diameter of the bearing corresponding to the shaft diameter. The model is set up like this since it is considered to be a normal case, and to facilitate the scaling (Lindsten, 2011).

No general equation for friction in external seals exists since the friction might differ between producers and models. It is therefore assumed that the friction torque for external seals can be written on the same form as the friction torque for integrated seals (equation 5), i.e. as:

$$T=C_1*d^2+C_2 \quad (6)$$

C_1 and C_2 are constants depending on the seal. It is assumed that C_2 is the same as for integrated seals, i.e. 50. The following equation is obtained for C_1:

$$C_1=(T_{ref}-C_2)/d^2 \quad (7)$$

C_1, C_2 and the inner diameter of the seven bearing are inserted in equation 6. This gives the friction torque for the same kind of seal for all bearing sizes. The power loss is calculated with equation 3 and is multiplied with the impact factor for electricity.

4.3.4.7 Bearing friction

The bearing friction is included in the model even though it is the same for sealed and open bearings. The bearing friction is included in order to set the other impact parameters in relation to something and to facilitate the evaluation of the effects of the seal. It can show whether the seal only makes a marginal difference, or if it actually affects the bearing's environmental performance significantly. The bearing friction is calculated with equation 1 and the power loss is assumed to be in electricity.

4.3.5 Presentation of results

The results are presented in three different tabs. The first tab shows the results for the studied bearing size as stacked columns showing the sources of the potential environmental impacts and costs as absolute values. The second tab shows the result for each of the seven bearing sizes included in the tool; also these are stacked columns showing the sources of the potential environmental impacts and costs. For this tab, the results are shown as percentage and the purpose is to clearly visualize the differences between sealed and open bearings.

The last tab contains two graphs showing curves for sealed and open bearing sizes with bore diameter 25-360 mm, one of the graphs shows the total potential environmental impact and the other one shows the total cost. The purpose with these graphs is to visualize how the results depend on the bearing size.

Under each tab it is stated what is included in the model as well as the limitations with the model. Together with the graph for GWP under the first result tab, the CO_2-emissions are related to the distance in kilometers that you can drive with an average car.

4.3.6 Tool validation and testing

The tool is validated and tested together with engineers from SKF, both with application engineers working with customers and product developers. It is tested with data representing bearing applications of different characteristics and the result from the testing is analyzed. The analysis has two purposes; the first one is to validate the plausibility in the tool and the second one is to evaluate which factors give the largest potential environmental impact in the different cases.

As stated in Section *4.3 Methodology for development of LCA-based tool*, the main purpose is not to evaluate the sources of the potential environmental impact but it is still discussed. The purpose with the discussion is to exemplify and clarify the potential usage of the tool.

The test persons are also asked about the potential usage of the tool and what they expect from it. The tool layout and content is adjusted after their preferences.

5 Result

The results from the methodology described in Section *4 Method* are presented in the following sections.

5.1 Result identification of parameters

The results from the identification of parameters are the parameters illustrated in Table 1 in Section *4.1 Identification of parameters.*

5.2 LCA result

LCA results for the impact categories global warming potential, abiotic depletion of resources, acidification, eutrophication and ozone layer depletion are presented in this chapter. The result shows that the potential environmental impact for the whole life cycle is lower for sealed bearings looking at all impact categories. In global warming potential, the total life cycle impact is approximately 50% lower for sealed bearings than for open bearings.

As seen in Figure 5, open bearings have higher potential environmental impact during all life cycle phases. The differences are larger for grease production, use-phase and end-of-life grease, than for bearing production and end-of-life bearing. The largest contribution to the total impact originates from the life cycle phase bearing production.

In Figure 5, the potential environmental impact expressed in global warming potential is shown. As seen, the bearing production is the life cycle phase with largest share of the global warming potential.

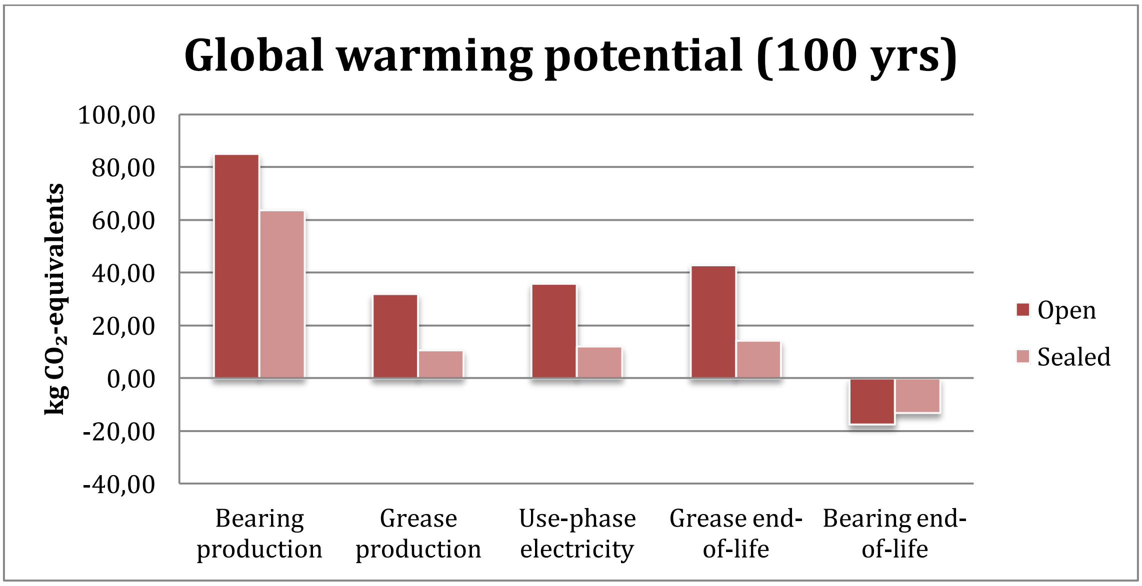

Figure 5 The potential environmental impact for sealed and open bearings expressed in global warming potential.

The potential environmental impact in abiotic resource depletion expressed in Sb-equivalents is shown in Figure 6. Bearing and grease production are the life phases contributing most in this impact category. The negative share from bearing end-of-life originates from the steel recycling.

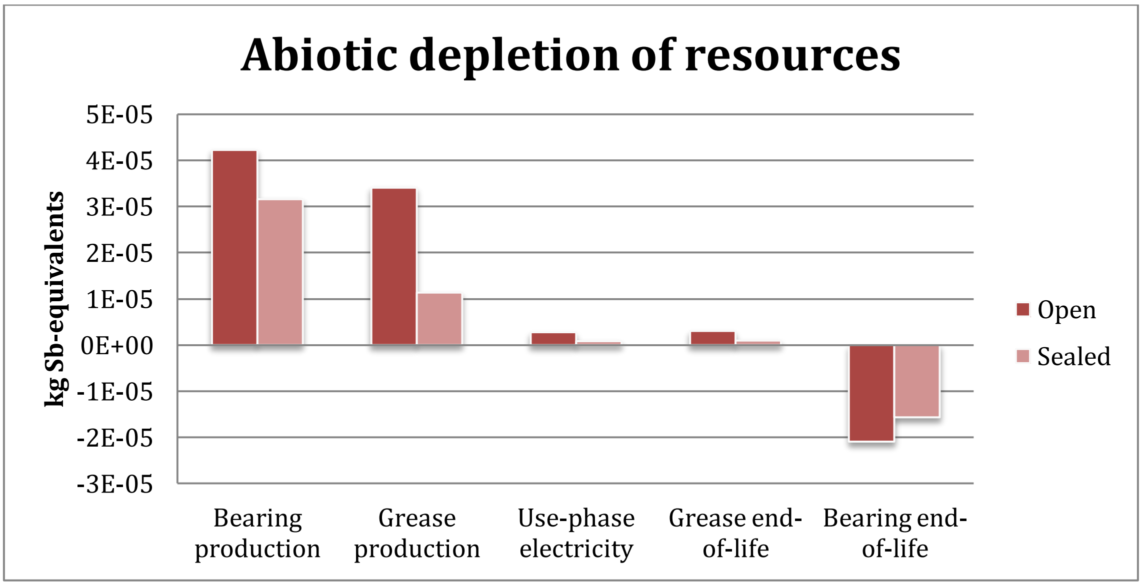

Figure 6 The potential environmental impact for sealed and open bearings expressed in abiotic depletion of resources.

The impact category acidification potential, shown in Figure 7, is dominated by bearing production. Grease production and use-phase electricity have also large shares.

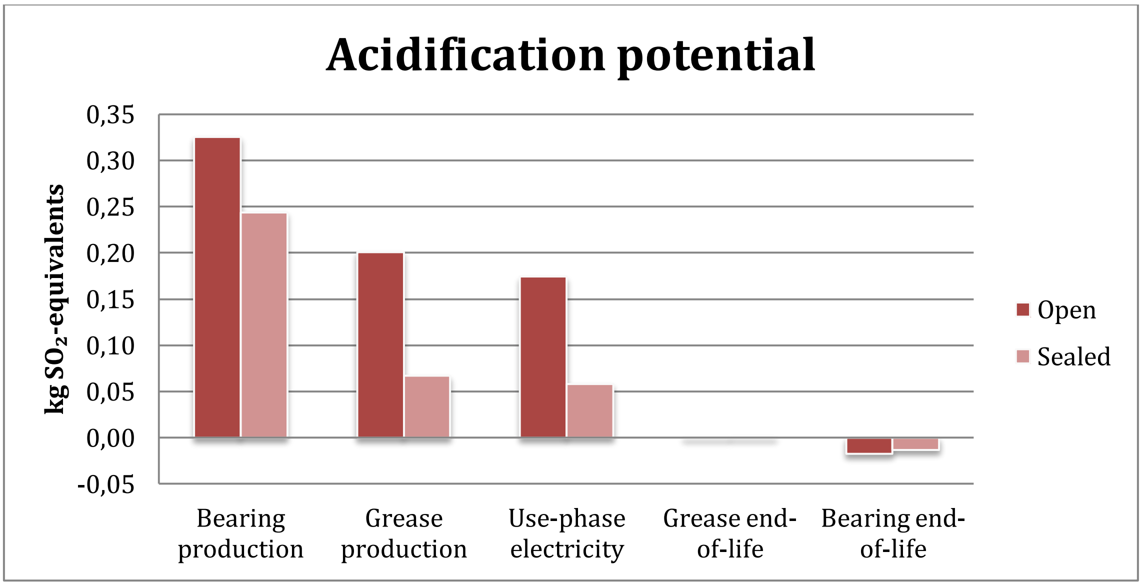

Figure 7 The potential environmental impact for sealed and open bearings expressed in acidification potential.

The potential environmental impact from eutrophication is shown in Figure 8, this is the only category dominated by grease end-of-life and grease production.

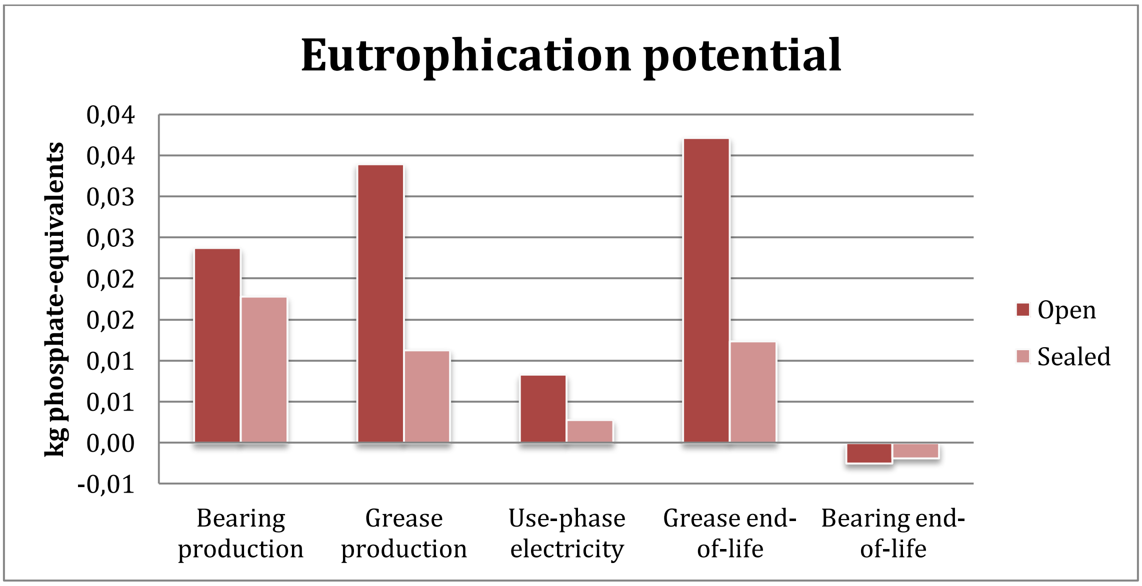

Figure 8 The potential environmental impact for sealed and open bearings expressed in Eutrophication potential.

The result for the impact category ozone layer depletion is shown in Figure 9, this category is dominated by bearing production and use-phase electricity.

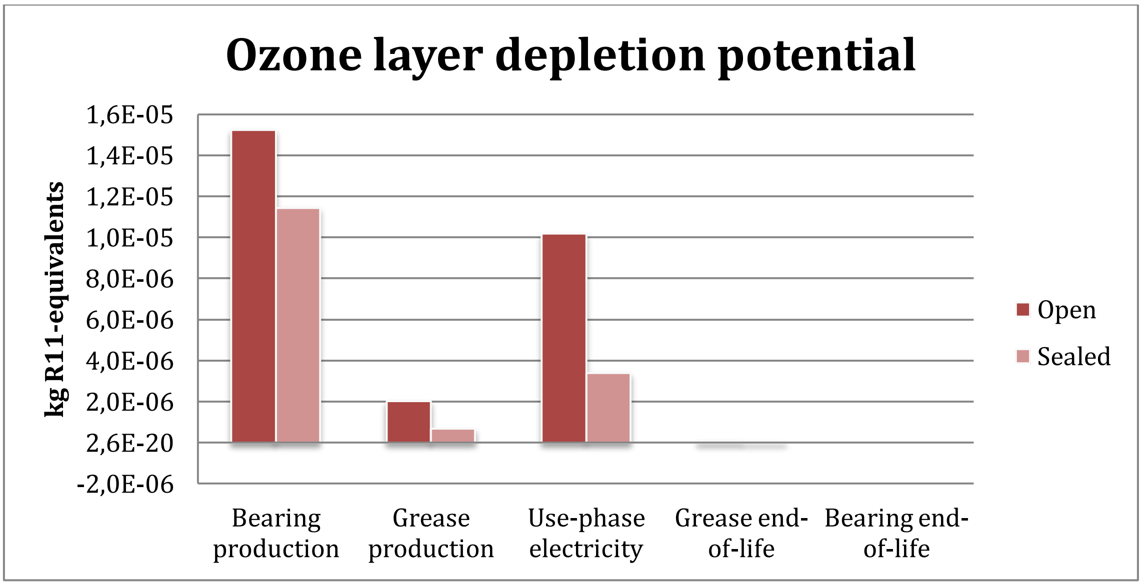

Figure 9 The potential environmental impact for sealed and open bearings expressed in ozone layer depletion.

5.3 Result from development of the life cycle based tool

The main result from this part of the project is the tool for comparison between sealed and open SRB. Screenshots from the tool are shown in the following section. In Figure 10, the first tab in the tool is shown. In this tab, explanations for the rest of the tool are presented in order to give the user a quick overview.

CO_2 and cost comparison between sealed and open bearings

Created by Karin Agestam in 2011 as master thesis project.

This tool is created to visualize differences in environmental and economic impacts between sealed and open SRB. The environmental impact is measured in CO_2-emissions and costs in Euro. Both costs and CO_2-emissions are calculated with a

Content

Background - *The included parameters and the background to the model is described*
Parameters - *Set the parameters for the application you which to study here*
Result 1,2&3 - *The results are presented in various graphs*
General conclusions - *General conclusions about different applications*

Content hidden tabs

If you which to change something in the model or get more understanding of calculations, unhide the hidden tabs[1]. You can change for example CO_2-emission factors, prices and constants in the friction models.

Impacts - *CO_2-emissions and costs are set for the parameters*
Bearings - *Data for the bearings included in the study*
Friction - *Friction formulas and factors*
Re-lube syst - *Calculation of impact from re-lubrication system*
External seal - *Calculations of impact from external seal*
Calculations - *Calculations for all factors and summary of those*

[1]To unhide hidden tabs: Right klick on one open tab below and select "Unhide..."

Figure 10 Shows the first tab in the tool.

In Figure 11, the content in the tab Background is shown. This tab is created to help the user understand the background and the differences in potential environmental impacts between open and sealed bearings. Colors are used in the layout to visualize connections. As seen, the green color is used for the potential environmental impacts and the red color is used to highlight important notes.

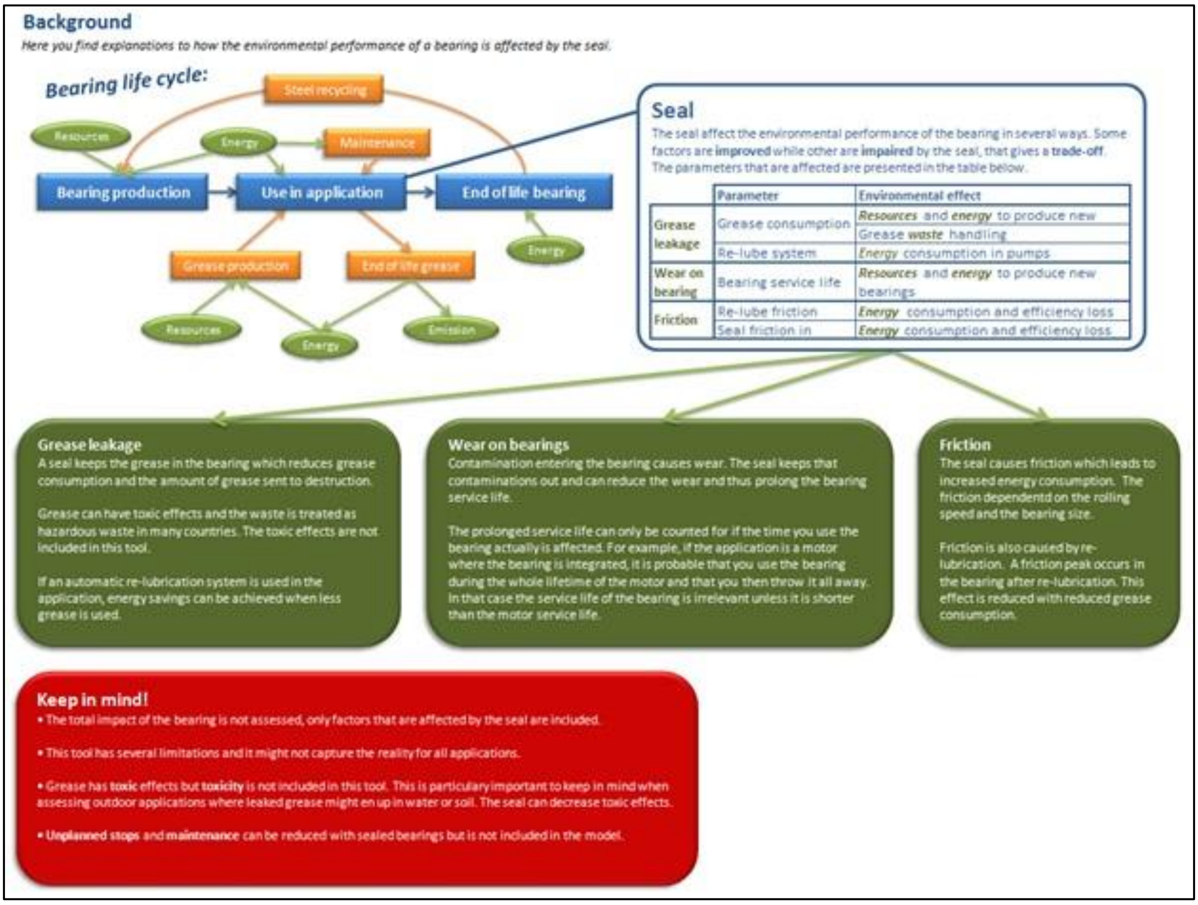

Figure 11 Shows the content in the tab Background

Figure 12 shows the content of the third tab called parameters. This tab is where the user specifies the bearing and the running conditions in the studied application. As can be seen, comments and explanations are provided in order to help the user.

Parameters

Set the parameters in the boxes for the studied application. All values should refer to **one bearing** of the defined size.
Boxes with thick borders have to be set, the others are optional.

Bearing

Pick a bearing from the drop down menu **OR** define the bearing size you want to assess

Bearing: Define

OR

D [mm]:
B [mm]:
d [mm]:
d_2 [mm]:
C [kN]:
Weight [kg]:

Only used if "Bearing" is set to "Define"

Price [€]: *If no price is defined, an approximated value is used*

General

Number of bearings: *Write the number of bearings that you want to scale the results for.*

Geographic region: Global *Different values for CO_2-emissions from electricity are used for each continent*

C/P: *Load ratio. 1 is extremely high load, 50 is very low load.*
Rotation speed [rpm]: *The rpm will be recalculated to ndm when scaling to other bearing sizes.*
ndm: 0

Percentage of hours per year: *Define the percentage of hours/year that the application is running.*
Hours per year: 0

Grease consumption and re-lubrication

The seal affects the grease consumption in the whole bearing house. The grease consumption affect the re-lubrication system.

Grease consumption
Grease per year in open bearing [kg/yr]: *Total amount of grease for re-lubrication in one OPEN bearing and its house during one year*
Grease reduction in sealed bearings: *Grease reduction in sealed bearings expressed in percentage of grease in open bearings.*

Re-lubrication
Type of re-lubrication *Select between manual and automatic re-lubrication.*

If manual set:
Number of re-lubrications per year: *See page 237-238 in SKF General Catalouge for recomendations.*

If automatic set:
Installed power in re-lube syst. [kW]: *Define the installed power in re-lubrication pumps.*
Load factor: *Define the percentage of the installed power that the pumps use.*
Number of bearings: *Define how many bearings the pumps re-lubricate.*
Electricity consumption [kWh/yr&brg]: 0,0

Production of new bearings

The seal decrease the wear in the bearing and that might increase the service life. Define the service life of sealed and open bearings here.

Service life open bearing [months]:
Service life sealed bearing [months]:

Customer's discount on bearings:

Maintenance

Changing to sealed bearings can affect the maintenance cost. Due to large differences in this factors between applications, it is difficult to make a general model for this. If it is possible to estimate the cost reduction, enter the value in €/bearing here.

Reduced maintenance cost [€/bearing & year]: *Reduced maintenance cost when using sealed bearings*

No environmental impact from maintenance is included which is a limitation in the model.

External seal

To compare the sealed bearing with an open bearing with external seal, select and change these parameters. It is relevant to make this comparison **if the integrated seal can replace an external seal.**

Open bearing with external seal? No
Estimated friction torque [Nm]: *In the external seal*

The external seal is assumed to have its contact surface on the same diameter as the inner diameter of the bearing, i.e. the same as the axis
The amount of re-lubrication grease can be adjusted with the re-lube ratio and frequency above. Remember to adjust the grease reduction for sealed bearings to obtain a correct comparison.

Figure 12 Shows the tab called Parameters where the bearing and the running conditions in the assessed case is defined.

The next three tabs contain the result presented in various ways. The first result tab shows the result for the specific studied bearing size and this tab is shown in Figure 13 for a fictive case. Some of the text in the tab is adjusted after the case, for example for which geographic region the potential environmental impact from electricity consumption represents, how many bearings the calculations are for and the difference in percentage between sealed and open bearings. A text is written in connection to the graphs telling how many kilometers by car the potential savings correspond to. This text is supposed to set the CO_2-emissions in relation to something and to make them more understandable.

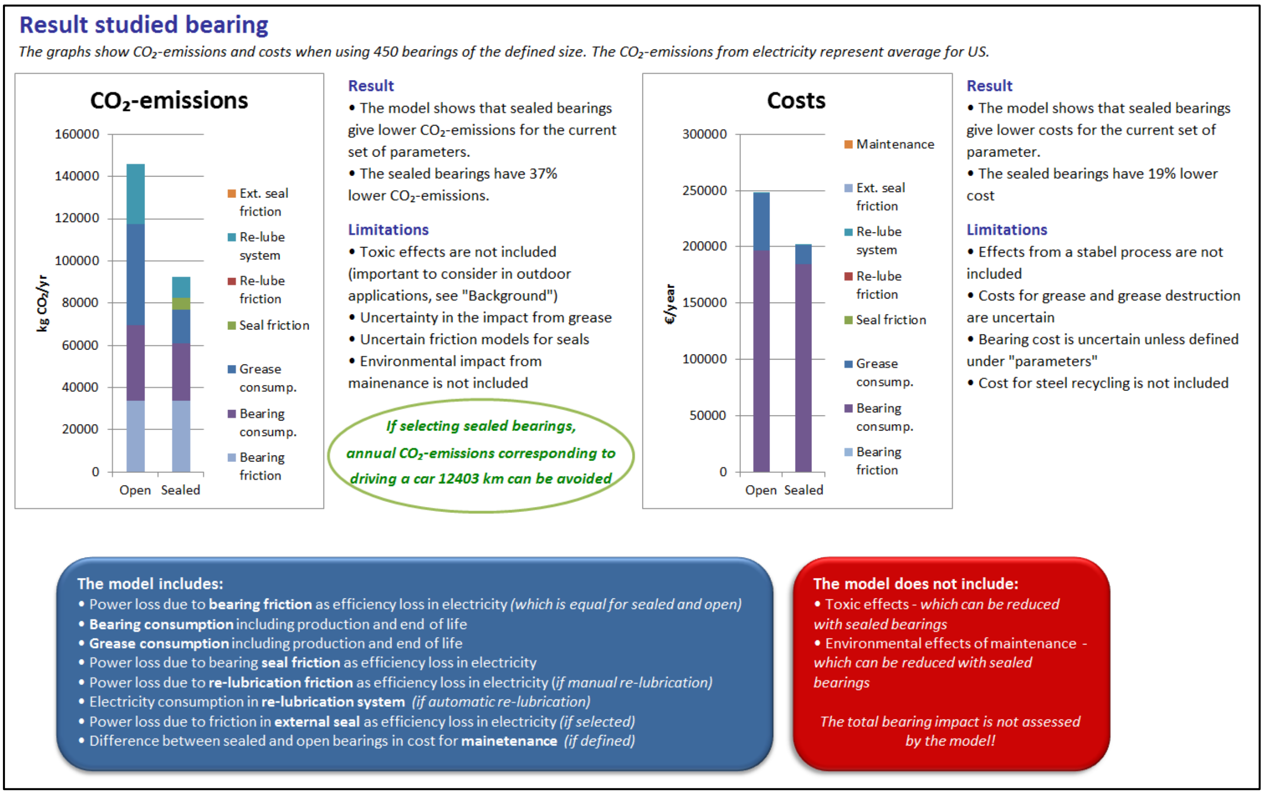

Figure 13 Shows the first result tab for a case set up with fictive parameters.

In Figure 14, a part of the second result tab is shown. In the figure some graphs are removed due to lack of space. This tab is supposed to show how the result and the impact parameters varies over the bearing bore diameter.

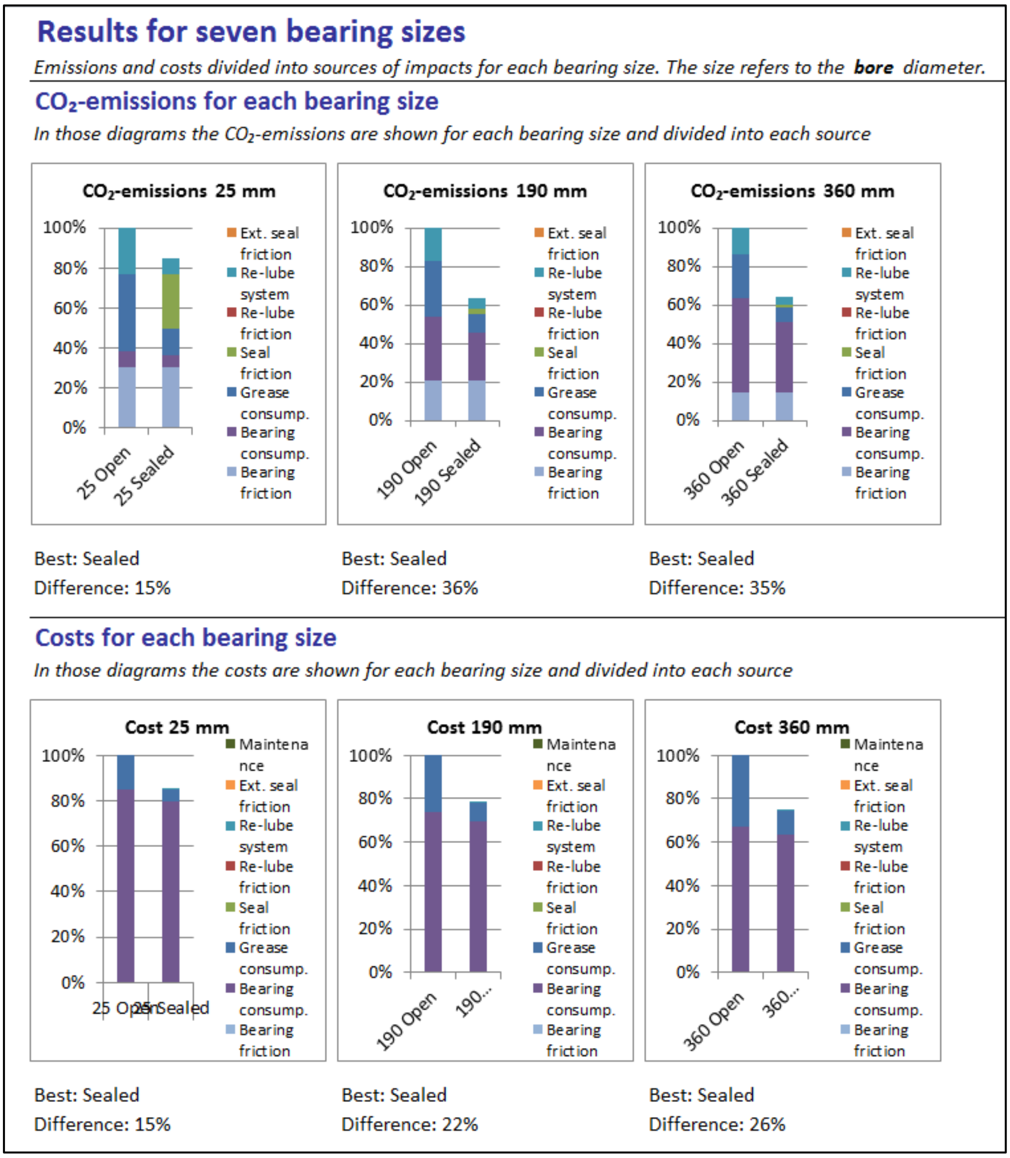

Figure 14 Shows the second result tab for a case set up with fictive parameters. In the real tool, there are graphs for seven bearing sizes but four of those are removed in this figure.

Figure 15 shows the content in the third result tab where the total impact for the two cases are plotted as a function of the bearing bore diameter. These graphs are supposed to illustrate how total impact varies and in some cases it can illustrate if a break-even point exists for the size between the sealed and open bearings.

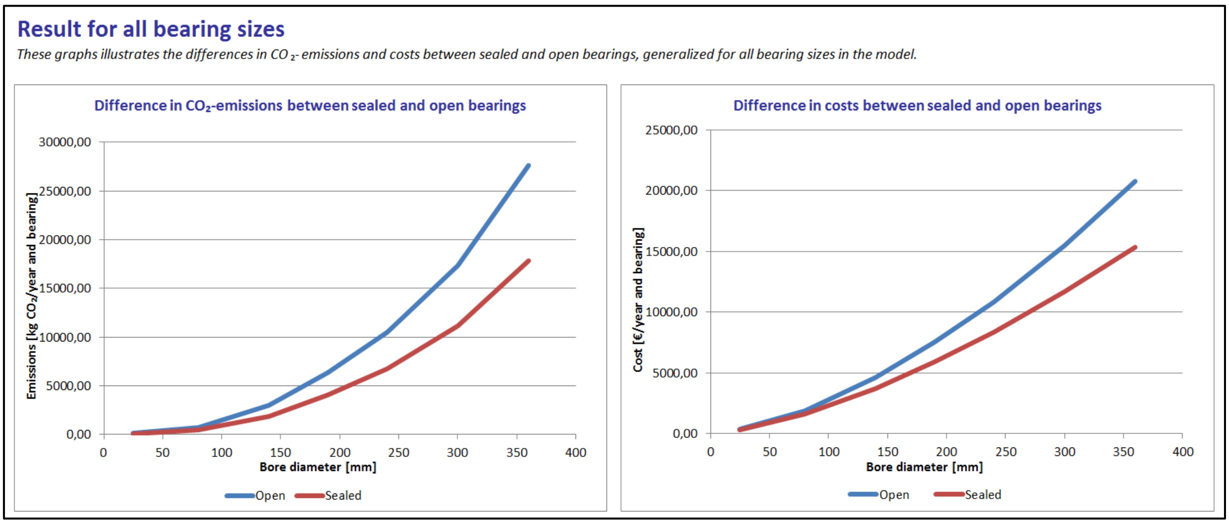

Figure 15 Shows the third result tab for a case set up with fictive parameters. The results for the seven bearing sizes are in this tool plotted as a function of the bearing bore diameter.

5.3.1 Testing of tool

The tool has been tested with data representing bearing applications of different characteristics. The data is based on approximations by experts.

In the first test, the data represent an application with high load, low speed and high contamination which leads to high grease usage. The test results are shown in Figure 16.

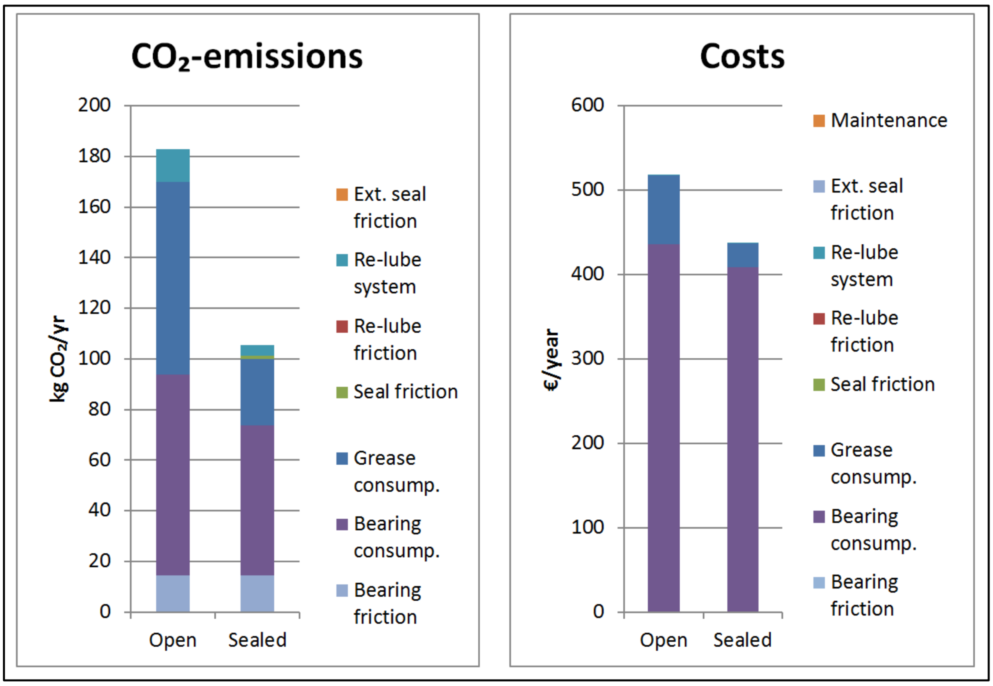

Figure 16 Result for calculations of CO2-emissions and costs when one bearing is used in the first test application.

The second test represents an application with medium rotating speed and high load for which the results are shown in Figure 17. In this case, manual re-lubrication is performed.

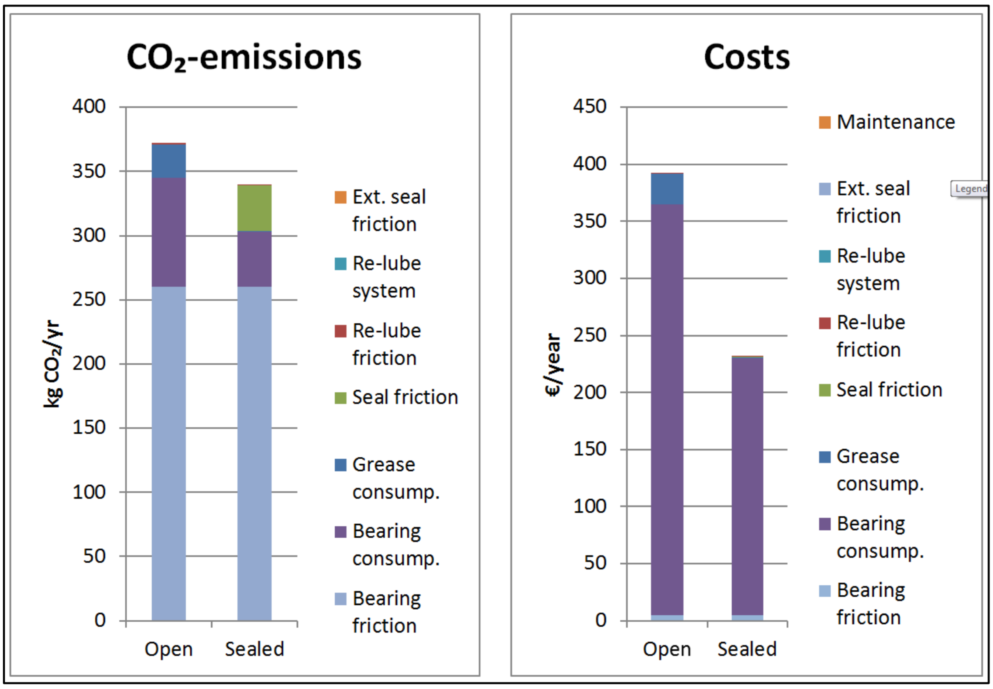

Figure 17 Result for calculations of CO2-emissions and costs when one bearing is used in the second test application.

In Figure 18, the results from testing the tool with data representing an application with high rotating speed and high load. This application has less running hours per year and a smaller bearing size than the previous applications.

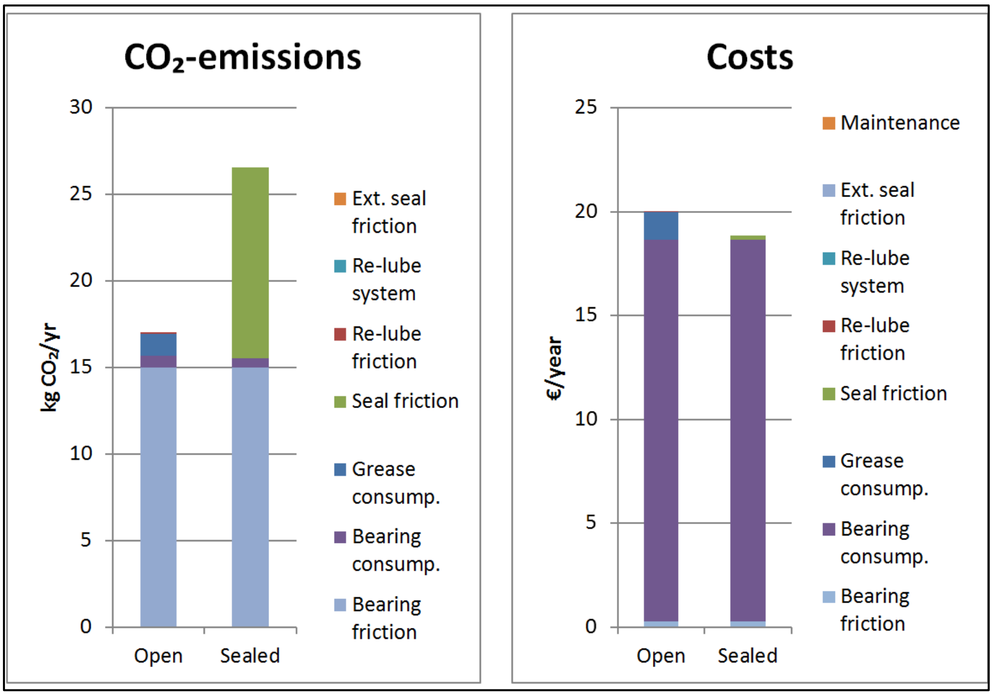

Figure 18 Result for calculations of CO2-emissions and costs when one bearing is used in the third test application.

5.3.2 Evaluation of tool reliability

The tool has been evaluated and tested together with product developers and engineers working with market communication. The evaluation had two purposes, the first is to evaluate the reliability in the model and the second is to evaluate the potential usage. Feedback and suggestions from the testers have been taken into consideration in the tool development and functions have been adjusted after discussions.

The result from the tool reliability evaluation is presented in this section. In order to evaluate the tool, the certainty in the data used for the impact factors, described in *4.3.3 Impact factors*, is evaluated as well as the impact parameters, described in *4.3.4 Impact parameters*. In Table 4 below, the certainty of the impact factors used in the tool is evaluated based on the system boundaries and the data quality.

Table 4 Evaluation of the environmental impact factors used in the tool

Impact factor	Certainty	Comment
CO_2 from electricity	High	The impact factor for each geographic region is based on the electricity mix and grid losses are compensated for. The data comes from PE international and the certainty is considered high.
CO_2 from grease production	Low	Certain data has not been possible to collect within the time limit of this study.
CO_2 from grease end-of-life	Medium	The certainty in the data is high but due to limitations in the model it is not possible to select either scenario or geographic region.
CO_2 from bearing production	High	The data for bearing production was collected for a specific ball bearing and not for a roller bearing. Since the manufacturing processes differ between ball bearings and roller bearings, this means that the certainty in the impact from manufacturing processes might be low. However, since it is shown that most of the potential environmental impact from bearing production comes from the steel production and the bearing weight is used as scaling factor, the certainty is considered high.
CO_2 from bearing end-of-life	Medium	The steel is assumed to be recycled to 75%. The certainty is considered high for an average case in Europe but it might be different for at specific case since it not is possible to specify geographic region or recycling rate.

In Table 5, the certainty of the cost factors used in the tool is evaluated based on the system boundaries and the data quality.

Table 5 Evaluation of the cost factors used in the tool.

Cost factor	Certainty	Comment
Electricity cost	Medium	The electricity cost is based on the average cost for industries in Europe consuming over 20 GWh/year. It is not possible to select geographic region or consumption level. If the system boundaries hold for the studied case, the certainty is high, otherwise it is medium. The user can adjust the price manually to raise the certainty.
Grease cost	Low	The grease cost is strongly dependant on the customer. The built in value is for a customer buying large amounts of grease and if this is the case the certainty is high. The user can change the grease cost manually to raise the certainty.
Grease disposal cost	Low	The grease disposal cost is based on what a customer pays for grease waste destruction and the amount of grease they add to the bearings per year. It is thus not the price for grease waste destruction and the uncertainty is high.
Bearing cost	Low	The bearing cost is based on values from SKF's price list which are adjusted to fit a power function. The prices are supposed to represent an average bearing of the size, but since the prices not only depend on the size but also on the bearing characteristics, this is a rough approximation. The user can define the price for the studied bearing and in that case the certainty is high, but for the approximated value it is considered low.

The result from the evaluation is that the certainty for the CO_2-emissions is higher than the certainty from the cost calculations. The main reason for this is that all cost factors are highly dependent on the specific customer and the geographic region. In order to raise the certainty, the model has to be more complex and include further parameters. That might help someone working with market communication, but for a product developer a general case is of interest.

For the impact parameters, the way of entering the input data, calculations of impacts and methodology scaling for other bearing sizes are evaluated in Table 6.

Table 6 Evaluation of the robustness of the impact parameters and the calculations in the tool.

Impact parameter	Robustness	Evaluation and comments
Bearing friction	High	The bearing friction is based on the formulas in SKF general catalogue. The in-data is the bearing size. The methodology is generally accepted and the robustness is therefore considered high.
Grease consumption	Medium	Grease consumption is entered as amount of grease per open bearing and year, as well as how much the grease can be reduced when using sealed bearings. When testing the tool, some users have claimed difficulties in estimating the grease consumption per bearing, but when developing the tool, no better methodology has been found.

		The grease consumption is scaled after the bearings width and outer diameter which seems to be fair since the grease consumption depends on the bearing size. To get a better approximation, the inner diameter could have been included as well.
Bearing consumption	High	The input data for bearing consumption is the bearing service life which is most likely known by the user. The service life gives the number of bearings used per year in the application and the bearing weight is used as a scaling factor. The methodology for this impact parameter is considered good.
Seal friction	Medium	No input data is needed for the seal friction but the bearing size. The certainty in the seal friction torque formula has not been possible to confirm in this study. The robustness is therefore considered medium.
Re-lubrication friction	Medium	The input data for re-lubrication friction is the re-lubrication interval which is only entered if manual re-lubrication is selected. It is most likely that the user can approximate the re-lubrication interval. The certainty in the formula for re-lubrication friction torque has not been confirmed in this study and it may be too simple. The robustness is therefore considered medium.
Re-lubrication system	Medium	The in-data for the re-lubrication system is the installed power in pump, a load factor and the number of bearings that are re-lubricated. The parameter that might be difficult to estimate by the user is the load factor. The used formulas are considered certain and the scaling factor is the grease consumption which seems to be reasonable.
Maintenance	Low	The user has the option to specify estimation on potential cost savings in reduced maintenance when using sealed bearings. This is claimed to be difficult to estimate by several potential users. The scaling factor is the bearing inner diameter which might not be the best approximation since it is likely that the maintenance cost not only depends on the bearing size.
External seal friction	Low	The input data for the external seal friction is the estimated friction torque in the external seal. This is claimed to be difficult to estimate by almost all potential users. When scaling the external seal friction, it is assumed the friction formula is on the same form as for the integrated seal and that a constant has the same value as the integrated seal, which not is validated. Therefore, the calculations are considered uncertain and the in-data is difficult to estimate.

The result from the evaluation of impact parameters is that the model gives an overall good picture of the potential impacts. As for the impact factors, the reliability is higher for the potential environmental impact than for the cost calculations, especially when it comes to the scaling since it is difficult to generalize the costs.

5.3.3 Evaluation of tool usage

The result from the evaluation of the tool usage is presented in this section. Overall, the engineers that have been asked about the tool usage have all been positive and they have claimed that they would use the tool.

As described in *4.3 Methodology for development of LCA-based tool*, the tool is developed for two different usage areas; market communication and product development. A contradiction in the requirements of the tool by the two groups of potential users is seen during the evaluation. Usage for market communication sets higher demands on usability and simplicity while usage in product development sets higher demands on flexibility. For product development, as many alternatives as possible are desired, but within market communication one wants to reduce the selection opportunities. The result is a compromise between the desires.

The methodology to solve this has been to select the market communication as the primary usage area; this means that the result you first see is adopted for a customer. When a product developer wishes to use the tool, the person can go in into the hidden tabs and achieve a greater understanding, it is assumed that the product developer can spend more time to understand the models. One good option can be to create two versions of the tool, one for each user group. In the version for market communication some graphs and features can be removed.

Some aspects that arose during the evaluation, including the methodology for solving the issues, are discussed below.

When using the tool for market communication, it is important to get a quick understanding of the functionality, the included factors and the results. It was suggested that a flow chart should be used to describe what is included. That flowchart was created and can be seen in Figure 11, page 33.

Another aspect was that the limitations have to be stated clearly together with the results. Due to this aspect, the limitations of the tool are stated clearly in red boxes and repeated on several tabs. This raises the credibility which has to be high when communicating to the market.

Product developers desire a tool that is flexible with many additional functions. This is partly solved through the possibility to change the constants in the functions and change the impact factors. It is also solved through comments and explanations of the calculations so that the user can adjust the model if desired. To raise the flexibility even more one could have created another hidden tab in which even more functions were included, this is not done within the project.

One potential usage in the area of product development can be as a part of decision basis in the development of new seals. When developing seals, there might be tradeoffs between seal closeness resulting in grease reduction and seal friction and since the tool illustrates the tradeoff between the seal friction and grease usage it can give additional aspects to the development.

For future usage, it could be possible to involve the models into bearing selection tools. Plans exist for developing new methodologies for bearing selection not only based on the traditional methodologies. One option could be to include the environmental aspects in the bearing selection process which would raise the awareness of the potential environmental impact.

The results that illustrate the differences between bearings sizes were not found useful by any user group. When generalizing the parameters for different bearings sizes you create scenarios that perhaps will never exist. It is rarely of interest to compare the running conditions for one bearing of a specific size operating in one application with the same running conditions for a bearing of another size. From the perspective of product development it would instead be of interest to be able to vary other parameters, for example the seal friction to evaluate how much it has to be reduced to reach a break-even point. For the usage in market communication you are most likely interested in assessing the specific case in the application.

Overall positive feedback has been given when testing the tool. It was claimed by one engineer that the tool fills a knowledge gap and assesses issues that haven't been assessed in this way before. Many suggestions and judicious feedback has been expressed which is taken as a sign on that the tool will be used and that there is a need for it. It has a good potential for spreading knowledge about the potential environmental impact and can function as a wake-up call.

6 Discussion and conclusions

The main part of the discussion is related to the research questions presented in Section *3 Purpose*. Those were:

1. What are the differences in potential environmental impact when using a sealed SRB compared to an open one in a continuous casting process? The focus will be on the use-phase.
    a. How is the waste water system in the continuous caster affected through reduced grease consumption?
2. Which parameters affect the differences in environmental performance between sealed and open SRB and how are the parameters affected by bearing size and operating conditions?
    a. How can these impacts be related to costs from a customer's perspective?
3. What is the potential usage of a tool for comparison of the differences in potential environmental impact between sealed and open bearings?

6.1 Differences in potential environmental impact when using sealed and open SRB in a continuous caster

This first research question has been investigated through the LCA. The LCA results are clear in the sense that sealed bearings contribute less to global warming potential than open bearings in a continuous caster. This holds for all life cycle phases and all impact categories. The difference in global warming potential between sealed and open is approximately 50% for the whole life cycle, which is sufficient to say that the results are robust. The results are also in line with results from previous studies.

In the continuous caster, the use of a sealed bearing instead of an open bearing, prolongs the service life, reduces the grease consumption and lowers the electricity consumption in re-lubrication pumps. These are all factors that lower the potential environmental impact. The only tradeoff is the increased friction, but since the rotating speed is less than 2 rpm, that friction becomes negligible. Due to these issues it is not possible to come to a different conclusion and therefore, no need for robustness check is seen.

Assumptions and delimitations were made in the LCA study. Transportations and seal friction were excluded and they were assumed to have a low contribution to the total environmental impact. The effect from excluding them is therefore considered minor.

Maintenance is not included in the LCA even though it is noted that it is reduced when changing from open to sealed bearings. The environmental impacts from maintenance in continuous casting are difficult to estimate and allocate to the bearings. Maintenance is performed on several parts of the caster at the same time.

6.1.2 Waste water treatment

One of the major knowledge gaps that the LCA study intended to fill was within the area of reduced grease in the waste water in the continuous caster. However, according to the experts tapped in this study from interviews, the effects of reduced grease would be minor since the process is extremely sensitive for insufficient cleaned water. No potential environmental impact from the waste water system has been included in the LCA calculations.

The inclusion of effects in waste water treatment system wouldn't affect the outcome of the LCA, i.e. that sealed bearings are beneficial in continuous casting. It would rather strengthen that conclusion since the potential gain would be in favor for sealed bearings. This can be concluded since the impact would have depended on the amount of leaked grease, which is smaller for sealed bearings. If the impact from effects within waste water treatment system would have been included, that impact would most likely have been minor compared to for example bearing production, which is the life cycle phase with largest contribution.

The conclusion that the effects of reduced grease in the waste water are negligible only is based on the presented information and it is not precluded that investigating other customers and other bearing application would have given a different the result. The case might be that the cleanliness of the water in other applications is not as critical as in continuous casting. Then it could be possible to make changes that can reduce for example the energy usage in the water treatment process without risking the production.

Despite this, no further investigations within the area of waste water treatment are considered needed when the results in an LCA are as clear as here. If one found a case where the difference in potential environmental impact between sealed and open bearings is not as big as here and a waste water treatment system is present, then it should probably be included.

6.2 Environmental parameters affected by the seal and their dependence on the bearing application

The parameters included in the life cycle based tool are:

- Bearing friction
- Bearing service life
- Grease consumption
- Seal friction
- Re-lubrication friction or re-lubrication system
- External seal

The parameters are discussed one by one in the following sections. From the discussions about the parameters, the main conclusion is that the difference in potential environmental impact depends strongly on the bearing application. The results are different in all tested applications and one cannot draw any general conclusions. Therefore the developed model is highly useful since it allows consideration of different conditions.

6.2.1 Bearing friction

The bearing friction is not affected by the seal; it is included in the model to set the other parameters in relation to something. Depending on the application, the contribution from the bearing friction to the total environmental impact varies. The share of the impact from the bearing friction is higher for small bearing sizes.

6.2.2 Bearing service life

The bearing service life is for many applications prolonged by the seal since the seal keeps contamination out and thus reduces the wear in the bearing. Reasons to why the bearing service life not is affected are for example if the bearing is integrated and the bearing service life is decided by the application service life, or if the bearing is operating in a clean environment where contamination of particles is rare.

6.2.3 Grease consumption

The grease consumption can be reduced for the sealed bearing. The effects of grease reduction, relative to other impact parameters, depend on the amount of grease used in the application. SKF have recommendations for re-lubrication intervals and quantities, but those are not always used by the industry where over greasing may occur.

If a large amount of grease is used in the application, the contribution from the grease to the total potential environmental impact is significant. In this case, if the grease usage cab be reduced by changing from open to sealed bearings, the grease reduction becomes an important parameter in favor of sealed bearings. This is the case in the continuous caster.

The grease consumption is rather complex to estimate since one has to choose between using the recommended value and the actual value which in some cases can be at least ten times higher.

6.2.4 Seal friction

The impact from the seal friction strongly depends on the rotating speed in the application. When the speed is low, the impact from the seal friction is negligible but when the speed gets higher, the potential environmental impact from the seal friction dominates the total life cycle impact. The share of the impact from the seal friction also depends on the bearing size and is higher for small bearing sizes.

The certainty in the seal friction formulas has not been possible to confirm within this study. It would be desirable to verify that the formulas are reliable since the impact from the seal friction is an important parameter.

6.2.5 Re-lubrication friction or re-lubrication system

The impact from re-lubrication depends on whether the re-lubrication is automatic or manual. In the case of manual re-lubrication, the impact originates from the increased friction which occurs in the bearing when adding a large amount of grease. For the tested applications, this impact does not correspond to a large share of the total environmental impact.

In the case of automatic re-lubrication, the re-lubrication friction is negligible since only a small amount of grease is added each time. The potential environmental impact originates in this case from electricity used in re-lubrication pumps. For the tested applications, the potential environmental impact from re-lubrication pumps corresponds to an important but not dominating share of the total potential environmental impact.

The electricity consumption in the pumps can be difficult to estimate since one has to know the load factor in the pumps. It is not probable that the pumps run on maximum load all hours.

6.2.6 External seal

In the developed model, one has the possibility to compare the sealed bearing with an open bearing with an external seal. This is relevant if it is possible to remove an external seal when changing from open to sealed bearings. Due to difficulties in estimating the friction torque in the in the external seal, this function has not been tested.

6.2.7 Excluded factors

It has been noted that in some applications, the maintenance can be reduced when using sealed bearings. The potential environmental impact from maintenance is not possible to estimate with a general model and it is not probable that the user of the tool can estimate the CO_2-emissions related to the maintenance operations. The maintenance is therefore excluded from the model.

6.2.8 Discussion about how the impacts can be related to costs

The developed tool for comparison between sealed and open bearings includes a cost calculation where the potential environmental impacts are translated into costs through for example the electricity and grease cost. The problem with the cost calculation is that it does not include all life cycle costs for the customer; for example the cost for labor is not included.

Another problem with the cost calculation is that the costs strongly depend on the specific customer. The built-in values for the cost factors in the model do not hold for all cases which means that they can be very misleading. The conclusion from the evaluation of the cost calculations is therefore that the model is not complex enough to give a correct picture. SKF already have better tools for cost calculations and it would be better to combine the CO_2 calculations from the developed tool with an existing tool for cost calculations.

However, one conclusion that is possible to draw from the tool cost calculations is that the relative values for costs do not correlates to the potential environmental impact. This is seen clearly in Figure 14 Section 5.3 where the upper graphs show CO_2-emissions and the lower graphs show costs, the cost columns are dominated by the bearing cost while the CO_2 columns are dominated by several parameters. This holds especially true for electricity. In the cases where the seal and bearing friction dominate the potential environmental impact in terms of efficiency loss in electricity, the cost calculations are not dominated by the electricity, but by bearing consumption.

6.3 Discussion about potential usage of the tool

The tool is developed for two different usage areas; market communication and product development. Discussions have been held with potential users from both groups and they all claim that they would use the tool, although the way it is presented might need to be modified. The potential usage in the two areas is discussed in the following sections.

6.3.1 Potential usage in the area of market communication

After discussions with engineers working with market communication, it seems likely that the tool could be used for market communication. In that case, the tool would probably need to be presented in a different way; two possible ways of presenting it are presented.

SKF have several tools on the internet for calculations of for example costs. The model developed for calculations of potential environmental impacts for sealed and open SRB could be integrated into that tool. In that way, the customers can go in and set up their own scenario. In this way, more focus could be paid to the environmental aspects in a purchasing decision and it would be completely in line with SKF's BeyondZero strategy.

Another way of using the tool for market communication could be through the development of a Smartphone application. The model can be presented in a relatively simple way and the result could be showed in graphs, as in Excel.

As stated in Section *1 Introduction* SKF uses environmental arguments in market communication and this tool could definitely be a part of that environmental work. The information is detailed but, as stated in Section *2*.2.1 LCA for marketing in environmental management it is possible to effectively communicate, since SKF operates within business to business relationships.

Using the tool for external communication can result in customers making selections based upon environmental considerations. It can also make the customers more aware about the sources of their potential environmental impacts, for example from grease consumption. Then the customers know how they can affect the potential environmental impact. This would also be in line with the environmental management strategy product differentiation.

6.3.1.1 Tool reliability

When communicating environmental work to the market, reliability is of the highest importance. It is therefore important that everything is approved and that the company communicating it is confident with the results. The tool is developed for usage together with customers but it contains limitations and uncertainties in the built in data and calculations. Some of the data is generalized and it is not certain that the data is possible to generalize in that way. The question is whether the reliability of the results is high enough or if further investigation is needed for approval.

When modeling the reality, as you try to do in a tool like this, it is not possible to cover all factors, the reality is simply too complex. But to get closer to the reality you can use more complex models and spend more time on finding data sources, so what it comes to in the end is a tradeoff between time and certainty.

In the developed model, there are limitations and uncertainties but the model might be appropriate to use anyway if presented in a correct way. This is done through stating limitations clearly together with all results and highlighting them. Since the user has to read the instructions to understand how the tool works and make approximations when setting parameters he becomes aware that the model not is precise. The purpose with the tool is not to give precise answers, rather to give a basis for discussions.

Another aspect when communicating to the market is that the possibility to use the information in a misleading way has to be managed. When using and presenting the results, one has to be aware of the system boundaries. Since the risk for misleading usage of results exists it has to be managed through for example educating potential users on how they should to use the tool.

It is concluded that the tool can be used in a credible way by SKF, for market communication, if the engineers are well educated on the use of the model, and if they set up the scenario together with customers. In this way, the customers become aware of the system boundaries and the risk for being abused for greenwash is minimized.

6.3.2 Potential usage in the area of product development

The second potential usage area is within product development. Through using the tool internally in the product development, one might identify potential areas for environmental improvements of future products. The product developer can learn about the potential environmental impacts related to bearings and become more aware about which improvements that can be done.

Potential improvement areas could for example be the development of low friction seals, biodegradable grease or even longer bearing service life. Through using the model, the product developer can also learn about how the environmental performance of the bearing strongly depends on the bearing application. Due to the recent focus on life cycle thinking among the product developers at SKF, it is likely that they are open for using the tool and they are already familiar with the life cycle perspective. The positive feedback also speaks for that.

As discussed in Section *5.3.3 Evaluation of tool usage* the usage in product development is more for learning about the performance of potential future products, rather than assessing today's products. Therefore the tool must be more flexible. It is not possible to predict which aspects future engineers will be interested in assessing and what they will want from the tool.

Due to this, it is perhaps not suitable to use the same interface as for market communication. One option could be to create two different versions of the tool, where the version for product development can be in Excel. That would allow the users to set up own models and adjust the tool. What is important in this case is to maximize the flexibility.

6.4 General discussions

SKF is a large company operating all over the world and they aim to have a strong environmental strategy. LCA as a methodology have been used within the company for many years and they have gathered much knowledge about their products. In this study, the knowledge from former studies, that mostly considered one specific bearing type, has been generalized and applied for bearing sizes operating under various running conditions. As far as known, this method of modeling a bearing's environmental performance is new.

In this study, a LCA was first carried out in order to learn about the bearing's environmental performance and map the impact factors. Using the LCA methodology facilitated the understanding of the life cycle impact and was a good methodology for structuring the work and the standardized way of conducting LCA helps to avoid overlooking important aspects. When developing the life cycle based tool, it has been essential to utilize life cycle thinking and a systems perspective.

7 Conclusions and recommendations for future work

The main conclusions from the study are summarized here.

- The developed tool can fill an important function in learning and communicating the potential environmental aspects of seals.
  - The tool will most likely be used at SKF.
- The difference in potential environmental impact between sealed and open bearings strongly depends on the application characteristics.
  - In continuous casting, the sealed bearings are better from an environmental perspective mainly due to high contamination, high grease usage and slow rotating speed.
- The most important among the assessed factors for differences in potential environmental impact between sealed and open bearings are bearing service life, grease consumption and seal friction.
  - When the rotating speed is high, the impact of the seal friction corresponds to a significant share of the bearing's total potential environmental impact.
  - Impact from for example increased reliability is not assessed but can be important.
- The seal affects the total environmental performance of the bearing since the affected parameters make a large difference even when including the bearing friction.
- The friction formula for bearing seals is important and it would be valuable to confirm the certainty in it.
- The development of seals with lower friction could bring large environmental benefits in many applications.

Based on the discussion and the conclusions, it is suggested that:

- the cost calculations are removed from the tool since better tools exists for that;
- investigate the external seal friction and develop a calculation model for this that can be included in the tool;
- remove the tabs called result 2 and 3 in the tool since they might be misleading and are claimed to not be of interest from any user group;
- the way the tool is presented/packaged is changed. It needs to be decided whether the tool should be integrated into existing SKF tools or used for a Smartphone application or both;
- connect the model to a bearing database so the user can select between further bearing types;
- extend the model to include other bearing types, for example deep groove ball bearings;
- educate potential users of the tool to give them good understanding and a system perspective;
- development of seals with lower friction;
- develop further similar tools for applying LCA results;

Due to all positive feedback, it seems to be a good method for applying LCA results.

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Appendix I – LCA methodology

LCA is a method to assess the potential environmental impact from a product or service during its entire life cycle, from cradle to grave. Coca-Cola completed what is claimed to be the first LCA in 1970. Since then, the methodology has evolved and standards have been developed. The ISO standard for LCA, ISO14040 came in 1997 and was updated in 2006. The document states that "LCA describes environmental aspects and potential impacts throughout a product's life cycle, i.e. raw material acquisition, production, use and disposal" (ISO, 2006).

LCA is a powerful tool since it helps provide a system perspective for a product or service. It can be used for different purposes, such as marketing, product development or learning about the product. The procedure of carrying out an LCA includes several different steps which might vary between different cases. In this study the method described by Baumann and Tillman (Baumann and Tillman, 2004) is used which also is in line with the ISO14040-14043 standard. The different parts of LCA procedure are described in the following sections, based on Baumann and Tillman unless otherwise stated.

Goal and scope definition

The first step when carrying out an LCA is to define the goal and the context of the study. This will influence future methodological choices. The scope and modeling requirements set the framework for the specific study and includes the following aspects:

- Options to model
    - For example if an average or specific product is assessed
- Initial flowchart including main processes and flows
- Definition of functional unit (FU)
    - The FU is the unit to which all flows in the system are related
    - The FU is an essential part in LCA since it affects the possibility to draw conclusions and the comparativeness with other LCA studies
- Choice of impact categories and method of impact assessment
    - Environmental impacts can be divided into different categories and they can be quantified for different stages in the cause effect chain. For example, when emitting CO_2, it causes global warming, which leads to sea level rise, which leads to flooding and so on. The question is where in the chain to focus.
    - Impact assessment method relates the emissions to the impact categories. If for example global warming is chosen as impact category, all emissions causing global warming are written as CO_2-equivalents. Depending on the scope, these factors can vary.
    - CML 2001 is the chosen impact assessment method
        - Focuses early in the environmental cause-effect chain to limit uncertainties (PEinternational).

- Type of LCA
    - An LCA can be either change-oriented or accounting. In the former, the impact of change in a system is evaluated and in the latter the total impact from a products lifecycle is assessed.
        - The type of LCA impacts the choice of data. Average data is used in accounting LCA and marginal data is used in change-oriented LCA.
    - An LCA can be comparative, i.e. it reflects differences between two solutions. A comparative LCA can be change-oriented or accounting depending on the scope.
- Specification of system boundaries
    - The system boundaries need to be defined in relation to natural system, geography, time horizon and within the technical system
- Data quality requirements
    - Requirements on data quality is specified depending on the scope of the study
- Assumptions and limitations
    - Assumptions and limitations have to be stated clearly since that limits the use of the result. This, together with the system boundaries, affects to a large extent if the study is comparable to other studies.

The goal and scope definition includes procedural aspects as well. Those specifies how reporting will be performed and if a critical review will be conducted. It is also stated which actors are involved.

Inventory analysis

Life cycle inventory analysis (LCI) includes data collection and to relate all flows in the system to the functional unit.

A detailed flowchart is constructed. This has to include all flows of material or energy to, within and from the system and how they are related to processes in the system. Data for the flows is collected. Since this is a time consuming task, good planning and a clear picture of needed data is essential. The data also need to be validated.

The calculation procedure aims at convert all the collected data to the FU. The system equations are set up to relate different flows to each other.

Allocation

Allocation problems can occur in LCA studies. According to the ISO standard allocations should, when possible, be avoided through system expansion or increased level of system details. If this not is possible, physical relationships between the flows can be a basis for allocation. As a last options, other relationships between the flows can be used, this can for example be the economic relationship between the products.

Life cycle impact assessment

The life cycle impact assessment (LCIA) is the part of the LCA that aims at converting the environmental loads from the LCI into potential environmental impacts. A schematic view of the parts in LCIA is illustrated in Figure 19. As shown, the parts are classification, characterization and weighting.

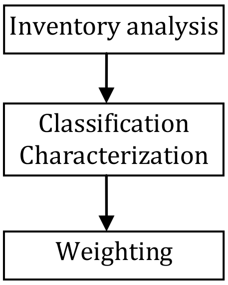

Figure 19 Components in impact assessment in theory (Baumann and Tillman, 2004)

Before starting the LCIA the impact categories need to be defined. The selection of categories is done in line with criteria in the ISO-standard which include for example completeness, practicality and relevance.

The baseline impact categories suggested by CML's guide to the ISO standard includes: (source Baumann and Tillman)

- Depletion of abiotic resource
- Impact of land use
- Ecotoxicity
- Human toxicity
- Climate change
- Stratospheric ozone depletion
- Photo-oxidant formation
- Acidification
- Eutrophication

Classification is the part when all flows are related to impact categories. Note that a flow can be related to more than one category. Equivalency factors are used in the characterization to model the size of the impact for each category. For example CO_2-equivalents are used for all emissions causing climate change.

To be able to compare the impact categories weighting factors can be used. This will not be described further since no weighting will be performed in this study.

Interpretation and presentation of results

Interpretation and presentation of result is strongly dependent of the scope of the study. Several methods for presenting results exist. One example is normalization of results used when presenting results from a comparative LCA. In the method, the impacts of one option are set to be one while the impacts from the others are shown relatively this.

Several methods for analyzing the results exist; some of those are presented here.

- Dominance analysis: Shows which part of the life cycle that dominate the impact
- Contribution analysis: Shows which substance that contribute most to the impact

- Break-even analysis: Is used to investigate trade-offs in environmental impact
- Testing robustness: Since uncertain and approximate data often is used in LCA, robustness of results needs to be checked. This can be done through for example uncertainty, sensitivity or variation analysis

Critical review

In some cases, a critical review is performed for the LCA by a third party. This can be done in order to raise the credibility of the results, get expert support, handle confidentiality issues or involve interested parties.