Life Cycle Assessment of a Roadheader MB650

Master thesis

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Leoben, 11. 2016

Affidavit

I declare in lieu of oath, that I wrote this thesis and performed the associated research myself, using only literature cited in this volume.

Leoben, 11.2016

(Simon Reith)

Forewords

First, I want to say thank you to my supervisor Mag. Karin Tschiggerl for her support, advice and also for her critical reviews which made my master thesis to what it is now. Her door was always open for me, even though I sometimes dropped by without an appointment and she was busy with her own projects. Furthermore, I want to thank her colleague Mag. Milan Topic who gave me an introduction to Umberto NXT and supported me during the whole modelling time with his knowledge.

This master thesis would not have been possible without Sandvik Mining and their endeavor to provide master theses which are related to practice. In particular I would like to thank my supervisor in Sandvik Mining and Construction Dipl. Ing. Egmont Lammer for the supportive meetings and his efforts to deliver all the data I needed. I would also like to extend my gratitude to his colleague Dipl. Ing. Günther Weissmayr for helping me out with the sometimes needed detailed information.

Special thanks to my friend Nicole Spreitz for the infinite hours she spent to proofread my master thesis. The critical reviews but also her temporal flexibility made it possible to finish my documentation in time.

My journey started in 2009 when I expressed my wish to my parents to go to the university. Since this moment my parents were always the save haven when the studies were getting difficult or when I needed family support. Without the help and care of my family I might not have come this far. Sincerest thanks to all my family.

From the bottom of my hearth I want to express my gratitude to my girlfriend Eva who supported and motivated me during my studies. Although our relationship was affected a little by the lack of time during the working process of the master thesis, it was with her support and continuous encouragement, that I kept going. Through her know-how about scientific writing I was able to acquire skills of how to properly make tables, graphs but also how to quote correctly. Thank you.

With deep gratitude,

Simon Reith

Kurzfassung

Ein gestiegenes Umweltbewusstsein der westlichen Bevölkerung und Regierungen in den letzten Jahren führten zu neuen und strikteren Umweltzielen und entsprechenden Gesetzen. So ist sich auch Sandvik Mining and Construction ihrer Verantwortung gegenüber der Umwelt und ihren Mitarbeitern bewusst und arbeitet stetig daran, ihren ökologischen Fußabdruck zu minimieren. Diese Ökobilanzierung soll als Basis für zukünftige Umweltaktivitäten dienen und langfristig die Umwelteinwirkungen reduzieren.

Basierend auf den internationalen Standards ISO14040:2006 und ISO14044:2006, ermöglicht es die Methode der Ökobilanzierung, die Umwelteinwirkungen, verursacht von der Herstellung bis zum Lebensende eines Produktes, zu evaluieren. Ziel dieser Ökobilanzierung ist es, die Umwelteinwirkungen der Teilschnittmaschine des Typs Miner Bolter 650 während der gesamten Lebensdauer zu evaluieren und den unterschiedlichen Lebensphasen zu allokieren. Die gesamte Lebensdauer wird in folgende Phasen unterteilt: (1) Rohstoffe, (2) Herstellung und Montage, (3) Transport, (4) Nutzung und (5) Entsorgung. Basierend auf den Ergebnissen werden Einsparungspotentiale lokalisiert und wenn möglich als Alternativszenario simuliert. Die Software Umberto NXT Universal in Kombination mit der Datenbank GaBi ermöglicht es, die Lebensphasen aber auch nachgelagerte und vorgelagerte Prozesse wie die Herstellung der unterschiedlichen Materialien der Teilschnittmaschine zu modellieren.

Hauptverantwortlich für die Umwelteinwirkungen ist die Nutzungsphase des MB650. Eine Detailbetrachtung dieser Phase zeigt auf, dass die Prozesse zur Stromerzeugung die potentiellen Umweltschäden in dieser Phase dominieren. In zwei alternativen Szenarien wird der Strom Mix im Jahre 2020 und 2030 simuliert. In diesen ist der Anteil an Erneuerbaren an der Stromerzeugung signifikant höher. Die Resultate dieser alternativen Szenarien verdeutlichen das ökologische Potential von Stromerzeugung durch Photovoltaik, Windkraft, Wasserkraft und Biomassekraftwerken. Des Weiteren wird auch die Lebensphase der Rohstofferzeugung und der Herstellung/Montage im Detail analysiert. Diese sind aufgrund der limitierten Datenbankeinträge im Detailierungsgrad und der Genauigkeit eingeschränkt. Als Empfehlung für zukünftige Ökobilanzierungen und umweltbezogene Aktivitäten, sollte dennoch der Herstellungs- und Montagephase oberste Priorität eingeräumt werden, da diese Phase relativ einfach durch Sandvik beeinflusst werden könnte.

Abstract

Purpose The increased environmental awareness of the western population and public administration has resulted in more ambitious environmental targets and laws in the last few years. Sandvik Mining and Construction is aware of its product responsibility and already decreasing its environmental impacts through various activities. This life cycle assessment serves as a basis for further environmental activities to increase the ecological efficiency.

Method Based on the International Standard ISO 14040:2006 and ISO 14044:2006 the life cycle assessment offers a way to evaluate the environmental impacts of a product regarding all life cycle phases, from the cradle to the grave. Main objective of this master thesis is to identify the environmental impacts of a roadheader Miner Bolter 650, allocate these impacts to the various life cycle phases and processes, and optimize the ecological efficiency. Furthermore, these environmental improvements are simulated as alternative scenarios. The total life cycle is separated into the following phases: (1) raw material, (2) manufacturing and assembly, (3) distribution, (4) usage and (5) disposal and recycling. The software Umberto NXT Universal makes it possible to model the LCA and the GaBi database provides information and data about additional processes such as the manufacturing of the materials or recycling processes.

Results and discussion The impact assessment shows that the “usage” phase is responsible for the major environmental impacts in all categories. A detailed phase assessment identifies the electrical power generation as main contributor in the “usage” phase followed by the impacts caused by the spare parts. Two alternative energy supply scenarios are assumed to determine the changes on the impacts categories and to analyse the environmental potential of power generated by renewables. Furthermore, the “raw material” phase and the “manufacturing and assembly” phase are assessed in detail. The level of detail of the “manufacturing and assembly” phase assessment is reduced through limited database entries. A recommendation for environmental improvement is to decrease the electrical power and heating consumption of the “manufacturing and assembly” phase on an annual base. If extensional databases are purchased a future LCA should focus on the “manufacturing and assembly” phase in detail and increase the level of accuracy because the Australian grid mix as biggest impact factor cannot be influenced by Sandvik Mining and Construction.

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List of Abbreviations

ADP	Abiotic Depletion Potential
CH_4	Methane
CO_2	Carbon Dioxide
FAETP	Freshwater Aquatic Ecotoxicity Potential
GWP	Global Warming Potential
HTP	Human Toxicity Potential
IA	Impact Assessment
ISO	International Organisation for Standardisation
kW	kilo-watt
kWh	kilo-watt hours
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MB650	Miner Bolter of the type 650
MEEUP	Methodology for the Ecodesign of Energy Using Products
MJ	mega-joule
MWh	mega-watt hours
PET	Polyethylene Terephthalate
PO_4	Phosphate
PVC	Polyvinylchloride
RET	Renewable Energy Target
RR	Recyclability Rate
SETAC	Society of Environmental Toxicology and Chemistry
SO_2	Sulphur Dioxide
TAETP	Terrestrial Ecotoxicity Potential

1 Introduction

In the last few years the environmental awareness of the western population and the public administrations has increased in a positive way. Also companies have improved their way in managing their environmental impacts. The reasons for this new environmental thinking are the pressure of the costumers, the environmental awareness of the managers and the responsibility for their employee's health.

In the next few years the industry will see stricter environmental laws due to new environmental objectives negotiated at the Paris agreement in 2015. The proposal of the president states the following:

> Recognizing that climate change represents an urgent and potentially irreversible threat to human societies and the planet and thus requires the widest possible cooperation by all countries, and their participation in an effective and appropriate international response, with a view to accelerating the reduction of global greenhouse gas emissions,…. (Adoption of the Paris Agreement 2015) [1]

As a result of this agreement national governments have to enact national laws to fulfil their environmental targets. One of the latest implemented environmental laws in Austria was the law for energy efficiency in 2014. The objective of the Austrian administration is called the 20/20/20 target. The aim is to increase energy efficiency until 2020 by 20 %, reduce the greenhouse gas emissions on a pan-European level by 20 % and a 20 % share by renewable energies in the energy mix. [2]

To achieve these 20/20/20 targets, environmental evaluation tools can help to identify greenhouse gas- and energy-intensive processes and phases. In addition it is possible to simulate alternative scenarios and their effects on the environmental impact. This master thesis discusses the Life Cycle Assessment method in detail.

The Life Cycle Assessment (LCA) is an evaluation of the inputs, outputs and the environmental impacts of a product system or service through its life cycle. In each phase of its life cycle the product is responsible for several environmental impacts, starting from the mining of the raw materials via the manufacturing, to the distribution, to the usage and the disposal. The LCA helps to identify these impacts and provides information for environmental decisions and a basis for further improvements including changes in the mechanical design or in the manufacturing process.

[1] United Nations (2015), p. 1
[2] Cf. Bundesministerium für Wissenschaft, Forschung und Wirtschaft (2014), p. 1

1.1 Initial Situation and Problem Statement

On one hand efficiency classes such as energy-, environment-, carbon dioxide efficiency of machinery are getting more and more important for companies due to environmental awareness. On the other hand new environmental laws force the companies to increase their environmental activities.

One of Sandvik's main objectives is to minimize the environmental impact caused by their products. The LCA offers a basis to evaluate further improvements for the decrease of an environmental impact. Therefore Sandvik has already commissioned LCA studies for similar products for their drilling rig.[3] The drilling rig LCA was processed by Katariina Rouhiainen (2008) and serves as a guideline for this master thesis.

The high complexity of the product system is classified as a possible problem in this master thesis. The product system consists of thousands of different parts and an enormous quantity of different material compositions and alloys. Additionally one of the main problems was to get the required data about the manufacturing process and product operator. Data which were not available through communication with the responsible department or extraction of the operational manual are assumed or approximated by calculations. Furthermore, it is essential to keep a balance between modularity and a holistic approach.

1.2 Goal and Research Question

The goal of this master thesis is predetermined by Sandvik Mining in the master thesis announcement. The main objective is to optimize the ecological efficiency of a roadheader by using a modified LCA according to ISO 14040. Based on a generic LCA-Model for roadheaders as a part of the master thesis in cooperation with Sandvik Mining and Construction the specific roadheader Miner Bolter 650 (MB650) is selected and analysed. Key aspect of the master thesis is to identify optimization potential regarding the energy efficiency by evaluating the product life cycle.

The second research focus is to analyse the current state of research concerning the interdependency of various life cycle phases.

1.3 Methodical Approach and Structure

The methodical approach of this master thesis is divided into five work packages and follows the different phases according to the ISO 14040. The schedule for the different packages is shown below in Figure 1.

After each work package a meeting with the company was arranged to give information about the results of the work package and to discuss further steps and possible changes. The

[3] Cf. Sandvik Mining, Master thesis announcement (2015)

documentation of the master thesis was a continuous process and happened parallel to the other work packages.

The dashed lines in the schedule of Figure 1 also illustrate the iterative process of an LCA. This means it was always necessary to consider changes in the previous steps.

The first work package comprises a literature research about LCAs followed by the first phase of an LCA called “goal and scope definition” which is explained in chapter 2.2 and applied in chapter 3.1. Particularly the level of detail and the system boundaries are defined in this first work package.

The purpose of the second work package is a complete inventory analysis of the reference product. In this stage Sandvik provided data such as material lists, maintenance schedules and assembly plans. However, it was also necessary to make assumptions and calculations. Regarding the “goal and scope definition” of the first work package, all relevant flow of material and energy is considered in this second work package. The inventory analysis is explained in chapter 3.2 and is subdivided into the different life cycle phases.

The third work package deals with the modelling of the system using the software “Umberto NXT Universal” and the database “GaBi”. Furthermore, the impact assessment methodology and the impact categories are chosen and applied. A detailed impact assessment is the result of this work package. Details about the simulation and the modelling are explained in chapter 3.3. Also various alternative scenarios were analysed and described to determine their impact and, more importantly, how exactly the changes effect the environmental impacts.

Results of the third work package are used and interpreted in the fourth work package in chapter 3.4. As a part of the fourth work package a summary and outlook beyond this master thesis and recommendations for further research projects are described in the final chapter 4.

The fifth and last work package proceeded parallel to the other work packages and covers the documentation for the master thesis.

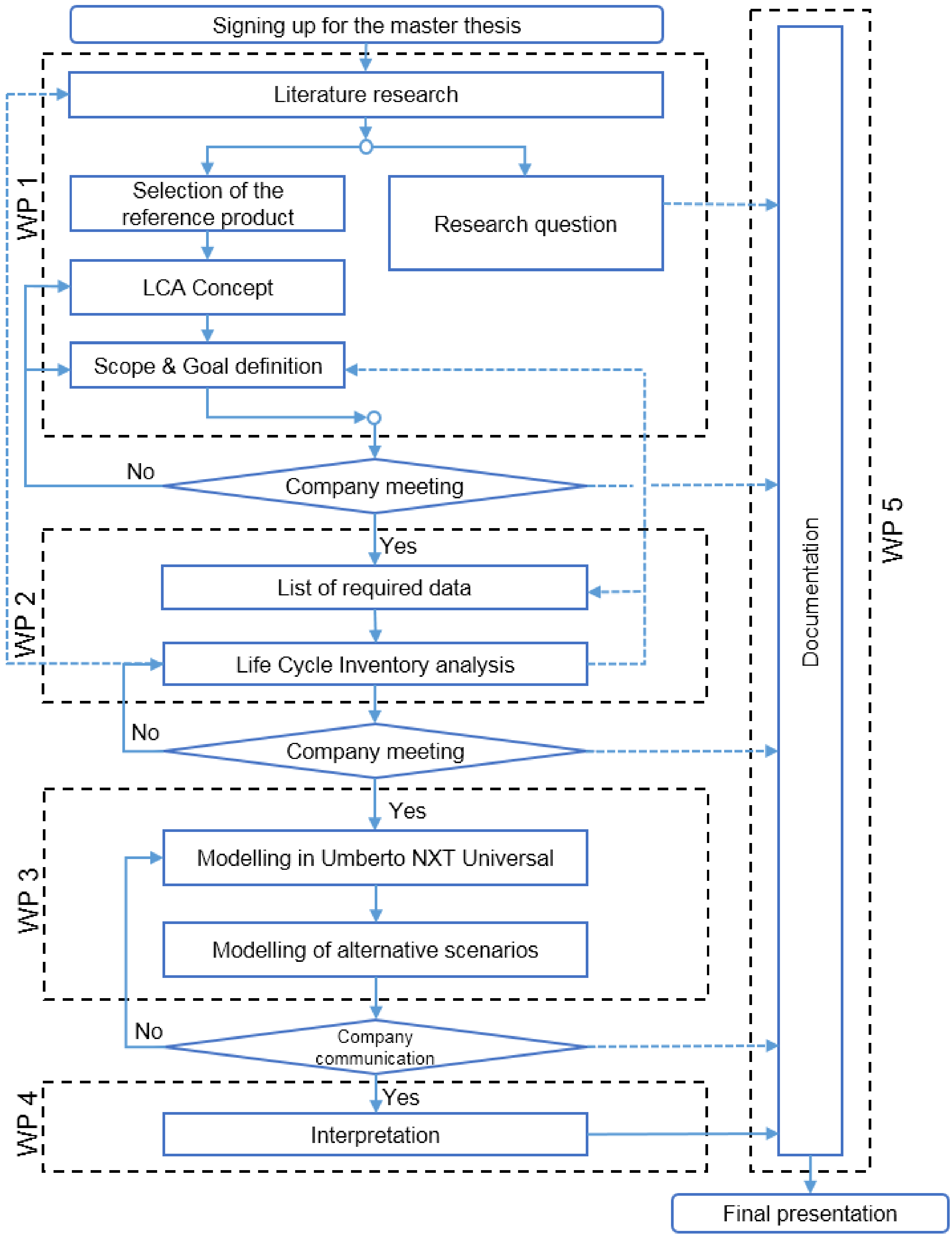

Figure 1: Work packages and working schedule [4]

[4] Source: own figure

2 Life Cycle Assessment

A LCA is used to evaluate and assess environmental impacts through products, product systems or services. Product LCAs differ regarding the considered phases. It is possible to distinguish three variants: (1) gate to gate (2) cradle to gate and (3) cradle to grave.[5] The first two variants analyse just parts of the life cycle of a product. In contrast with the first two variants, the third, cradle to grave LCA, considers all life cycle phases. The difference between the three variants is shown in Figure 2. In this master thesis the focus was on variant (3) the cradle to grave LCA, also called a full LCA.

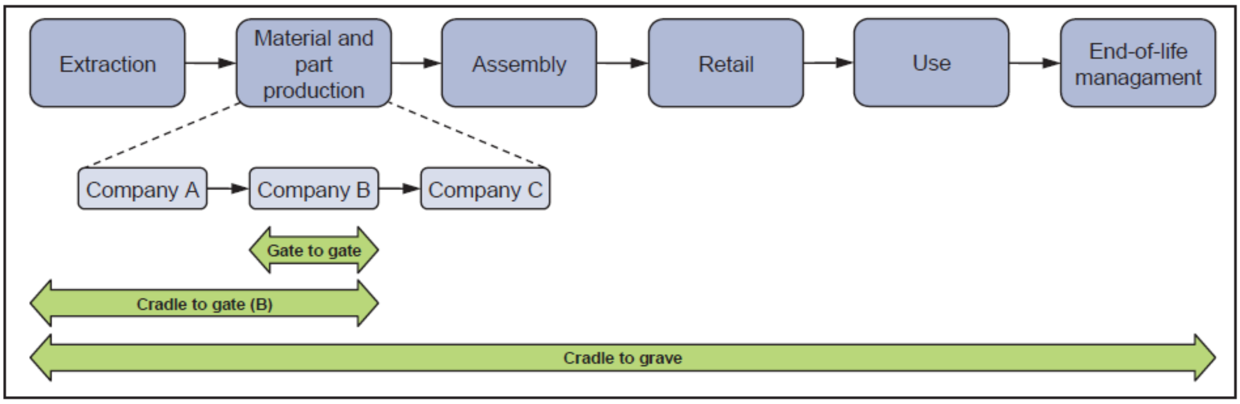

Figure 2: LCA variants, (1) gate to gate, (2) cradle to gate and (3) cradle to grave [6]

A cradle to grave LCA study includes the “raw material production”, “energy production”, the “product manufacturing”, the “distribution”, the “usage” and the “disposal/recycling” phase, which illustrate the whole life cycle of a product. During this life cycle all environmental impacts are identified, recorded and critically processed. Simplified, it is an evaluation of all inputs, outputs and the potential environmental impacts of a product or product system.[7] One main objective of the LCA study is to find options to reduce and prevent these environmental impacts. The used International Standards for life cycle assessment are called ISO 14040:2006 and ISO 14044:2006. Many workovers and advancements have led to these existing standards.

During the 20th century different methods were developed to determine and assess environmental impacts by considering flows of material and energy. In 1991 the Society of Environmental Toxicology and Chemistry (SETAC) hosted a workshop with the objective to structure life cycle assessments. Result of this workshop was the SETAC-Triangle shown in Figure 3. Two years later further development led to the new SETAC-Triangle in 1993. The new

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[5] Cf. JRC European Commission (2010b), p. 96
[6] JRC European Commission (2010b), p.96, fig.12
[7] Cf. Calkins, M. (2008), p. 54

triangle was used as a basis for the methodology of the International Standards for LCAs: ISO 14040:1998, 14041, 14042 and 14043. [8]

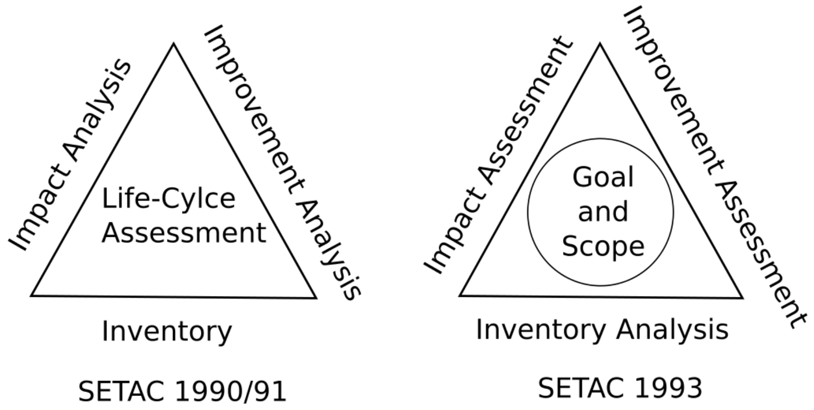

Figure 3: LCA-Triangle by SETAC [9]

In 2006 the technical committee IDO/TC 207 in cooperation with den CEN-Management-Centre overhauled the International Standards ISO 14040:1998, 14041, 14042 and 14043 and created the new versions of the ISO 14040:2006 and 14044:2006. The content stayed almost the same but four standards got compromised into two. The old four standards, for example, all contained requirements in contrast with the new ones. All requirements are collected in the ISO 14044:2006. The links between the old ISO 14040-43 and the new versions 14040 and 14044 are shown in Figure 4. ISO 14040:2006 describes the principles and framework of LCAs, while 14044:2006 describes the requirements and guidelines to conduct LCA studies.[10]

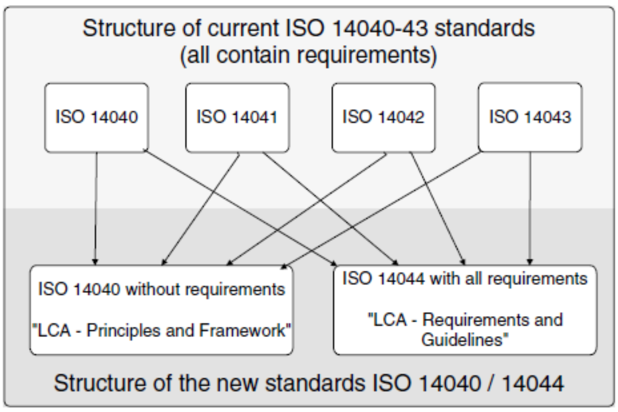

Figure 4: Link between ISO 14040-43 and the new ISO 14040 / 14044 [11]

[8] Cf. Klöpffer, W.; Grahl, B. (2009), pp. 7-9
[9] SETAC; Fava, J. A. et. al. (1991)
[10] Cf. ISO 14044:2006, p. 7
[11] Finkbeiner, M.; et al (2006), p.81, fig.1

2.1 ISO 14040:2006 – Principles and Framework

As explained in the introductions of chapter 2, ISO 14040:2006 describes the principles and the framework of an LCA. This standard can be used for LCA studies and life cycle inventory studies. One of the most relevant guiding principles for an LCA is transparency. To ensure this principle results of the study have to be reproducible and comparable.[12] In addition, it is important to mention that the International Standard is not intended for regulatory purposes or registration and certification.

Basically a LCA can be divided in four phases:

- Goal and scope definition
- Inventory analysis
- Impact assessment
- Interpretation

These four phases and the framework of an LCA are shown in Figure 5. The double arrows between the different stages illustrate the iterative nature of an LCA. This means that the results of one phase can be used for the next phase but it also implies that it is possible to modify boundaries, data requirements, objectives or other assumptions of earlier phases. Details of the different stages can be found in ISO 14040 as well as in ISO 14044. Because they constitute kind of requirements and guidelines, they are described in the following chapter 2.2.

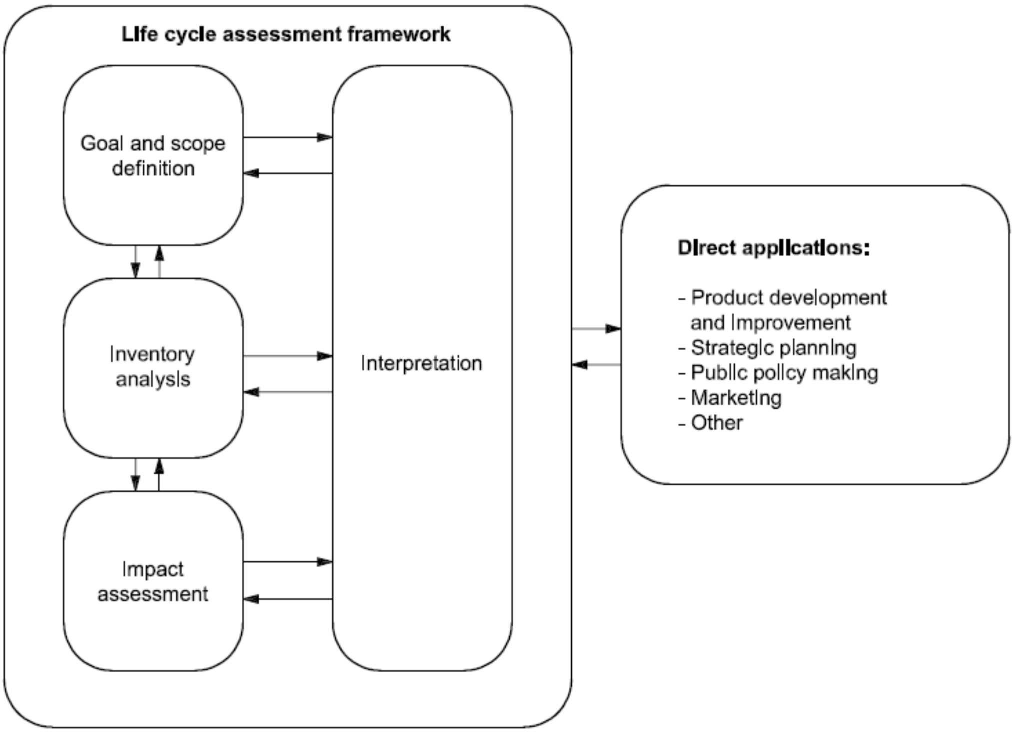

Figure 5: Stages of a LCA [13]

[12] Cf. ISO 14040:2006, p. 15
[13] ISO 14040:2006, p.17, fig. 1

2.2 ISO 14044:2006 – Requirements and Guidelines

As explained in chapter 2 the standard ISO 14044:2006 describes the requirements and guidelines of an LCA. This International Standard does not cover specific methodologies or techniques for the individual phases. This chapter describes the following points: [14]

a) Goal and scope definition
b) Life cycle inventory analysis(LCI)
c) Life cycle impact assessment (LCIA)
d) Life cycle interpretation
e) Reporting
f) Critical review

In the succeeding part these points are elaborated on in further detail.

a) Goal and scope definition

In the phase "goal and scope definition" it is important to determine the reason why the LCA is conducted and what its purpose is. Furthermore, it is necessary to state to whom the LCA is addressed and if the assessment is intended to be published. This point also serves to identify the specific product, the functional unit, the system boundary, data requirements and which method is used for the life cycle interpretation. [15]

b) Life cycle inventory analysis (LCI)

In this phase all required data for the life cycle inventory analysis are collected. For the data inquiry various methods are used for instance calculation, estimation, external sources and measurement. Whatever method is used, it is necessary to document any estimations and calculations as well as to specify the source of the data. As described in chapter 2.1 LCAs have an iterative nature and it is possible to adjust the system boundary during the next stage, the life cycle impact assessment (LCIA). If there are any adjustments it is crucial to keep a record and describe the reasons for them. [16]

c) Life cycle impact assessment (LCIA)

There are no specific methods for the LCIA required in the ISO 14044, but the ISO describes what the method has to include. For example it is necessary to state which impact categories and indicators are used. Moreover, the impact category indicators have to be calculated in this phase and it is required that assigning the results of the LCI to the different life cycle impact categories is possible. [17]

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[14] Cf. ISO 14044:2006, p. 7
[15] Cf. Klöpffer, W.; Grahl, B. (2009), pp. 7-9
[16] Cf. ISO 14044:2006 , pp. 18-22
[17] Cf. ISO 14044:2006 , pp. 23-30

There are various LCIA methodologies known which can be applied: [18]

- CML 2001
- Eco-indicator 99
- Ecological Scarcity Method 2006
- EDIP 2003
- ILCD 2011
- Impact 2002+
- ReCiPe 8
- TRACI 2.1

These methodologies can differ in the covered impact categories, in selection of indicators, and in their geographical focus. [19]

d) Life cycle interpretation

The life cycle interpretation includes the identification of significant parameter based on the previous phases. Additionally, this phase includes an evaluation which considers checks for completeness, sensitivity and consistency. Also conclusions, limitations and recommendations are part of the life cycle interpretation. [20]

e) Reporting

The structure and content of the report of an LCA should allow readers to understand the complexity and interdependency of the study. Therefore, the report has to contain all results, data, methods, assumptions and limitations used during the LCA. If there is the intention to publish the results for a third party further requirements have to be fulfilled. [21]

f) Critical Review

The requirements for methodology, data, interpretation and reporting have to be consistent with the principles. Before being accepted for publication in international scientific journals the article has to be peer-reviewed. There are various options for critical review outlined in ISO 14044. [22]

[18] Cf. Lehtinen, H. et al. (2011), p. 8
[19] Cf. Lehtinen, H. et al. (2011), p. 8
[20] Cf. ISO 14044:2006 , pp. 31-35
[21] Cf. ISO 14044:2006 , p. 36
[22] Cf. Weidema, B. P. (1997), pp. 1–6

2.3 Interdependency of Life Cycle Phases

The main research question of this master thesis is to analyse the interdependency between different life cycle phases. The life cycle assessment method can be used to identify how modifications in one phase influence the environmental impacts of other phases.

Generally a product’s life cycle can be separated into following phases: [23]

- Planning and designing
- Manufacturing
- Transport and distribution
- Usage and maintenance
- Disposal/recycling

Analysation of several product LCA has shown that usually the life cycle phase “product planning” and “designing” is not considered. This could have different reasons. As shown in Figure 6, on one hand the environmental impacts during this phase compared to the other phases are quite low, and on the other hand it is difficult to relate the environmental impacts to the products. For example the used energy in the development department for heating and lighting occur only during the development process. But usually at this moment it is not possible to determine how many units of this product will be manufactured so it is not possible to identify the impact share of one unit.

Figure 6 shows in which phase of a product life cycle the environmental impacts are specified and in which phase they actually occur:

Figure 6: Specified and accumulated environmental impact trend in different life cycle phases [24]

The diagram shows that approximately 80% of the environmental pollution are specified during the designing phase and just 20% during the other three phases. This figure from De Winter et

[23] Cf. PLM-Portal, http://www.plmportal.de/index.php?id=1182 (Retrieved: 14.10.2016)
[24] De Winter; Kals (1994), p. 289

al. (1994) distinguishes between active products and passive products.[25] As an active product a car, for example, distributes its environmental impact of approximately 80% during the usage phase and only 20% in the manufacturing and disposal phase. In contrast a passive product, for instance a beverage bottle made out of polyethylene terephthalate (PET), produces about 64% of its overall environmental pollution when it gets produced and 25% in its disposal phase.

To illustrate the importance of the design phase for the remaining product life cycle phases an LCA study is described in chapter 2.3.1. Particularly the interdependency between the “product design” and “usage” phase is accentuated in this case study.

2.3.1 Case Study: Interdependency of Life Cycle Phases

Marcel Torrent et al. (2011) published an LCA regarding the influence of the mechanical design and the energy efficiency class of induction motors.[26] Subjects in this study were induction motors with a torque output of 0.75-4 kW because they feature the highest room for improvement in terms of energy efficiency. [27]

The study considered one induction motor with the energy efficiency class 1 (IE1) and one with the energy efficiency class 2 (IE2). Furthermore, Torrent calculated one prototype motor which will not be considered in this master thesis. To assess the environmental impacts Torrent used the Methodology for the Ecodesign of Energy Using Products (MEEUP). [28]

In the LCA study the following phases were observed: production, usage, disposal and recycling. Because the weight and the packaging of the two motors are similar the transport and distribution to the customer were not taken into account in this study.

Figure 7 shows that the induction motor IE2 with the energy efficiency class 2 comes off worse than the induction motor IE1 in the “production” phase. On average the IE2 performed in all impact categories 15% to 20% worse than the IE1. The cause herefore might be that used resources for the IE2 motor harm the environment more than those used for the IE1 motor.

[25] Cf. De Winter; Kals (1994), p. 287
[26] Cf. Torrent, M. et al. (2011), p.1
[27] Cf. De Almeida, A. et al. (2014), p.12
[28] Cf. Torrent, M. et al. (2011), p.1

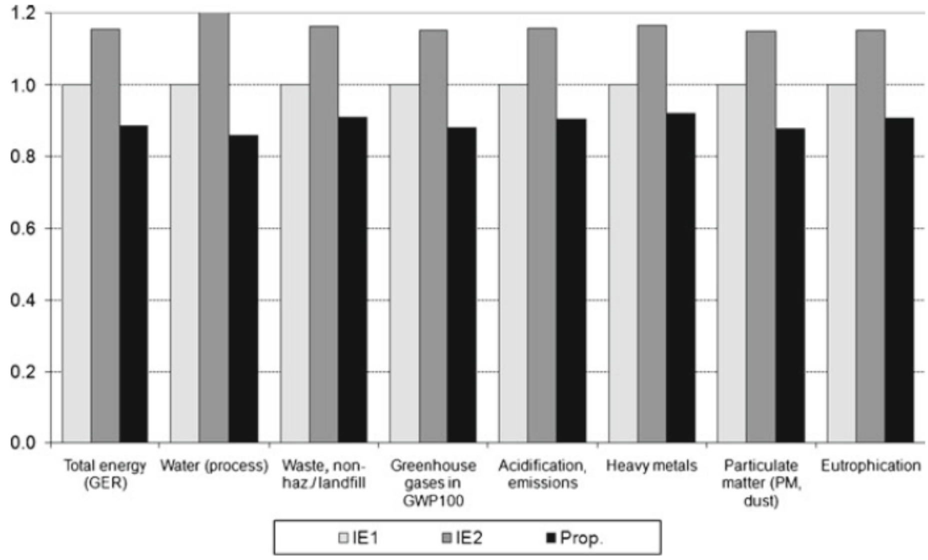


Figure 7: Environmental impact caused by the production phase [29]

However, the motor with the energy efficiency class IE2 performed 20 % to 30 % better during the usage phase which can be seen in Figure 8. A reason for the lower environmental impacts of the usage phase is the lower consumption of electric power. No further data has been published about the disposal and recycling phase.

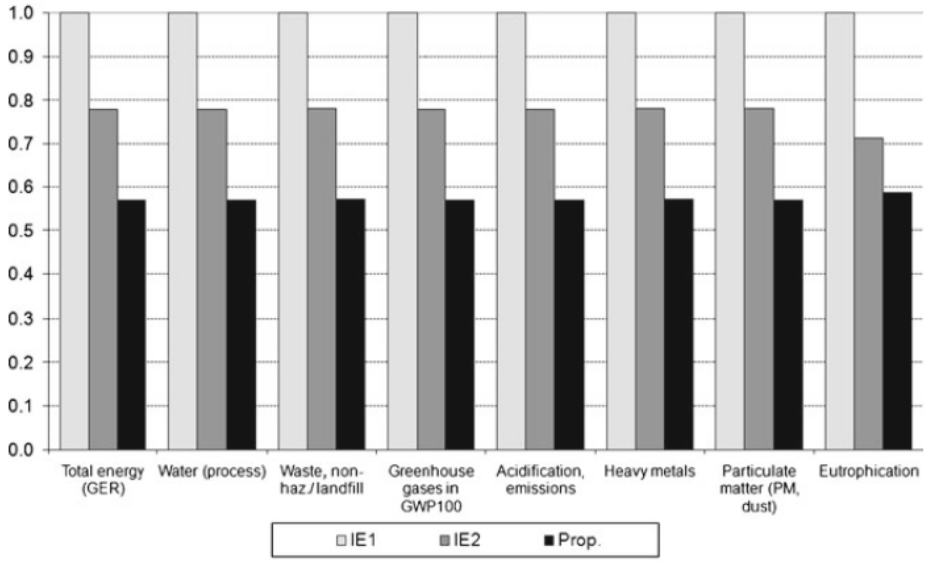


Figure 8: Environmental impact caused during the usage phase [30]

The accumulated environmental impact of the entire lifecycle is shown in Figure 9. The figure shows that the induction motor IE2 performed in all impact categories approximately 10 % to 30

[29] Torrent, M. et al. (2011), p.7, fig. 5 a)
[30] Torrent, M. et al. (2011), p.7, fig. 5 b)

% better than the motor IE1. Referring to Figure 6 this engine would be an active product because the share of the environmental impact in the usage phase outweighed the environmental impact of the production phase. Essential for this lower impact is the higher efficiency degree which reduces the amount of consumed electric power. The energy efficiency of the IE1 motor was calculated and tested by Torrent and was specified with 78 %. In contrast the energy efficiency degree of the IE2 motor was 82 %. This means there is an efficiency gap of 4 %.

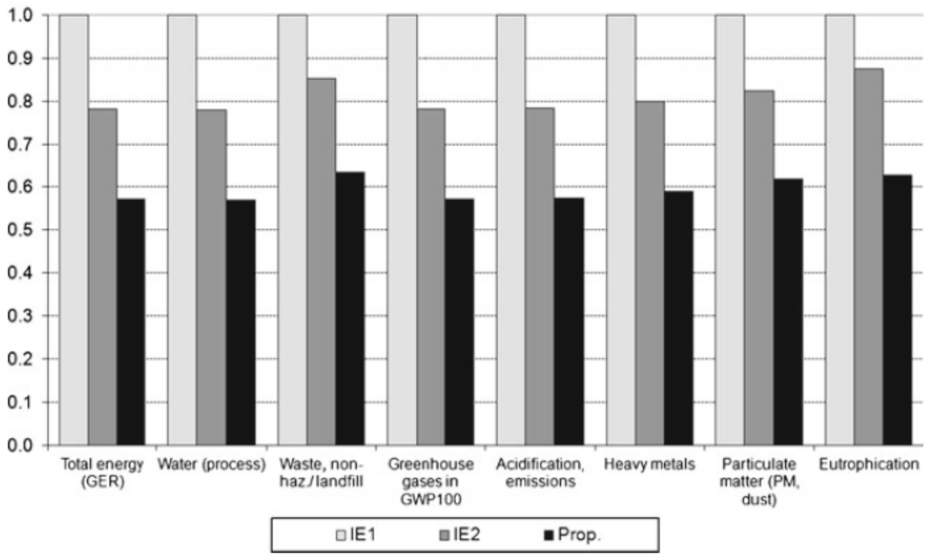


Figure 9: Accumulated environmental impact of the entire lifecycle [31]

This case study was used because it illustrates how changes in the design phase affect other life cycle phases. Additionally, it shows that it is important to keep a holistic view of the product. If the manufacturer would only care about the environmental impacts during the manufacturing phase they would tend to increase the production of the IE1 motor. The holistic view enables the manufacturer to see beyond the edge of their field of activity and allows them to take environmental responsibility for their product.

Electric motors are also part of the MB650 life cycle assessment. However, in contrast to the above discussed LCA the power output and the efficiency degree of the electric motors in the MB650 are much higher. Torrent described in his study the potential energy savings in industrial electric motors as a function of motor output power. All motors used in the MB650 have a power output higher than 30 kW and have therefore a lower potential for energy savings. Nevertheless the electric motors could be a lever to decrease the environmental impacts. Changes about the efficiency degree of the electric motors are not further discussed or simulated in this thesis.

[31] Torrent, M. et al. (2011), p.7, fig. 5 c)

3 Life Cycle Assessment of a Roadheader

Sandvik Mining and Construction is a worldwide leading provider of subsurface roadheaders for various applications in the mining industry, especially in coal mining. In 2015 critics voiced their concern about the coal industry, its part as resource for the worldwide energy supply and the environmental impacts caused by power generation out of coal. Sandvik as an actor within this industry is aware of its responsibility and is engaged in decreasing their environmental impact continuously. The master thesis is part of the continuous improvement and it is the foundation for many further efforts for a responsible usage of natural resources.

Based on the results of the master thesis Sandvik Mining and Construction in Zeltweg can increase their awareness about the environmental impacts of the roadheader Miner Bolter 650 (MB650). In addition to the master thesis the simulation model and the various considered scenarios can be used to develop ideas about possible steps to decrease the overall environmental impact of their products.

As already explained in chapter 2 there are three variants of LCAs. For the MB650 all phases of the life cycle are analysed and considered. This means it is a full cradle to grave life cycle assessment.

For the modelling of the LCA the software “Umberto NXT Universal” was used. It is developed and distributed by the company “ifu hamburg”. The software provides the possibility to visualize the different processes and phases of a product life cycle. Additionally, a database was needed to supply the background data. “Umberto” supports two database providers: (1) ecoinvent and (2) GaBi.[32] For this LCA the Montanuniversität Leoben provided the “Umberto NXT Universal” software and the “GaBi professional” database.

The “GaBi professional” database is the standard database and contains more than 2,400 processes including data from “PlasticsEurope”, “Worldsteel”, “European Aluminium Association” and “Eurofer”. Further, there are twenty extension databases available. They are more specific about one topical field and contain each up to additional 4,600 processes. All the data are developed in accordance with ISO 14044, ISO 14064 and ISO 14025 standards. Examples for the extension databases are:[33]

- Extension database II: Energy
- Extension database VIII: Coatings
- Extension database X: Manufacturing
- Extension database XI: Electronics

[32] Cf. ifu hamburg, https://www.ifu.com/en/umberto/environmental-management/umberto-nxt-lca/ (Retrieved: 15.10.2016)

[33] Cf. ifu hamburg, https://www.ifu.com/en/umberto/umberto-gabi-databases/ (Retrieved: 14.10.2016)

Because these extension databases were not provided it was not possible to consider some specific and detailed materials or pre-processes, and thus further simplifications were necessary. Missing data were documented in the "Inventory Analysis" in chapter 3.2.

3.1 Goal and Scope Definition

As explained in chapter 2.1 the "goal and scope definition" is the first stage of a life cycle assessment. Basically it is the cornerstone for a successful and transparent LCA study. Regarding to ISO 14044:2006 it can be separated into two subsections: the goal and the scope.

The goals and the scope were defined in cooperation with Sandvik.

3.1.1 Goal

In consultation with Sandvik Mining and Construction in Zeltweg several goals were fixed and recorded in alignment with ISO14044:2006.

a) Intended application

   The intended application is to use this LCA as a basement for further environmental improvements. The module-based structure makes it possible to use the modelling for other roadheaders. For this LCA a further goal was to analyse and assess the energy efficiency of the Miner Bolter MB650 and to determine approaches of how to increase this energy efficiency.

b) Reasons for the study

   Main reason for this study was the environmental awareness of Sandvik Mining for their products and their environmental impacts. Sandvik steadily decreases its environmental footprint. Therefore, an LCA of one of their most innovative products was one more effective way to identify improvement potential.

c) Intended audience of the study

   Intended audience of this study is the "Health Safety and Environmental" department of Sandvik Mining and Construction in Zeltweg. Publishing this master thesis for a third party is not planned and thus no conduction of an external critical review will be necessary.

3.1.2 Scope

The required content of the scope is described in ISO 14044:2006 and specifies the LCA regarding the following points:

a) Product system

   Reference product system is a roadheader of Sandvik Mining with the classification "Miner Bolter MB650/248". The number 248 means that it is the 248th roadheader of the type MB650. The roadheader was designed for the Australian subsurface coal mining industry. A special feature of this roadheader type is the integrated bolting unit. Usually there is an additional machine used to drill and set the rock bolts. In consultation with Sandvik Mining the product system is subdivided into two modules: (1) the rock bolting unit, responsible for the drilling and the installing of the rock bolts and (2) the cutting unit, responsible for the cutting of the stone coal, the removal of the coal from the front of the machine and the movement of the Miner Bolter.

This break down of the Miner Bolter into two modules makes it possible to compare future LCA studies with the LCA of the Miner Bolter, even if the other one has no integrated bolting unit. The Miner Bolter MB650 is shown in Figure 10. In addition, a third module termed as “ventilation” is necessary. It is not part of the product system but it is still considered in some impact assessments. The ventilation system is responsible for the exchange of air. Further details are explained in the sub-item d) “system boundary”.

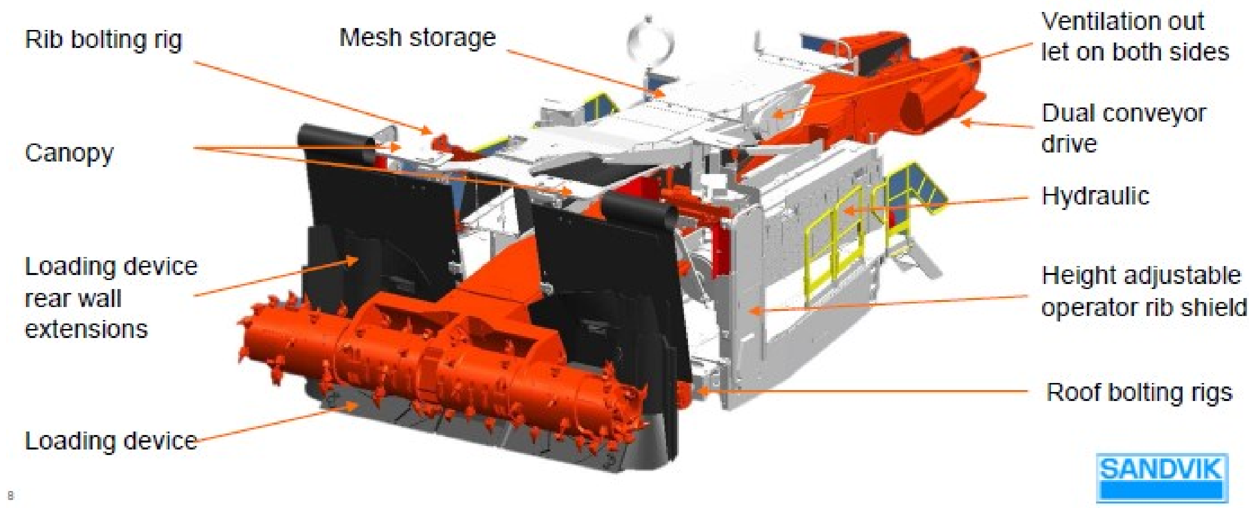


Figure 10: product system - Miner Bolter MB650[34]

b) Function of the product system

The cutting, moving and bolting cycle is shown in Figure 11. The Miner Bolter MB650 has to fulfil the following functions:

- Mechanical cutting of stone coal
- Loading of the haulage means
- Drilling and installing of rock bolts
- Binding the powdered coal

[34] Sandvik (2013), p. 18

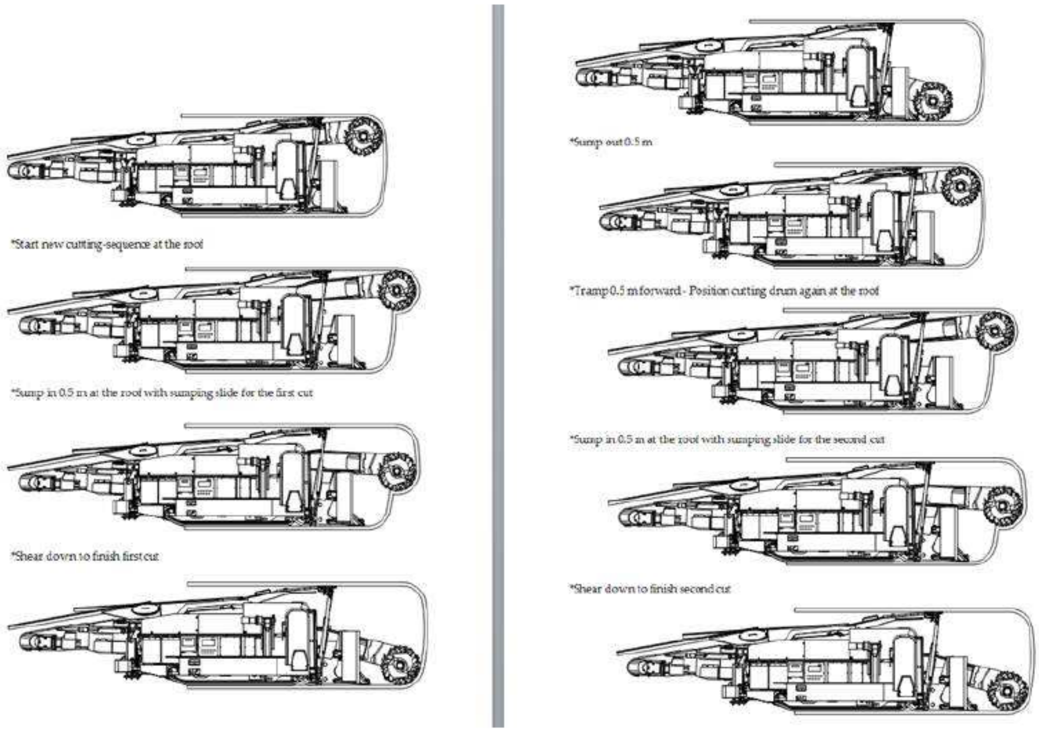


Figure 11: One full cycle [35]

c) Functional unit

The functional unit is used to define the quantification of the identified functions and it provides a reference for inputs, outputs and the environmental impacts. [36] There are several possibilities for the functional unit including operational hours, pumping hours or even produced tons of coal. For this LCA study the functional unit was the roadheader model MB650. This means the environmental impacts were related to the MB650 and the two modules. The functional unit was selected in consultation with Sandvik. Katariina Rouhiainen used in 2008 for her LCA about the Sandvik DX780 drilling rig also the product system for the functional unit.

d) System boundary

The system boundary specifies which unit processes are included in the system and which not. It should be set in a way that all material flows crossing the boundaries are exclusively elementary flows. [37]

System boundaries can be specified in relation to (1) natural systems, (2) geographical boundaries, (3) time boundaries and (4) boundaries within the technical system.[38] [39]

[35] Sandvik (2013), p. 22
[36] Cf. Weidema, B. et al. (2004), pp. 3-10
[37] Cf. Tillman, A.-M. et al. (1993), p. 21
[38] Cf. Rouhiainen, K. (2008), p. 46
[39] Cf. Tillman, A.-M. et al. (1993), p. 22

For the natural system the boundaries are set by the type of a cradle to grave life cycle assessment. This means when a flow enters the technical system it leaves the natural system and when a flow leaves the technical system it enters back to the natural system.[40]

Geographical boundaries are necessary because the location of the required materials, electricity production and waste management influence the results of the LCIA. The "GaBi" database allowed to choose the geographical source of the data. So it is, for example, possible to select Germany, Central Europe or Australia as geographical location for the required entries.

Time boundaries need to be considered because it matters how old database entries are. For example electric power generation from renewable sources increased in the last years and there is a difference if the data for the electric supply are from the year 1999 or from 2015. The used "GaBi" database was updated in 2014 which means there are no problems with time boundaries.

Information about details concerning the parts inside or outside the system boundaries are the following:

Inside the system boundary are:

- Production of raw materials
  The LCA includes the production of different alloy compositions out of the raw materials. Depending on the provided database the pre-processes of the material production are also included. This part of the master thesis is more or less a result of the inventory analysis of the manufacturing as well as the assembly phase and the level of accuracy is strongly reliant on the quality of the provided database entries and pre-processes.
  Moreover, it includes an assumed transport of the raw materials to the assembly and manufacturing plant in Zeltweg.

- Manufacturing and assembly of the MB650
  The LCA considers operation and auxiliary materials during the manufacturing and assembling in Zeltweg. This includes for instance the electrical power consumption, the required heating share, the painting and the share of waste produced. Details about the manufacturing and assembly phase are described in chapter 3.2.2. This chapter also outlines limitations of the provided database.

[40] Cf. Rouhiainen, K. (2008), p. 46

- Operation of the MB650
  Part of the operation of the product system is the supply of spare parts, electrical power supply, the supply with operational material like hydraulic oil or hydraulic fluid and the disposal and recycling of the waste produced during the operation time.

Outside the system boundary are:

- Design engineering
  The first phase of a product life cycle as shown in Figure 6 is not included in the study.

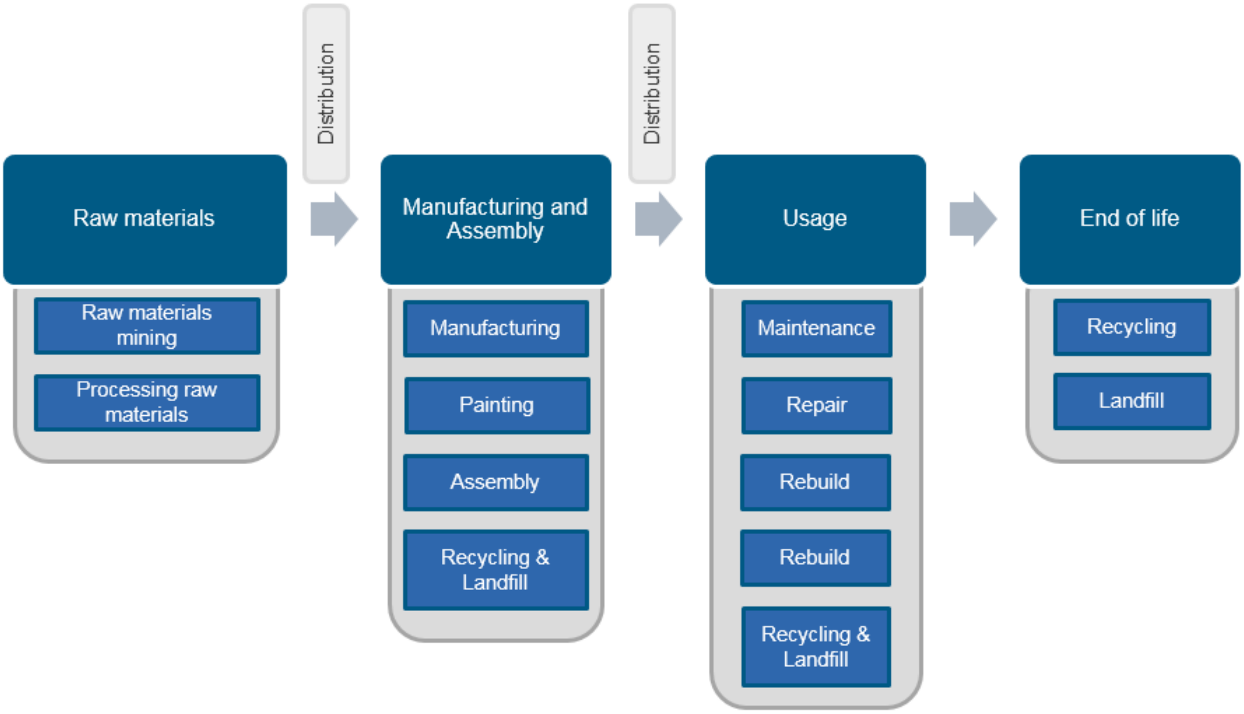
- Infrastructure
  Neither infrastructure such as roads, railways or bridges, nor the production of the means of transport are considered.

- Production facilities
  The environmental impact to manufacture production facilities, for example welding equipment, turning machines, milling machines, drilling machines and other equipment and facilities are not included. Neither is the construction of the production facilities.

- Rock bolts
  One of the main functions of the Miner Bolter MB650 is the drilling and installing of rock bolts. However, the rock bolts are not included in the study because the same amount of rock bolts are required also if another machine is installing.

- Equipment of the external ventilation system
  Sometimes roadheaders or other mining machines are using an integrated ventilation system. For the MB650 an external ventilation system is used. The production and manufacturing of this ventilation system is not included in the LCA study. Although in consultation with Sandvik the electrical power to run the ventilation system is considered because it is an essential process to operate the MB650. In addition in future LCA it enables the possibility to compare the impacts caused by the external ventilation system with an integrated ventilation system. Regarding the results of the impact assessment the external ventilation system is designated as a separate module.

- Evacuation of stone coal up to the surface
  A loading device and a conveyor transport the extracted coal from the front of the Miner Bolter behind the Miner Bolter. The further evacuation of the stone coal up to the surface of the mine is not considered in this study.



Setting the boundaries is the basis to create a LCA phase scheme. This scheme illustrates the main phases and the sub-processes which are shown in Figure 12.

Figure 12: LCA phases and sub-processes [41]

e) Allocation procedures

Sandvik provided data about power consumption, heating and waste on an annual base. Nevertheless, no specific data for one manufactured MB650 were available. Therefore allocating these annual data to one specific Miner Bolter is necessary. During the inventory analysis two possible approaches emerged: (1) machine-dependent allocation and (2) sales-dependent allocation.

"Machine-dependent" allocation means to split up the annual data through the amount of manufactured machines. For example Sandvik Mining and Construction Zeltweg manufactured 34 machines in 2014. In the same period they needed 214.7 kWh energy in form of pressurized air. To determine the specific share for the MB650 the annual amount of energy needs to be divided by 34. It would also be possible to calculate a proportional factor and use this factor to calculate the proportional share on the annual values.

$$pf_{MB650} = \frac{1xMB650}{manufactured\ machines\ in\ 2014} * 100 = \frac{1}{34} * 100 \approx 3\ \%$$

$$E\_air_{MB650} = energy\ in\ form\ of\ pressurized\ air_{annual} * pf_{MB650}$$

$$E\_air_{MB650} = 214.7kWh * 3\% = 6.315\ kWh/Machine$$

[41] Source: own figure

E_air_{MB650} ... $energy\ in\ form\ of\ pressurized\ air\ [kWh]$

pf_{MB650} ... $proportional\ factor$

This approach presupposes that all manufactured machines have the same size and weight which is not the case. Sandvik Mining and Construction offers various models of roadheaders and provides additional customization according to customers' specific requirements. In agreement with Sandvik the "sales-dependent" approach represents a more accurate allocation procedure for this LCA.

The "sales-dependent" approach uses the annual revenues and the revenues of one MB650. By calculating the percentage share of one MB650 to the annual revenues a proportional factor results. This proportional factor is used to calculate the share of annual values such as the power consumption, the heating or the waste for the production of one MB650. The sales dependent proportional factor is 3.63%.

$$E\_air_{MB650} = 214.7kWh * 3.63\% = 7.794\ kWh/Machine$$

This proportional factor is used to allocate the following annual data:

- Power consumption
- Heating
- Pressurized Air
- Waste
- Auxiliary material
- Water consumption

To ensure a high level of modularity and the possibility for detailed analyses an additional allocation for major components is applied during the "manufacturing and assembly" phase. The allocation itself will not influence the consumption of the whole phase because the overall data stay the same. But it provides the possibility to identify which parts cause more environmental impacts than other parts. The additional allocation method depends on the considered data. Three different allocation methods are possible: (1) number dependent allocation, (2) weight dependent allocation, (3) process time dependent allocation.

The (1) number dependent allocation divides the analysed data by the amount of major components. This would for example result in dividing the power consumption by 16 because the structure used in this master thesis separates the MB650 into 16 major components. Yet not all major parts have the same weight and require the same time of mechanical work, therefore this allocation is not quite accurate. For instance the major part "frame" weighs more than 20,000 kg in contrast to the major part "water supply" which only weighs 750 kg. The major part "electric motors" is a purchased part and does not require intensive additional processing in Zeltweg.

The (2) weight dependent allocation is more accurate than the (1) number dependent allocation because usually heavier parts need more time for being processed. Nevertheless, this method is also flawed because although some major components are heavy they are purchased externally. The major part “electric motors”, for example, weighs nearly 4,000 kg but is not manufactured or processed by Sandvik.

A (3) process time dependent allocation considers the process time and set-up time for the allocation. Depending on the amount of time the parts need to be processed the consumption data are being proportional allocated to this part. If a major component, for instance, is responsible for 10 % of the overall process time and set-up time, 10 % of the power consumption and heating is allocated to this part. The disadvantage of this method is that the provided data are not 100 % complete. The process time and set-up time of the various major parts is shown in Table 1.

To compensate this lack of information a small part of the consumption was allocated to the number dependent allocation and a bigger part was allocated by using the (3) process time dependent allocation.

For example 20 % of the pressurized air share of a MB650 was first divided by the amount of major components. These 20 % should compensate the incomplete provided data. The remaining 80 % were allocated depending on the process time and setup time. By considering the process time and setup time, also different efforts for mechanical processing are taken into account.

Major Part	**Share**		
	process time	**set-up time**	**combined**
cutting drum	13.94%	8.04%	12.34%
cutting gear	25.63%	17.74%	23.49%
cutting arm	1.10%	1.09%	1.09%
charging device	10.21%	14.31%	11.32%
swivel conveyors	4.57%	3.84%	4.38%
frame	13.29%	10.37%	12.50%
electric motors	0.02%	0.07%	0.03%
electrical equipment	0.00%	0.00%	0.00%
Cover and consoles	0.68%	1.71%	0.96%
hydraulical equipment	15.31%	20.15%	16.62%
zylinder	10.13%	13.93%	11.15%
lubrication system	0.51%	0.68%	0.56%
water supply system	2.11%	3.14%	2.39%
tools and accessories	0.61%	0.37%	0.54%
additional device	0.64%	0.71%	0.66%
Bolting Unit	1.26%	3.87%	1.97%
	100.00%	100.00%	100%

Table 1: Major parts of the MB650 and their process time/set-up time proportion

f) Impact categories and methodology of impact assessment

The methodology of the impact assessment depends on the used database. As explained in chapter 3, the “GaBi” database provides the background data for the LCA software “Umberto NXT Universal”. The database supports the following methodologies and provides full transparency to assess the LCA:[42]

- CML 2001
- EDIP 2003
- Impact 2002+
- New impacts ILCD recommendation
- ReCiPe 1.08
- TRACI 2.1
- USEtox

Katariina Rouhiainen (2008) used for the Sandvik DX780 drilling rig LCA the methodology “Eco-Indicator 99”. “GaBi” does not support this methodology, therefore it was not possible to use this method for the MB650. For this LCA the impact assessment method “CML 2001” was selected.

“CML 2001” was developed at the “Centrum voor Milieukunde” in Leiden, Netherlands, in 1992. The method is based on midpoint modelling and makes it possible to sum up emission from different sources but with the same effect.[43] The covered pathways and categories are shown in Figure 13. The CML method contains several impact categories. All of them are calculated in this LCA, but not all results are explained and shown in detail. Further details are explained in chapter 3.3. The following impact categories are supported and defined by the CML 2001 methodology:

- Acidification potential
- Climate change
- Eutrophication potential
- Freshwater aquatic ecotoxicity
- Human toxicity
- Land use
- Marine aquatic ecotoxicity
- Photochemical oxidation (summer smog)
- Resources
- Stratospheric ozone depletion
- Terrestrial ecotoxicity
- Freshwater sediment ecotoxicity
- Malodours air
- Marine sediment ecotoxicity
- Ionising radiation

[42] Cf. ifu hamburg, https://www.ifu.com/en/umberto/umberto-gabi-databases/ (Retrieved: 14.10.2016)
[43] Cf. Springer Gabler, http://wirtschaftslexikon.gabler.de/Definition/cml-methode.html (Retrieved: 14.10.2016)

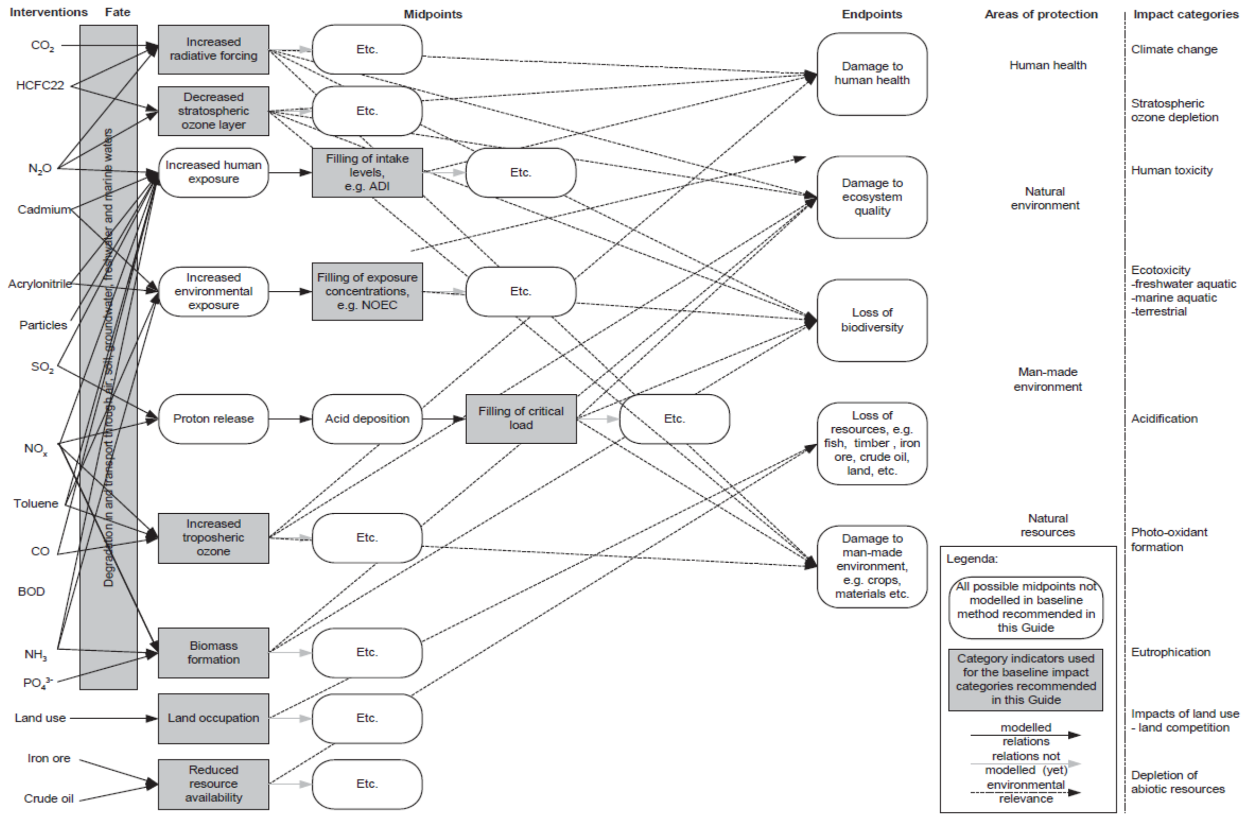


Figure 13: Impact categories and pathways covered by the CML methodology [44]

g) Data requirements

The geographical ties of the data have to be considered. For the manufacturing and production data from Europe are used. The usage and disposal phase data originate from Australia. The applied data should not be older than four years.

For the modelling of the LCA, using the software "Umberto NXT Universal", the additional database "GaBi" was necessary. The database provides predefined materials and processes.

h) Assumptions

It was necessary to make some assumptions to conduct the LCA. Among others, the material composition of many precast elements such as electric motors, pumps, control units, measuring elements and other electronics are not manufactured by Sandvik and their components are unknown. The manufacturers of these components mostly do not publish these material compositions due to nondisclosure of internal know-how and competitive advantage. To include also these unknown parts some simplifications are made.

[44] JRC European Commission (2010a),p. 25, fig.1

Simplification E-Motors:

Sahni et Al. (2010) published a paper of a LCA about electric motors with the title "Electric Motor Remanufacturing and Energy Savings".[45] In their case Sahni and his team used electric motors with an energy output of 22 kW and 200 kW. They also studied different energy classes. The material composition of analysed electric motors is shown in Figure 14.

The power output and the weight of the electric motors of the MB650 are different to the motors shown in Figure 14. To get the information about the bill of materials the proportion of the power output and the weight were calculated and compared. These proportions were compared to the used motors and the one with the minimal spread was selected for the calculation of materials. The proportion factors are shown in Table 2. For the Motor 2 of the MB650 series with a weight of 1,135 kg and a power output of 132 kW the proportion factor is 0.1163 which is close to the factor of the 22 kW Standard Efficiency Motor. For the bill of materials of this Motor 2 the material distribution of the 22 kW Standard Efficiency Motor was used.

	22kW			200kW	
Material (Kg)	**Standard Efficiency**	**Energy Efficiency**	**NEMA Premium**	**Standard Efficiency**	**NEMA Premium**
Electrical Steel	79	106	134	620	800
Other Steel	21	22	23	134	154
Cast Iron	29	22	29	600	600
Aluminium	20	17	24	36	50
Copper	14	20	24	108	140
Insulation Material	0	0	0	2	2
Inpregnation Resin	2	2	2	10	10
Paint	1	1	1	2	2
Total (Kg)	**166**	**190**	**238**	**1,512**	**1,758**
Energy using Smil (MJ)	**13,779**	**15,419**	**19,716**	**90,040**	**109,860**
Energy from EuP Lot 11 (MJ)	**13,216**	**15,590**	**16,754**	**98,822**	**101,316**

Figure 14: Bill of material of different electric motors [46]

[45] Cf. Sahni, S. et al. (2010)
[46] Sahni, S. et al. (2010), p. 20, fig. 13

Table 2: Proportion factors of the electric motors

Electric Motors	Weight [kg]	Power Output [kW]	proportion factor [kW/kg]
Standard Efficiency	166	22	0.1325
Energy Efficiency	190	22	0.1158
NEMA Premium	238	22	0.0924
Standard Efficiency	1,512	200	0.1323
NEMA Premium	1,758	200	0.1138
Motor 1 MB650	1,500	270	0.1800
Motor 2 MB650	1,135	132	0.1163
Motor 3 MB650	320	36	0.1125

Simplification Pumps:

Several hydraulic pumps and water pumps of different designs and sizes are used in the MB650 series. Pumps consist of various parts, for instance pistons, gaskets and valves. As a simplification it is assumed that the pumps are made completely out of steel. For this assumption a corrosion-resistant steel had to be used and therefore X5CrNi18-10 was selected. It is high-alloyed steal used in several applications such as the chemical industry, the automotive and petroleum industry.[47] In addition, this steel is already used by Sandvik for other components of the MB650, for example for the filter housing or the water inlet.

Further assumptions and simplifications were necessary and are described in the associated chapters in the following inventory analysis.

3.2 Inventory Analysis

For the inventory analysis it was first necessary to analyse the kind of required data. A list of needed data for the different life cycle phases was created and forwarded to Sandvik. This list is shown in Figure 15.

During the phase ”inventory analysis" but also during the modelling of the LCA simulation it was necessary to stay in close contact with Sandvik for requests of additionally required data or questions concerning transmitted information.

For a data example Sandvik provided a bill of material of the MB650 and they transmitted a list of parts which are regularly replaced due to reaching their end-of-life. The bill of materials of the MB650 contained more than 8.000 individual parts.

[47] Cf. Deutsche Edelstahlwerke, https://www.dew-stahl.com/fileadmin/files/dew-stahl.com/documents/Publikationen/Werkstoffdatenblaetter/RSH/1.4301_de.pdf, (2015), p.2

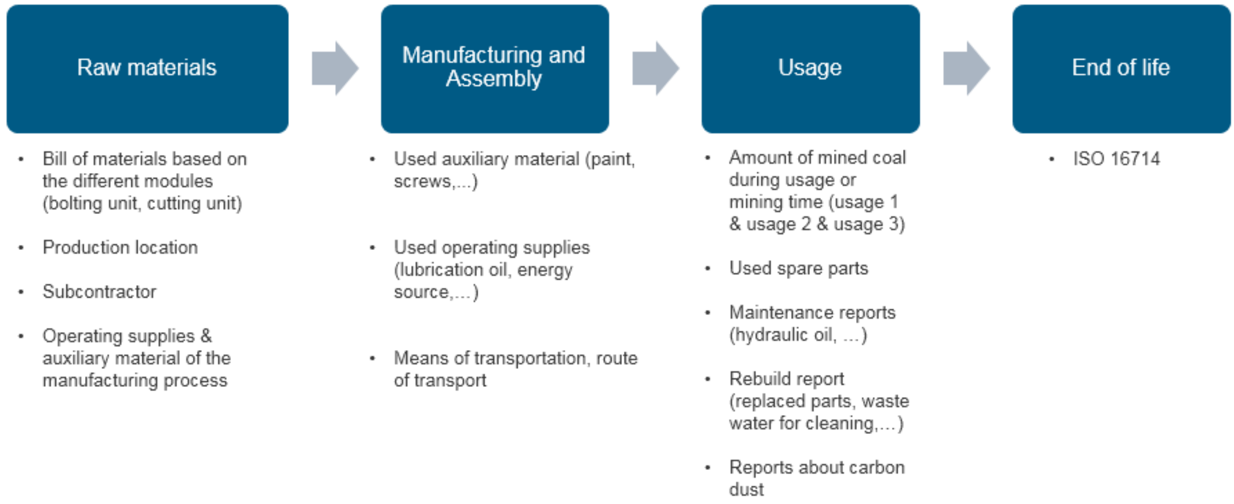


Figure 15: List of required data for the LCA [48]

The simplified results of the inventory analysis are shown in appendix 3. They are separately listed according to the cutting unit module and the bolting unit module.

3.2.1 Raw materials

For the “raw materials” phase the software “Umberto NXT Universal”, from here on referred to as Umberto, and the “GaBi” database provided support. By using the results of the inventory analysis of the “manufacturing and assembly” phase all required materials were extracted. Through modelling the LCA in Umberto the inventory of the raw material phase was calculated by the software.

For the manufacturing and assembling of the cutting unit 68 various types of material are required. The GaBi database does not contain all these different types of materials. However, all types of materials are modelled in Umberto. This detailed modelling enables the possibility to increase the level of accuracy of the LCA if additional databases are available in future.

In order of clarity, the inventory analysis of the raw materials was subdivided into groups of materials for example metals, rubber and plastic. These are discussed in the part below.

Simplified input/output balance-sheets of the two modules are shown in the appendix 3.

- Metals

The cutting unit is made by nearly 50 different alloys. For aluminium and copper GaBi provides material flows and pre-processes. Various different steel alloys provided by the GaBi professional database are shown in Figure 16. These material database entries act as a basement for other alloy compositions. GaBi, for example, does not offer a 17CrNiMo6 but a 100Cr6 which is similar to the 17CrNiMo6. The pre-process of the 100Cr6 was adjusted by editing the input to fit the 17CrNiMo6. The steel alloy 100Cr6 contains no appreciable amount of

[48] Source: own figure

molybdenum and nickel but nearly the same amount of chromium. In order to consider the different alloy compositions the input of the pre-process of the 100Cr6 was modified by adding 0.3 % molybdenum and 1.55% nickel. The chromium content was already close to the target value of 1.65 % and no modification was necessary. Table 3 shows a few steel alloys which is needed for the LCA as an input as well as the 100Cr6 which is used for few materials as a basis.

Metals	Steel billet (St) [Metals]	Good	kg
Metals	Steel billet (28Mn6) [Metals]	Good	kg
Metals	Steel billet (20MoCr4) [Metals]	Good	kg
Metals	Steel billet (16MnCr5) [Metals]	Good	kg
Metals	Steel billet (100Cr6) [Metals]	Good	kg

Figure 16: Different steel alloys provided by GaBi professional database [49]

Table 3: Different used steel alloys and their alloying composition in percent

Name	C	Si	Mn	Cr	Mo	Ni	V
34Cr4	0.34	0.25	0.85	1.50	0	0	0
20MnV6	0.20	0.25	1.50	0	0	0	0.15
17CrNiMo6	0.17	0.25	0.50	1.65	0.3	1.55	0
100Cr6	1	0.25	0.35	1.50	0	0	0

The cast parts were split into cast iron parts such as G-20Mn5 and grey cast iron like GJL-250. The GaBi database provides material flows and pre-processes for these types of metal. The MB650 contains several different types of grey cast iron but the alloy composition difference of these types is so marginal that the input of the pre-process was not edited. The material flows were still modelled separately to exchange them if additional databases were available which might contain different grey cast iron alloys. The used pre-process for grey cast iron and EN-GJL-500 is shown in Figure 17.

[49] ifu Hamburg; thinkstep GaBi (2014)

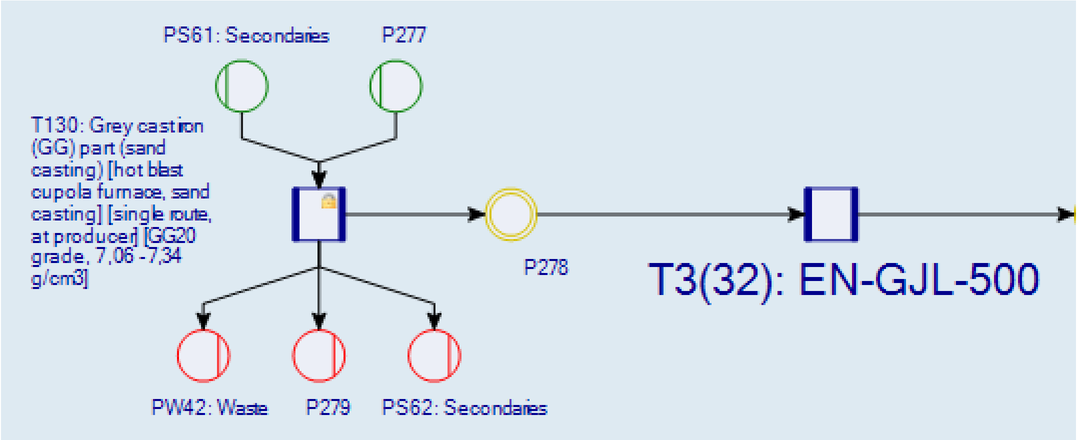


Figure 17: Material flow and pre-process for grey cast iron parts [50]

Cast iron parts are also not altered through changing the input because of the marginal difference of their alloy composition. Nevertheless, they were modelled separately as well to exchange them with the correct alloy composition if additional database entries are available in the future. The pre-process is different in comparison to the grey cast iron process because additional data concerning thermal energy and electricity are necessary to complete the process. Geographically the manufacturing of the cast iron part but also the data about the thermal energy and electric power are located in Germany. The thermal energy is provided by natural gas.[51] The production process for cast iron parts is shown in Figure 18.

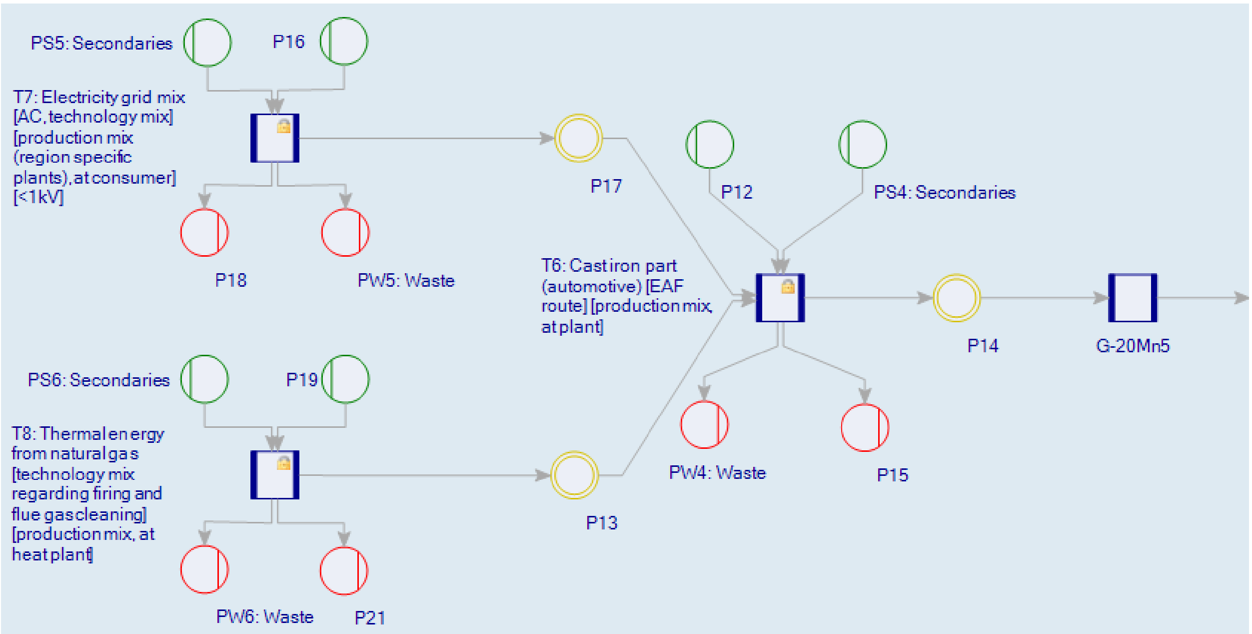


Figure 18: GaBi database pre-process for cast iron parts (automotive) [52]

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[50] Source: own figure
[51] Cf. Blesl, M.; Kessler, A. (2013), p. 220
[52] Source: own figure

- Rubber

To manufacture a MB650 various kinds of rubber are required. The weight and the name of the rubber-like materials required for one MB650, in both modules, are shown in Table 4. The GaBi database does not provide proper material for all kinds of rubber so a similar material compensated the missing ones.

Table 4: Rubber-like materials used in a MB650 (cutting unit + bolting unit)

Name	Weight [kg]
Nitrile-Butadiene-Rubber - NBR	49.81
Silicon rubber	650
Synthetic rubber	831.77

To replace the missing material Styrene-Butadiene-Rubber was used. This kind of rubber also provides a proper pre-process which is shown in Figure 19. This means all environmental impacts are considered. The level of accuracy of this LCA is much higher as if these material flows were left out because the exact same material is not provided by the database. If further database extensions are available this material can be easily replaced by the correct one. Each material flow is modelled separately.

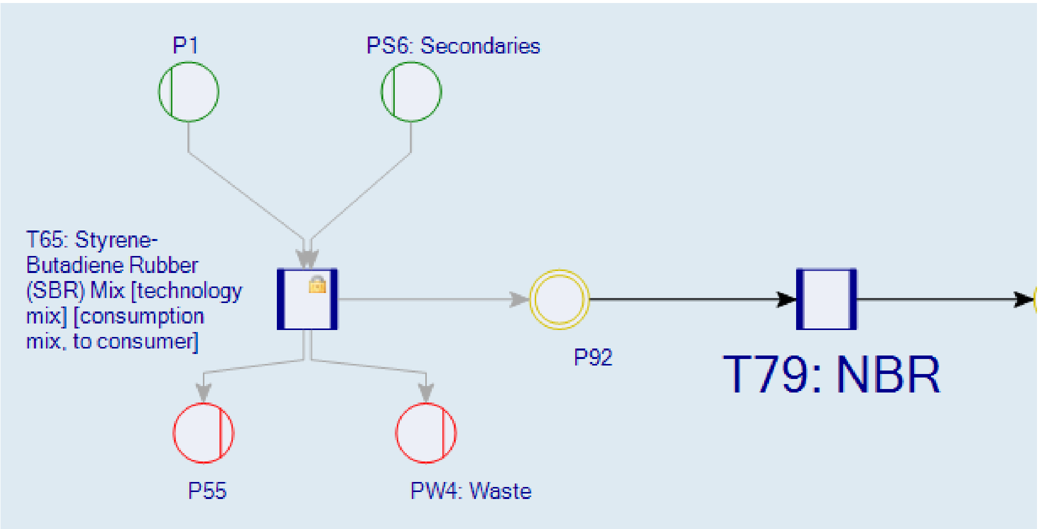

Figure 19: Styrene-Butadiene Rubber provided by GaBi as substitute for other kinds of rubber [53]

[53] Source: own figure

- Plastic

Same as for the rubber, various types of plastics are required to manufacture a MB650. Some examples including the total amount used in a MB650 are shown in Table 5.

Table 5: Plastic materials used in a MB650 (cutting unit + bolting unit)

Name	Weight [kg]
Polyvinylchlorid – PVC	1,054.4
Polyester	29.72
Polytetrafluoroethylene - PTFE	4.27

GaBi provides a proper database entry and pre-processes for polyvinylchloride (PVC). For polyester no pre-processes were available. It was substituted by polyethylene terephthalate (PET) because it is a member of the polyester family.[54]

For PTFE GaBi does not provide any material flow and it was not possible to substitute it with another material which is supported by GaBi. Because the amount of these materials is comparatively low (4.27 kg compared to 1,054 kg of PVC) it was modelled in Umberto, but the environmental impacts were not considered.

3.2.2 Manufacturing and assembly

For the inventory analysis of the “manufacturing and assembly” phase several data were collected and prepared in order to be used for the modelling of the LCA. All data for the inventory analysis are allocated to the two main modules: bolting unit and cutting unit. In addition to ensure a higher degree of modularity for further steps regarding energy efficiency, the cutting unit was separated into 15 different major components. Besides a bill of materials, also power consumption, heating, waste, operating materials and varnish mattered in the “manufacturing and assembly” phase.

- Bill of Materials

The bill of materials of the MB650/248 is one of the principal elements of the inventory analysis. However, to use the list it was necessary to revise it. Not only contained the file just the single components, but also superior component groups. Without any revisions many parts would have been double counted and the weight of the material would not be correct. The structure of this unformatted bill of material is shown in Table 6. The column “level” defines the level of details. In this example the parts metal sheet and hub are relevant for the inventory analysis because they are the semi-manufactured parts which form the major components. Level 1

[54] Cf. Encylopaedia Britannica, https://www.britannica.com/science/polyethylene-terephthalate (Retrieved: 14.10.2016)

defines one of the sixteen major components for the allocation. As a result it was necessary to exclude all Level 2, 3 and 4 parts. This exclusion is only valid for this example.

Table 6: Bill of material - structure of the raw data

LEVEL	Name	Amount	Material	Weight [kg]
1	Cutting drum 5600-2,5Z	1.00		8,360
2	Cutting drum 5600 2,5Z sp soft rock	1.00		8,000
3	inner drum re m Mh kpl	1.00		1,227
4	inner drum o Mh 1200 tr kpl	1.00		950
5	metal sheet	2.00	S355J0	113
5	hub	2.00	S355J0	290
….	….	**….**	**….**	**….**

The bill of materials contained not only superior component groups, and on some levels it was incomplete. Thus it was necessary to make assumptions for missing data. An example for missing components is shown in Table 7. The component mesh box consists of three different types of steel. The sum of these three components results in a weight of 329 kg. The real weight of this mesh box is 2,310 kg though, which means 1,982 kg are missing. In agreement with the supervisor of Sandvik an assumption for the missing 1,982 kg was necessary. The solution was to fill up the missing weight with the steel type S355J0. This steel type was already the dominating type of material in this component. If there were more dominant materials in the component the additional weight was shared between these.

Table 7: Missing data in the bill of material and assumption

Name	Material	Weight [kg]
Mesh box		2,310
	34Cr4	3.45
	S355J0	320
	X17CrNi16-2	5
	Sum	**329**
	MISSING	1,982

Name	Material	Weight [kg]
Mesh box		2,310
	34Cr4	3.45
	S355J0	2,302
	X17CrNi16-2	5
	Sum	**2,310**
	MISSING	0

For some main components of the MB650 the material data were missing completely. Additionally to the bill of materials of the MB650, Sandvik transmitted the bill of materials of the MB670. The MB670 is quite similar to the MB650 but was modified for another field of application. This bill of materials is more detailed so it was possible to apply the material composition of several components and use it for the MB650. There are, for instance, no data available for the material composition of the drilling and bolting unit (ABSE) of the MB650 but there is detailed information available for the MB670. By using a proportional factor of 1.245 the material composition of the MB670 was transferred to the MB650 which is shown in Table 8. This proportional factor results by dividing the target component weight of the MB650 with equivalent component weight of the MB670. Important to note here is that the sum of the material weight did not hit the target weight. The reason for this discrepancy is that the bill of materials contained also semi-manufactured parts, for example metal sheets. During the “manufacturing and assembly” phase several operational activities such as milling are necessary. These operational activities result in a loss of material. Further details about these metal scrap and metal chips are explained in a separate sub-item in this chapter.

Table 8: Calculation of material composition of the MB650 by using the MB670

Name	Material	Weight [kg]
ABSE MB670		4,850.00
	17CrNiMo6	6.00
	34Cr4	14.38
	42CrMo4	11.04
	45H	0.08
	A514F/1300	9.60
	E335	16.00
	Fst	0.16
	Kst	0.80
	S355JO	5,196.75
	St	6.00
	X17CrNi16-2	58.00
	Sum	**5,318.81**

Name	Material	Weight [kg]
ABSE MB650		6,040.00
	17CrNiMo6	7.47
	34Cr4	17.91
	42CrMo4	13.75
	45H	0.10
	A514F/1300	11.96
	E335	19.93
	Fst	0.20
	Kst	1.00
	S355JO	6,471.83
	St	7.47
	X17CrNi16-2	72.23
	Sum	**6,623.84**

- Power consumption

Next to the bill of material it was necessary to consider the production machines, curing ovens, workshop lighting, heating and the waste produced during the “manufacturing and assembly” phase. All these data were annual-based and not allocated to one manufactured MB650. As already explained in chapter 3.1.2 a sales-dependent allocation approach was used to calculate the exact share. But before this proportional factor could be used the data needed to be prepared. The unit for the power consumption is mega-watt hours (MWh).

For the annual data of the power consumption it was necessary to consider lighting and production machinery like turning machines and curing ovens. But the provided annual data also included the power usage of the office building including copiers, fridges and fans. Non-production relevant consumption was subtracted from the annual usage. Afterwards the proportional factor was applied and the exact power consumption share was calculated. The power consumption for the building and the results of the calculation are shown in Table 9.

Table 9: Electric power consumption distribution

Description	Power consumption in 2014 [MWh]
Overall	4,829
Office building	288.4
Workshop	4,540.6
MB650 share (Workshop x 3.63%)	164.82

Subsequently, the electric consumption of the MB650 was divided into 16 major parts. Details about the allocation method are explained in chapter 3.1.2.

For the LCA modelling in Umberto an Austrian electricity grid mix is used. The database entry also contains the pre-processes of this input.

Electricity grid mix [AC, technology mix] [production mix (region specific plants), at consumer] [<1kV]

- Heating power

Before using the proportional factor to calculate the share of the annual heating data for the MB650, the data had to be adapted. The workshop in Zeltweg uses district heating and the thermal power plant is operated by biomass. The provided data contained the combined heating consumption of the office building and the workshop. In agreement with the responsible expert in Sandvik 90 % of the heat consumption were allocated to the workshop and 10 % to the office building.

Table 10: Heating consumption distribution

Description	Heating consumption in 2014 [MWh]
Overall	6,351
Office building	635.1
Workshop	5,715.9
MB650 share (Workshop x 3.63%)	207.5

The GaBi database provides three different thermal energy sources which are shown in Figure 20. Oil and gas for creating heat were excluded because Sandvik uses thermal energy from the biomass district heat plant. The third option, heating from wood, is the closest one to biomass.

Thermal energ	Heat [from residential heating system incinerating light fuel oil (low sulphur content)] [consumption mix, at con	Good	MJ	Master Data: GaBi Professional database
Thermal energ	Heat [from residential heating systems from natural gas] [consumption mix, at consumer] [at a temperature lev	Good	MJ	Master Data: GaBi Professional database
Thermal energ	Heat [from residential heating systems from wood] [consumption mix, at consumer] [at a temperature level of	Good	MJ	Master Data: GaBi Professional database

Figure 20: GaBi database entries for heating [55]

By expanding this input material for the pre-process an option is provided by GaBi. A thermal energy source run by wood and geographical origin in the EU can be seen in Figure 21.

Name	Geography
Heat [residential heating systems from wood pellets, boiler, max. heat output 14.9 kW] [consumption mix, to consumer] [at a temperature level of 70°C]	EU-27

Figure 21: Expanding heating systems from wood for pre-process [56]

It has to be mentioned that Umberto and GaBi use the unit megajoule (MJ). Sandvik provided all energy related data in MWh. Thus it was necessary to convert the MWh in MJ by using the multiplier 3,600.

- Painting

The painting of the different components is done by the service company Sepero in Zeltweg and not by Sandvik itself. The service company provided a list of purchased and disposed coating materials related to service work for Sandvik. The transmitted file contained several different coatings, hardener and universal thinners. The GaBi database does not comprise any painting or coating materials. Most of the coatings consist of polyurethane acrylate and a hardener for resin. In order to consider the painting in the LCA it was necessary to find a similar material in the database. The decision was made for polyurethane flexible foam and for epoxy resin with a 50/50 distribution. Figure 22 shows the two pre-processes. Together, the polyurethane foam and the epoxy resin form the painting. The green circles symbolize additional inputs and the red circles symbolize waste from the pre-processes.

[55] ifu Hamburg; thinkstep GaBi (2014)
[56] ifu Hamburg; thinkstep GaBi (2014)

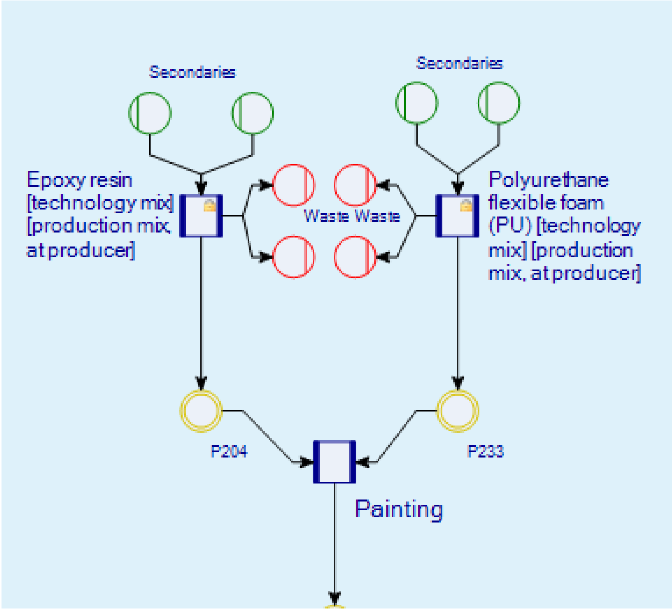

Figure 22: Pre-processes for the painting [57]

- Additional input and waste

In the manufacturing and assembly phase several different types of waste accumulate. The provided data include 59 different types of waste from rubble to oil sludge to scrap metal. It was necessary to sort out which types are involved in the manufacturing and assembling of an MB650. Therefore, for example rubble was not production relevant. The scrap metal and metal chips are discussed in more detail in a separate point. Moreover, the list of waste was also used as a source of information for additional input of the "manufacturing and assembly" phase. All waste outputs are also inputs for the assembling process.

After editing and calculating the share of waste for one MB650, 10 types of waste remained and are shown in Table 11.

Table 11: Edited list of waste for the assembly and manufacturing phase

Material	Weight [kg]
Wood	3,265.08
Used oil	2,194.92
oil seperator	717.44
oil contaminated workshop waste	417.51
sand trap residues	406.22
cardboard	365.53
oil-water mixture	248.98
plastic package	110.91
oil sludge	108.11
greases	13.43

[57] Source: own figure

Most of the wooden waste comes from wooden euro pallets. The GaBi database has a special material flow and process for this type of input and waste. Yet it requires one of the extension databases which was not available for this master thesis. As an input the material flow “Wood soft, standing [Renewable resources]” was selected because euro pallets are often made of spruce which is a soft wood.[58] The input unit is m³ so it was necessary to convert the kg into m³ with the ratio 1 m³ = 400-500 kg.[59]

All available wooden waste material flows are shown in Figure 23. The second best suitable material flow “Wood [Waste for recovery]” was also not supported by the available database. Third best option was the “Waste incineration of untreated wood [10.7 % H2O content]”. For wooden pallets usually the H_2O content should not exceed 20 %, thus this material flow was acceptable.[60]

Group	Name	Material	Displa	Data Source
	wood	bad		gabi
Waste for reco	Wooden residue [Waste for recovery]	Bad	kg	Master Data: GaBi Professional da
Waste for reco	Wooden pallet (EURO) [Waste for recovery]	Bad	kg	Master Data: GaBi Professional da
Waste for reco	Wood [Waste for recovery]	Bad	kg	Master Data: GaBi Professional da
Particles to air	Wood (dust) [Particles to air]	Bad	kg	Master Data: GaBi Professional da
Waste for reco	Waste incineration of wood products (OSB, particle board) [average European waste-to-energy plant, without collecti	Bad	kg	Master Data: GaBi Professional da
Waste for reco	Waste incineration of untreated wood (10.7% H2O content) [average European waste-to-energy plant, without collect	Bad	kg	Master Data: GaBi Professional da

Figure 23: GaBi database items for wooden waste [61]

Oil containing waste such as used oil, oil separator, oil contaminated workshop waste and grease were summed up into two material flows namely “oil for recovery” and “oil for deposit”. The share was extracted by the provided waste list. For the input material flow “Lubrication oil [Operating materials]” was selected because GaBi provides pre-processes for this material.

For the modelling of the waste the material flow “Used oil [without water] [waste for recovery]” and “Oil [for disposal]” were selected. In the GaBi database no processes and data are provided for neither material flows. The waste was considered in the LCA but it did not result in any environmental impacts.

For the oil-water mixture and the oil sludge separate material flows were integrated, although also for this type of waste no further data and processes are deposited in the GaBi database. Therefore, the environmental impact was not considered in this master thesis. For future detailed calculations the appropriate databases can be purchased and easily implemented by using the expand function.

The cardboard is mainly used for the packaging purpose. For the input material flow the GaBi data entry “Paper for corrugated board [Materials from renewable raw materials]” was selected.

[58] Cf. Schramm & Co,http://schrammpalette.de/ratgeber/Allgemeine-Fragen-zu-Paletten-Europaletten/aus-welchem-holz-werden-paletten-hergestellt/ (Retrieved: 14.10.2016)
[59] Cf. holz-bearbeitung http://www.holz-bearbeitung.de/Holzmuster-Dateien/Raumgewicht/Raumgewicht.htm (Retrieved: 14.10.2016)
[60] Cf. Virginia Tech, http://www.unitload.vt.edu/education/FAQs/ (Retrieved: 14.10.2016)
[61] ifu Hamburg; thinkstep GaBi (2014)

The pre-processes are also defined by GaBi. For the output material flow, for example waste, the selection was not that clear. The database does not contain any cardboard related waste. “Waste paper [Waste for recovery]” does not contain any environmental impacts and processes. The most relevant option to replace the waste cardboard was “Waste incineration of paper fraction in municipal solid waste…”. This material flow also contains additional processes and the result also comprises the environmental impacts.

For plastic package the material flow entry “Polyethylene low density granulate [Plastics]” was selected. Literature research shows that Polyethylene is the most commonly used plastic and is known for its resistance against oil, acids and greases.[62]

For the output material flow the entry “Waste incineration of plastics (PE, PP, PS, PB)..” was used.

Incineration was the only available and supported option for wood, cardboard and plastic waste. It does not quite reflect the Austrian waste politics but otherwise it would not have been possible to consider these material flows.

- Metal scrap and metal chips

During the “manufacturing and assembly” phase several parts of the MB650 pass through mechanical processing where metallic scrap is generated. The waste list provided by Sandvik also contains the weight of the annual accumulated metal scrap and metal chips in their work shop. Similarly to the other annual values it was at first necessary to calculate the appropriate share of these for one MB650 by using the sale dependent approach. This allocation resulted in 23,247kg of metal scrap and chips for the complete Miner Bolter. Depending on their weight these values were split into the share for the “cutting unit” and the “bolting unit”. Afterwards the material composition of the total input was analysed and was separated into various types of material. The non-metallic input was not relevant and thus subtracted. The proportional share of metallic material was calculated and used for modelling the waste process. A further assumption was that the recycling rate of metallic scrap and chips is 100 %.

- (Non-metallic) - subtracted from the total input weight
- Steel - 99.04%
- Copper - 0.58%
- Aluminium - 0.38%

For the steel scrap one database entry “Credit for recycling of steel scrap” worked because for further steel recycling entries extensional databases would have been necessary. The process transforms the steel scrap for recycling 1:1 into steel scrap as an external source in the Umberto LCA model without any further positive or negative environmental impacts. Afterwards the accumulated steel scrap was read and subtracted manually by the required steel scrap input in the raw material phase.

[62] Cf. Verbraucherzentrale, https://www.verbraucherzentrale.de/kunststoffverpackungen (Retrieved: 14.10.2016)

In contrast to steel scrap, the GaBi database provides recycling processes for copper and aluminium. These recycling processes consider attributes not only as credits to copper scrap as they do for the steel scrap, but they subtract the positive from the negative environmental impacts of this phase and reduce the overall environmental impacts. The modelled recycling tree with the three recycling processes for copper, aluminium and steel is shown in Figure 24.

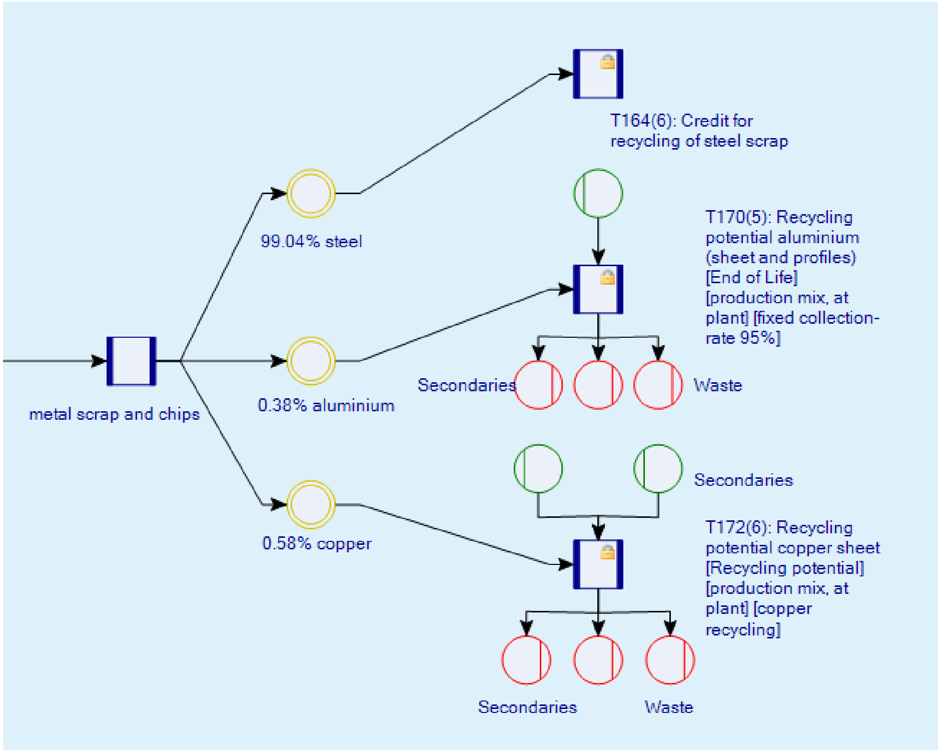

Figure 24: Recycling tree for the manufacturing and assembly phase modelled in Umberto NXT [63]

- Transport

Not all parts of the MB650 are manufactured by Sandvik in Zeltweg. For example pumps and electric motors are purchased from abroad and also some heavy iron parts are manufactured outside of Austria. This means emissions for the transport from the manufacturing plant to Zeltweg have to be considered. Since no data was available about the exact manufacturing location an assumption had to be made.

The average transport distance for all inputs of the assembly and manufacturing phase are assumed to be 300 km. To illustrate a distance of 300km linear distance, Figure 25 shows a circle around the production facility in Zeltweg. It displays the linear distance and not the actual distance along the road. Additionally, two further scenarios were assumed. In one scenario the average distance decreased to 200 km. In the second alternative scenario the average distance increased up to 400 km. The aim is to see the influence of the transport distance assumption

[63] Source: own figure

and if it is necessary to increase the level of accuracy concerning the transport in the assembly and manufacturing phase.

Figure 25: Circle with a 300 km radius around the assembly location Zeltweg [64]

To model the transport in Umberto the GaBi database entry “Transport (ELCD)” was used and expanded by the process shown in Figure 26. It consists of a European mix of lorry transports with the emission standards 0 to 4. Additionally to the average distance of 300 km, entering the transport weight was required. The transport weight is the total input weight of all goods for the “assembly and manufacturing” phase of approximately 123,000 kg. Output of this transport process are emissions, for instance carbon dioxide or waste heat which affected the environmental impact categories.

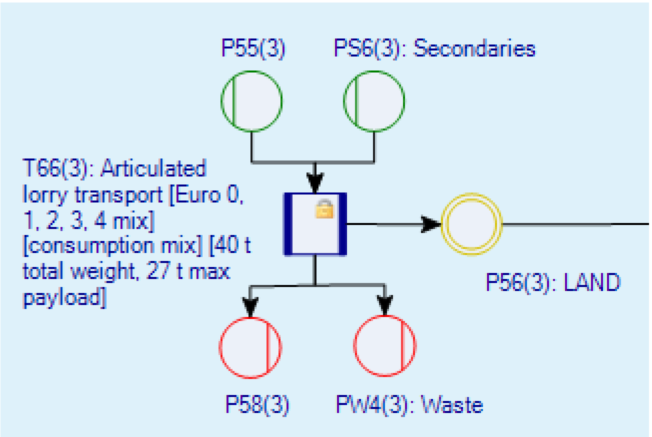

Figure 26: GaBi database process for lorry transport [65]

[64] FreeMapTools, https://www.freemaptools.com/radius-around-point.htm (Retrieved: 14.10.2016)
[65] Source: own figure

3.2.3 Distribution

After the “manufacturing and assembly” phase the MB650 needs to be transported to the mining spot. As explained in chapter 3.1.2 the mining scenario location for this miner bolter is Australia.

The product is transported from Zeltweg, Austria, to the cargo port Hamburg, Germany, by truck. The distance was calculated by Google Maps. The next transport step is a ship from Hamburg to Sydney, Australia. Using the online tool “MarineTraffic-Voyage Planner”, the sea route was calculated.[66] Finally, from the cargo port in Sydney the Miner Bolter is transported by trucks to the mine site. The distance from Sydney to the mine site was assumed because an exact mine location was not defined. All transport routes and distances are shown in Table 12.

Table 12: Transport distance by google maps and marine traffic

Route	Distance [km]
Zeltweg – Hamburg cargo port	1,078
Hamburg - Sydney	25,383
Sydney – mine site	550

3.2.4 Usage phase

The usage phase is the fourth main phase of the LCA. Besides the usage, this phase also contains sub-processes such as maintenance, repair and the rebuild. Information responding the usage phase was provided by Sandvik Mining. Sandvik transmitted an assumption that the miner bolter operates 3,000 pump motor hours per year and the maintenance schedule is also designed for these 3,000 hydraulic hours. These pump hours refer to an operating grade of 34 %, based on a 24 hours and seven days mining operation.

All results of the usage phase were divided and allocated to the two modules namely the “rock bolting unit” and “cutting unit”. The total life time of the MB650 is twelve years. There are two rebuilds, one after the first five years of usage and one after ten years of usage. A simplified network map of the usage phase is shown in Figure 27 displaying the elementary input and output flows.

Data about annual replaced spare parts were provided by Sandvik. Also the parts which are replaced by the rebuild are listed in an excel file. All maintenance schedules were based on hydraulic pump hours.

[66] Cf. MarineTraffic, http://www.marinetraffic.com/de/voyage-planner/ (Retrieved: 14.10.2016)

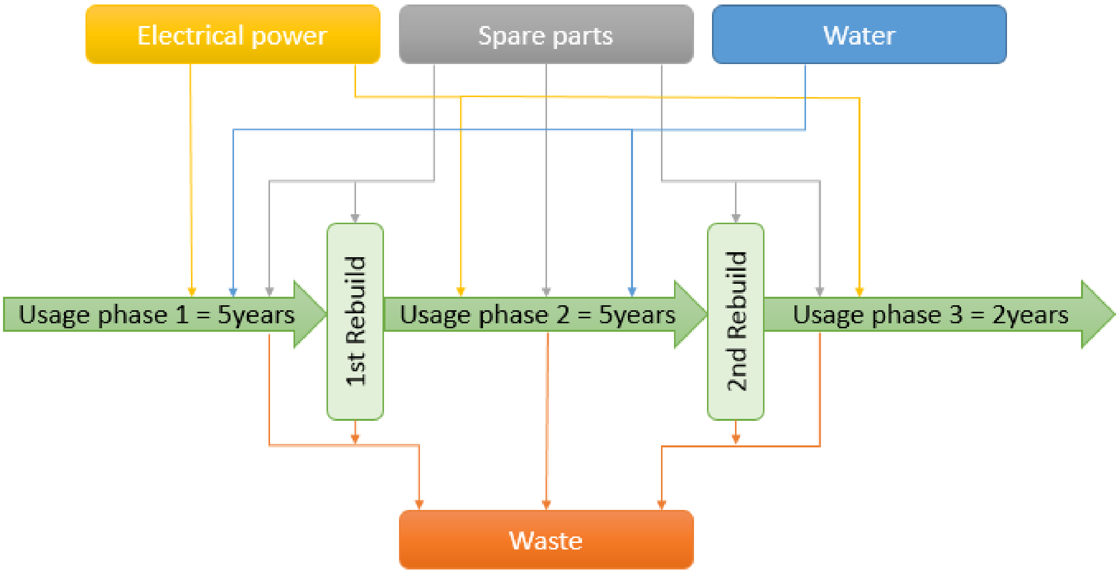

Figure 27: Simplified network map for the usage phase [67]

These hydraulic pump hours were also used for further calculations to determine the cutting and bolting time. These times were necessary to calculate the demanded electrical power and the water consumption. The relation between the pump time and the cutting time is shown in Figure 28. It was assumed that the proportion between the pump, cutting and bolting time are constant for the whole usage phase.

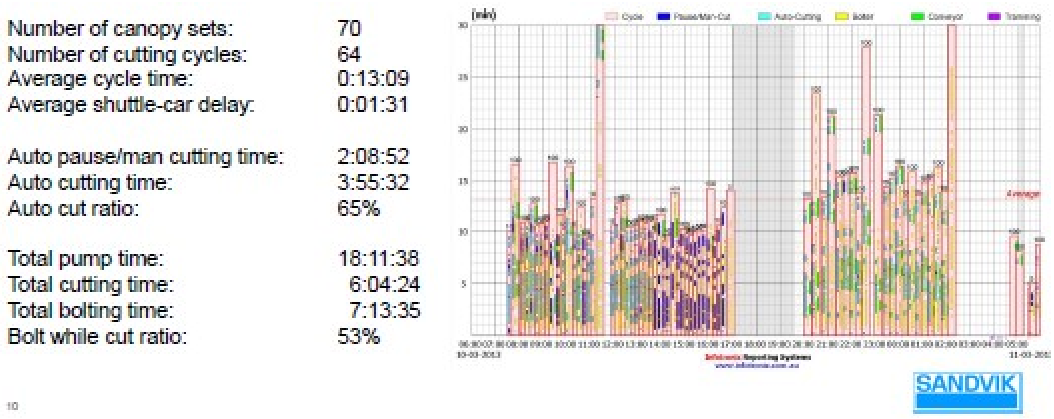

Figure 28: Cutting cycle including pump time and bolting time [68]

[67] Source: own figure
[68] Sandvik (2013), p. 10

This relationship between the pump time, the cutting time and the bolting time was used to calculate the cutting time and the bolting time of one year:

$$pump\ time_{24h} = 18hours11min38sec$$

$$cutting\ time_{24h} = 6hours04min24sec$$

$$bolting\ time_{24h} = 6hours04min24sec$$

$$pump\ time_{cutting\ cycle\ 1year} = 3{,}000\ hours$$

$$\frac{pump\ time_{24h}}{cutting\ time_{24h}} = \frac{pump\ time_{1year}}{cutting\ time_{1year}}$$

$$cutting\ time_{1year} = \frac{pump\ time_{1year}}{pump\ time_{24h}} * cutting\ time_{24h}$$

$$\frac{pump\ time_{24h}}{bolting\ time_{24h}} = \frac{pump\ time_{1year}}{bolting\ time_{1year}}$$

$$bolting\ time_{1year} = \frac{pump\ time_{1year}}{pump\ time_{24h}} * bolting\ time_{24h}$$

$$pump\ time_{1year} = 3{,}000\ hours$$

$$cutting\ time_{1year} = 1{,}001.54\ hours$$

$$bolting\ time_{1year} = 1{,}191.70\ hours$$

These operating time data were used for the calculation of the consumed electric power and water.

- Electric power consumption

There are various electric motors used to operate a Miner Bolter. The different motors and their power output is shown in Figure 29. To calculate the power consumption, different factors had to be considered. These factors were operating hours, power output, efficiency factor, operating point, and depending on which motor was considered, also the share between the "cutting unit" and "bolting unit".

Electric supply	[V]	1140
Electric supply	[Hz]	50
Total installed power	[kW]	546
Cutter motor	[kW]	1 x 270
Hydraulic drive motor	[kW]	1 x 132
Loader motors	[kW]	2 x 36
Conveyor motor	[kW]	2 x 36

Figure 29: General electric data of the MB650 [69]

[69] Sandvik (2013), p. 16

Efficiency factors for the cutter motor, loader motors and conveyor motors were extracted from the operating manual. The operating hours depend on which motor equals to the pump time or cutting time. The electrical power consumption calculation of all electric motors is shown in Table 13.

Table 13: Electrical power consumption calculation for the electric motors

	Cutting motor	Hydraulic drive motor	Loader motor	conveyor motor
Output [kW]	270	132	32	32
Operating hours [h]	1,001.54	3,000	1,001.54	1,001.54
Efficiency factor	0.95	0.92	0.9	0.9
Input Power [kW]	283	143.5	40	40
operating point	80 %	60 %	80 %	80 %
Annual consumption [kWh]	226,749	258,300	32,049	32,049
annual consumption [MJ]	816,297	929,880	115,378	115,378

All engines except the hydraulic drive motor are used by the cutting unit. The hydraulic drive motor is responsible for the movement, the drilling for the rock bolts and the water supply for the cooling and dust binding. To allocate the power consumption to the appropriate module it was assumed that 55 % of the consumption is caused by the “cutting unit” and 45 % by the “bolting unit”. This estimation was applied in consultation with Sandvik.

The GaBi database provides an Australian grid mix to model it in Umberto. The database entry requires mega-joule so it was necessary to calculate the consumption into the same unit. The power consumption of the two and five year usage cycles are shown in Table 14.

Table 14: Power consumption of the two different usage cycles

	module	
	Cutting unit	**Bolting unit**
2 years of usage	3,578,483 MJ	836,892 MJ
5 years of usage	8,946,207 MJ	2,092,230 MJ

- Water consumption

The Miner Bolter uses water to cool the cutting and drill bits as well as to bind the dust. For this reasons the machine uses a complex water sprinkle system. On one hand the used water accumulates on the floor. A part of this water just seeps away and another part is pumped out of the mine site. On the other hand, the water is imbibed by the coal and the wet coal is transported up to the surface.

The required water had to be calculated and allocated to the two modules.

For the bolting unit the water consumption was defined in consultation with Sandvik. The Miner Bolter was estimated to use 75 l per excavated meter. In order to convert these litre per meter into litre per hour or litre per day some calculation and research was necessary. By using the notes and scenario seen in Figure 28 it was possible to calculate the meter per cutting hour. One cutting cycle is approximately equal to one headed meter. In 6hours04min cutting hours 64 cutting cycles are ran through. This means when the Miner Bolter cuts one hour it will head 10.54 m forward. And for 10.54 m, 790.1 l water are required for cooling and dust binding. By extrapolating these calculations it was possible to estimate the water consumption per year and per usage phase. Important to note is that the treated scenario does not cut 6hours04min per day. Details about the calculation of the cutting hours are explained in the beginning of this chapter. The results of the water consumption for the bolting unit is shown in Table 15.

Table 15: Water consumption of the bolting unit of a MB650

Name [unit]	Value
Consumption per meter [l]	75.0
meter per day	29.0
meter per year	10,550.5
consumption per year [l]	791,290.5
consumption 2 years [m³]	1,582.6
consumption 5 years [m³]	3,956.5

Besides for the cooling of the cutting bits, the cutting unit has several additional water jets for several reasons. The different water jets and their consumption are shown in Table 16. Summed up they consume 98 l water per minute if the machine is cutting. Regarding the 1001.5 hours per year the Miner Bolter requires 5,889 m³ water. Referred to the two different usage phases of five years and 2 years the water consumption of each usage phase can be extrapolated. The results are also shown in Table 16.

Table 16: Different water jets and consumption by the cutting unit of a MB650

Name	Consumption
Canopy	16 l/min
Conveyor	16 l/min
Apron	22 l/min
Cutterbroom	44 l/min
Per year	5,889 m³
2 year phase	11,778 m³
5 year phase	29,445 m³

For the modelling in Umberto NXT the database entry “Water”, i.e. ground water, was applied without any specific geographical links. The waste water leaves the system boundaries, as already described, in three ways: absorbed by the produced coal, pumped up by external water pumps and seeping into the floor. Simplified, just one database entry for emissions “Water (groundwater from technosphere, waste water) [Other emissions to fresh water]” was selected and the amount of water was 1:1 as it was for the input of the corresponding module.

It is important to state that the water consumption did not affect the environmental impacts. The consumed water was modelled and simulated. Furthermore, the consumption was changed significantly but the environmental impacts did not change. The required water for cooling and other processes leaves the system 1:1 which means the amount of water entering the system is also leaving the system and only the contamination of the water was considered by the “CML2001” method. But there were no further data available about the degree of pollution in the water and it would have gone beyond the scope of this master thesis to start a detailed analysis of the water pollution.

- Spare parts

Another part of the usage phase is the supply with spare parts. Additionally to the spare parts, the production of the raw materials and the transportation for the spare parts had to be taken into account.

For the transportation of the spare parts it was assumed that they are all purchased by Sandvik Zeltweg and also manufactured in Zeltweg. This means that the transport route is the same as described in chapter 3.2.3.

The raw material production was also assumed to be located in the same plants as already the materials for the “manufacturing and assembly” phase. As a result all pre-processes modelled in Umberto were copied for this phase. It is worth mentioning that it is not enough to link the required materials for the spare parts to the pre-processes of the “raw material” phase. The reason for this is that the environmental impacts caused by the spare parts would be taken into account in the “raw material phase. This means that copying these pre-processes and pasting them in the usage phase was essential.

All materials for the spare parts were split into the different spare part groups including the cutting gear, pumps, crawler string and running gear. If the spare parts were responsible for a large share of the environmental impacts it would be possible to analyse which spare parts affect the phase more than others in a future LCA. The impact share and results of the spare parts are explained in chapter 3.3.4 in Table 23.

All spare part inputs in the usage and rebuild processes had to be balanced on the output side of these processes. Depending on the recycling rate they were separated into two mass fluxes on the output: (1) waste for disposal (2) waste for recovery. The recycling rate is described in chapter 3.2.5.

The mass flux “waste for disposal” was split into the following two basic materials: ferrous metals and plastic. The GaBi database does not contain additional disposal processes for synthetic rubber or polyester so it was necessary to summarize all non-metals in the group plastic waste. The landfill process tree is shown in Figure 30.

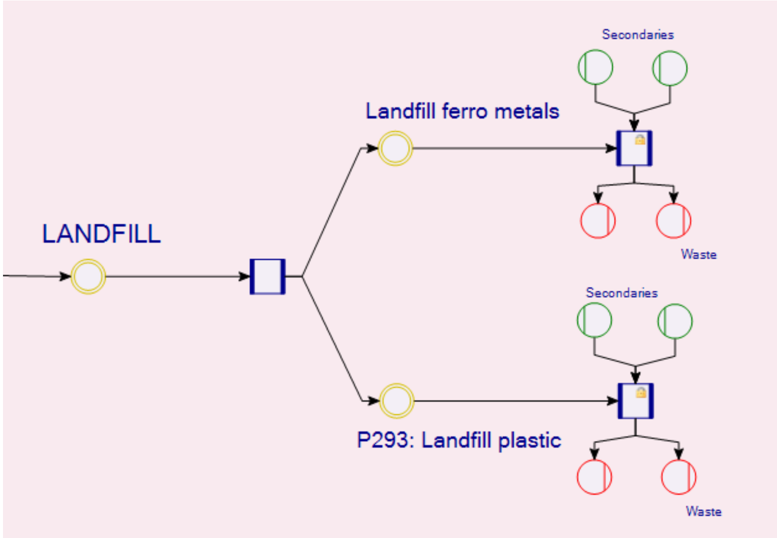

Figure 30: Disposal process tree of spare parts [70]

According to the manufacturing of the spare parts, the mass flux "waste for recovery" is separated into different materials as it was done in the "manufacturing and assembly" phase. The recycling tree in Umberto is similarly modelled as the one in Figure 24. The recycling tree also contains one recycling process for plastic waste. For rubber and rubber similar materials the GaBi database does not provide any recycling processes so they were added to the recycling of plastic. The accumulated waste for landfill and recycling of the cutting unit is shown in Table 17.

Table 17: Waste for recycling and landfill of the different usage phases and rebuild (cutting unit)

	Material	Usage phase 1	Rebuild 1	Usage phase 2	Rebuild 2	Usage phase 3
Land -fill	Ferro metals [kg]	808	1,423	944	1,407	404
	Plastic [kg]	42	2.42	12	22	8
Recycling	Steel [kg]	16,013	26,703	17,783	26,732	7,693
	Aluminium [kg]	48	114	54	114	0
	Copper [kg]	81	271	96	266	18
	Plastic	27	46	236	48	117

An important part of the spare parts was the exchangeable cutter bits on the cutting drum. In consultation with the experts of Sandvik the cutter bit consumption was compiled. A MB650 has

[70] Source: own figure

an average consumption of 300 cutter bits per month. This means for the operation 3,600 cutter bits per year are required. They are used until a major part of them is worn out and then they get replaced. For the modelling in Umberto it was assumed that the cutter bits lose 30 % of their mass until they get replaced. This means that 30 % of their material composition scatters into the environment as dust. This was modelled by the GaBi database under the emission entry “Metals (unspecified) [Particles to fresh water]”. The remaining 70 % of the cutting bits are recycled and landfilled together with the other spare parts and at the appropriate recycling rate.

- Hydraulic fluid and gear oil

To operate the MB650 it is essential to exchange the hydraulic fluid and the gear oil periodically. This depends as well on the contamination degree. Because no data about any contamination records were available the periodical approach was used. The exchange periods were extracted from the maintenance manual of the MB650/269.[71]

The first change of the hydraulic fluid is after 400 hours. Referring to the operational manual the fluid gets changed after every 1,000 hours or annually. The hydraulic pump operates in average 3,000 hours per year which makes three changes per year necessary. In regard to the three usage processes there are two 5-year cycles and one 2-year cycle. The MB650 uses 600l of hydraulic fluid.[72]

$$hydraulic\ fluid_{5year\ cycle} = first\ change + annual\ change * years$$

$$hydraulic\ fluid_{5year\ cycle} = 600 + 3 * 600 * 5 = 9{,}600 litre$$

$$hydraulic\ fluid_{2year\ cycle} = first\ change + annual\ change * years$$

$$hydraulic\ fluid_{5year\ cycle} = 600 + 3 * 600 * 2 = 3{,}600 litre$$

A drawback in the modelling in Umberto was that the GaBi database does not contain a hydraulic fluid. The most similar fluid offered by GaBi is lubrication oil. This pre-process was selected for hydraulic fluid and for the gear oil. To consider the difference of hydraulic fluid and gear oil a different density was selected. The maintenance manual provided the change rate in litre and the GaBi database and pre-processes provided lubrication of oil into kilos. With this knowledge it was possible to calculate the required hydraulic fluid and gear oil in the unit kg.

$$density_{hydraulic\ fluid} = 0.88\ kg/litre$$

$$density_{gear\ oil} = 0.9\ kg/litre$$

The first change of the gear oil is required after 30 hours. Afterwards every 1,000 hours or every 6 months the gear oil is required to be changed. The running time of these gearboxes is equal to the calculated annual cutting time by 1,005 hours per year. This means that the changing period for the gear oil depends on the 6 months and not on the used time. The gear oil is mainly

[71] Cf. Sandvik (2014), pp. 325–330
[72] Cf. Sandvik (2014), pp. 325–330

used in the cutter gearbox, the leader gearbox and the conveyor gearbox. All gearboxes together require 200l oil and inclusive the motor oil it results in 204l oil for every 6 months.

$$gear\ oil_{5year\ cycle} = first\ change + annual\ change * years$$

$$gear\ oil_{5year\ cycle} = 204 + 2 * 204 * 5$$

$$gear\ oil_{2year\ cycle} = first\ change + annual\ change * years$$

$$gear\ oil_{2year\ cycle} = 204 + 2 * 204 * 2$$

3.2.5 End-of-Life

As a last phase of a product life cycle the "end-of-life" phase defines what happens with the product after the usage phase. Will the product be reused, recycled or disposed on a landfill site?

The International Standard "Earth-moving machinery – Recyclingability and recoverability – Terminology and calculation method" ISO 16714:2011 specifies a method for calculating the recyclability and recoverability rate. An overview of the recyclability rate and recoverability rate is shown in Figure 31. To apply this calculation method more data about the pre-treatment, dismantling or metals separation were required than provided. As a result, this standard could not be applied and a simplification was necessary.

<table>
<tr><td></td><td colspan="2">Recovery</td><td>Undefined residue</td></tr>
<tr><td>(Component parts)
Re-use</td><td>(Materials)
Recycling</td><td rowspan="2">(Materials)
Energy recovery</td><td rowspan="3">(Materials)</td></tr>
<tr><td colspan="2">Recyclability rate a</td></tr>
<tr><td colspan="3">Recoverability rate a</td></tr>
<tr><td colspan="4">Total shipping mass</td></tr>
</table>

Figure 31: Recyclability rate and recoverability rate overview according to ISO 16714:2011 [73]

Based on Katariina Rouhiainen (2008), one general recycling rate for the product was applied for this LCA. According the directive 2000/53/EG of the European Parliament and the Council of the European Union about end-of-life vehicle the recycling rate had to reach 80% and the recovery rate 85 % until 2006. The directive defines additionally an increase of the recoverability rate of up to 95 % in 2015.[74] This means just 5 % of the weight is allowed to be disposed as landfill. Because a recoverability rate was difficult to apply in a LCA without further details, a simplification was used.

The recyclability rate was easier to model in Umberto and two scenarios were assumed and calculated. The first scenario assumes a recyclability rate of 95 % and a landfill rate of 5 %. The

[73] ISO 16714:2011, p.3, fig.1
[74] Cf. European Parliament; Council of the European Union (2000), p. 38

second scenario assumes a recyclability rate of 90 % and a landfill rate of 10 %. These two different scenarios take into account that this directive is maybe not applied in Australia and the directive call is for a recoverability rate of 95 % in 2015 and not a recyclability rate of 95 % in 2015.

These two recyclability rate scenarios were also applied to the worn-out spare parts of the usage phase as well as for the metal scrap and chips of the manufacturing and assembly phase.

As for the waste of the ”usage phase” and the ”manufacturing and assembly phase” the MB650 was split into various material groups depending on the material relation of the raw materials which are necessary to build an MB650. Finally, a similar recycling process tree as in Figure 24 and disposal tree as in Figure 30 was used for the end-of-life simulation.

As explained in chapter 3.2.2 for the sub-items metal scrap and metal chips the database entry “Credit for recycling of steel scrap” was used to model the recycling of the steel. This database entry results in a credit for scrap metal. Parts of this steel scraps are used in the raw material phase to manufacture different steel alloys. This means the credit of the steel scrap does not reduce the environmental impacts directly but it reduces the required steel scrap in the raw material phase and for the production of the spare parts. Concluding, it reduces the required input of scrap steel. During total life time of the MB650 237,062 kg steel scrap accumulates by the recycling processes. For the manufacturing of the raw materials required in the manufacturing and assembly phase but also for the spare parts during usage, 162,507 kg steel scrap are required. This results in a positive steel scrap credit of 74,555 kg.

3.3 Impact Assessment (IA)

The next stage of the LCA after the inventory analysis and the modelling in Umberto NXT is the impact assessment.

As already explained in chapter 3.1.2 Umberto and GaBi support a big number of various impact categories. Steinmann (2016) and his team analysed the relevance of impact categories.[75] In coordination with Sandvik eight impact categories were selected. These categories are in accordance with Steinmann's research. The results of the following impact categories are shown in detail in this LCA:

- Abiotic Depletion (ADP fossils)
- Abiotic Depletion (ADP resources)
- Global Warming Potential, incl biogenic carbon (100years)
- Human Toxicity Potential (HTP infinite)
- Acidification Potential (generic)
- Eutrophication (generic)
- Freshwater Aquatic Ecotoxicity (FAETP infinite)
- Terrestrial Ecotoxicity (TAETP infinite)

The characterization model of abiotic depletion is a function of natural reserves and their rate of extraction. It makes it possible to give a statement about the relationship between consumed elements and their reserves provided by the earth's crust.[76] Since 2009 the abiotic depletion is split into "abiotic depletion of fossil fuels" and into "abiotic depletion of elements". The impact category indicator is calculated by multiplying the abiotic factors by the mass of the extracted element. The formula for the calculation is:

$$abiotic\ depletion = \sum_i ADP_i * m_i$$

The global warming potential was used to compare and add the global warming impacts of different gases. This was accomplished through measuring how much energy the emissions of one ton of a specific gas are absorbed relatively in contrast to the emissions of one ton of carbon dioxide (CO_2). The GWP of one ton of Methane (CH_4), for example, is 21 times higher than of one ton of CO_2.[77]

The human toxicity potential is used to reflect the harms and health impacts of carcinogen and non-carcinogen chemicals released into the environment.[78] The most harmful by-products such as arsenic or sodium dichromate are mainly created through the electric production from fossil fuels. The impact category is measured in 1.4-dichlorobenzene equivalents.[79]

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[75] Cf. Steinmann, Z. J. N. et al. (2016)
[76] Cf. van Oers, L.; Guinée, J. (2016), p. 5
[77] Cf. US Environmental Protection Agency (2016), p. 1
[78] Cf. Mc.Kone, T. E.; Hertwich, E. G. (2001), p. 105
[79] Cf. Acero, A. P. et al. (2014), p. 19

Acid gases that are released into the air react with water in the atmosphere and form "acid rain". If this rain falls, and gets absorbed by plants, soil and surface water, it causes a reduction of the pH value and harms the environment. Consequently it damages the quality of the ecosystem and decreases the level of biodiversity. The equivalent unit of this impact category is one kilogram of sulphur dioxide (SO_2).[80]

Eutrophication represents the opposite of the acidification potential. In water it will result in nutrient over-enrichment and lead to hypoxia and harmful algal boom. Phosphate (PO_4) is used as an equivalent unit.

The freshwater aquatic ecotoxicity is part of the ecotoxicity impact category group. Ecotoxicity can be split into freshwater aquatic ecotoxicity, marine ecotoxicity and terrestrial ecotoxicity. As a reference equivalent unit 1.4-dichlorobenzene is used for all three of them.[81] For this LCA the marine ecotoxicity was not taken into account because it is not quite relevant for subsurface coal mining.

Various scenarios were applied to determine the changing impact on the environment. However, not all scenarios were analysed. For example the change of the transport distance in the "manufacturing and assembly" phase does not affect the overall results because the influence of the whole "manufacturing and assembly" phase is marginal. Through analysing the "manufacturing and assembly" phase separately the effect of the transport and the adjustment of the distance can be determined by analysing changes in the environmental impact.

Depending on which scenario is analysed, the environmental impacts were calculated separately based on the following scheme:

- Recyclability rate

The modification of the recyclability rate can be seen in the overall results. The basic scenario implies that the recyclability rate is 95 % as stated in the directive 2000/53/EG for end-of-life vehicles. The alternative recycling scenario assumes a recyclability rate of 90 %. This means the environmental impacts of the two different recyclability scenarios can be compared. Details about the recyclability rate are explained in chapter 3.2.5.

All other variables for example the electrical power supply or the transport distance were not changed in this scenario and are equivalent to their basic scenarios.

- Australian grid mix

The fourth biggest proven coal reserves were located in Australia in 2015.[82] As a result, also the energy sources of electric power generation is dominated by coal. In 2014 coal was the largest source of electricity generation in Australia with 61 % which is shown in Figure 33. However, in

[80] Cf. Acero, A. P. et al. (2014), p. 16
[81] Cf. Acero, A. P. et al. (2014), p. 17
[82] Cf. Statista.com (2016), https://www.statista.com/statistics/237096/proven-coal-reserves-of-the-top-ten-countries/ (Retrieved: 05.09.2016)

2013-14 the coal-fired generation had declined by 5 %. Renewable contributions to the Australian grid mix increased up to 14.9 % in 2014. Also a trend towards renewable energy suggests that the share of renewables will increase in the next few years. The Australian government agreed in 2015 to implement the Renewable Energy Target (RET). The RET involves the increase of the renewables share on the electricity generation to 23.5 % until 2020.[83] Christiaan Heyning et al. from McKinsey published in June 2016 a study about the role of natural gas in Australia's future energy mix. This study states that in 2030 renewables will contribute 37 % to the electric power generation.[84]

Regarding this future changes of the Australian grid mix two alternative energy scenarios were applied in this master theses to determine the environmental impacts of a Miner Bolter 650 in 2020 or 2030.

The GaBi database entry for the Australian grid mix considers a grid mix of the year 2014 which corresponds with the underlying literature research. Main contributors to the renewable power generation in 2014 were hydro (49.66 %), wind (27.5 %), photovoltaic (13.4 %), and biomass energy (9.4 %). Since it is not possible to determine the exact contribution in 2020 or 2030 it was assumed that the renewable energy mix stays the same and the total value increases proportional.

A Miner Bolter is designed to operate twelve years. The basic energy scenario considers the first five years of usage of the Australian grid mix as indicated in the GaBi database for 2014. For the remaining seven years of operation the share of renewable energy was considered to increase close to the RET target of 2020. This means that for the following seven years 23.5 % of the electric power would be generated by renewables. The average contribution of renewables to the electric power consumption is 19.86 % for the basic scenario.

The first alternative energy scenario assumes an increased input of 23.5 % of renewables to the electric power generation for the whole life time of a Miner Bolter of twelve years.

For the second alternative energy supply scenario the contribution of renewable energy sources to the power generation was increased up to 37 % for the total life time. This high share of renewables is in line with the forecasted grid mix in 2030.

In Umberto it was more complicated to model an alternative grid mix for the future energy scenario. The GaBi database entry for the Australian grid mix already contains the share of the renewables of the year 2014 and it was not possible to adjust this pre-process to fulfil the other scenarios. To consider also the two alternative energy supply scenarios an additional energy production process termed “T213” was implemented. This alternative energy supply process is fed by the four renewable electric power supplies from hydro, wind, photovoltaic and biomass plants which is shown in Figure 32. All these renewable electric power generation pre-processes are provided by the GaBi database. Depending on which energy supply scenario is analysed the share of this additional energy production process increases or decreases.

[83] Cf. Australian Government, https://www.environment.gov.au/climate-change/renewable-energy-target-scheme (Retrieved: 14.10.2016)

[84] Cf. Heyning, C.; Segorbe, J. (2016), p.4

The impact of this alternative scenario was analysed regarding the overall environmental impact. Also the impact of the usage phase was examined in detail.

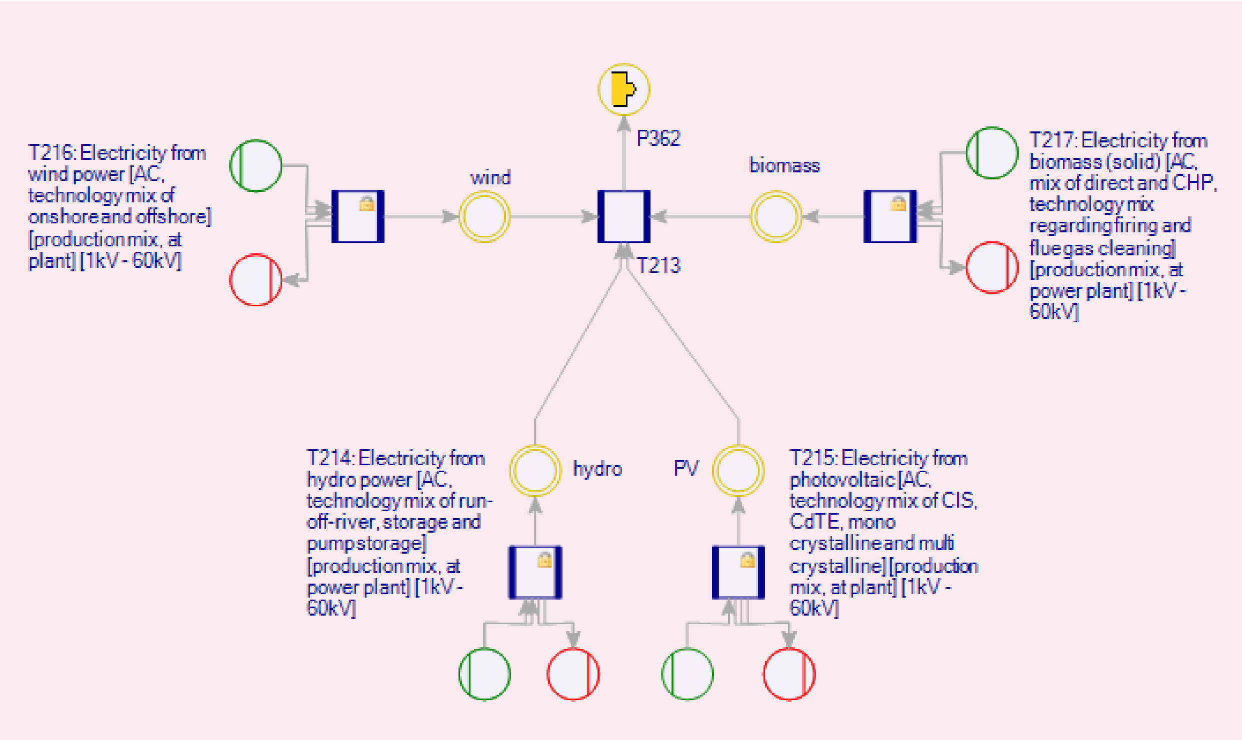


Figure 32: Alternative energy supply process [85]

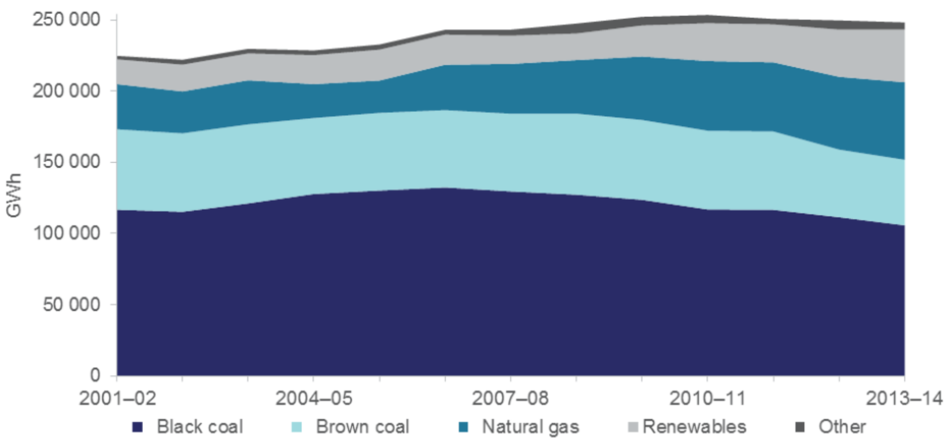


Figure 33: Australian electricity generation, by fuel type [86]

[85] Source: own figure
[86] Ball, A.; et al. (2015), p.20, fig. 4.2

- Transport distance

As explained in chapter 3.2.2, there are no specific data available regarding the manufacturing locations' origin of many purchased parts of the MB650. To compensate this lack of information alternative transport scenarios were assumed to determine the effect on the environmental impact of the "manufacturing and assembly" phase. If the impact of the transport distance would affect the environmental impacts significantly, further information would be necessary for a more accurate and detailed assessment.

The basic transport scenario assumes an averaged transport distance of 300 km. This means it was assumed that all parts are travelling 300 km from their original manufacturing location to the final assembly location in Zeltweg, Austria. For the alternative electrical supply and recyclability scenarios the basic transport scenario was considered. In return, for the various transport scenarios no other changes in the manufacturing and assembly scenario were taken into account and all other assumptions and variables besides the transport distance stayed constant.

Alternative transport scenarios consider a shorter average transport distance of 200 km and a longer transport distance of 400 km.

All results and interpretations of this scenarios are explained and shown in chapter 3.3.3.

3.3.1 IA - Total life cycle

The first impact assessment of LCA contains the environmental impacts separated into five various life cycle phases: "raw materials", "manufacturing and assembly", "distribution", "usage" and "end-of-life" phase. It considers the basic scenarios concerning transport distance, electrical supply and recyclability rate as explained in the introductions of chapter 3.3. The environmental impacts of the two modules "bolting unit" and "cutting unit" were combined. The results of the first impact assessment are shown in Table 18.

The results clearly show that the usage phase is mostly responsible for the environmental impacts in all impact categories. Except the impact category "abiotic depletion of resources" the "usage" phase cause between 86 % and 96 % of the environmental impacts in the other categories. The impact category "abiotic depletion of resources" is, as explained in the introductions of chapter 3.3, a function of natural reserves and their rate of extraction. Resources like iron, copper or aluminium are used to manufacture the miner bolter and the spare parts of the miner bolter. This is the reason why the life cycle phase "raw materials" is also responsible for a big part of the impacts in this category. Details about the environmental contribution and allocation to the different processes inside the "usage" phase are described in chapter 3.3.4.

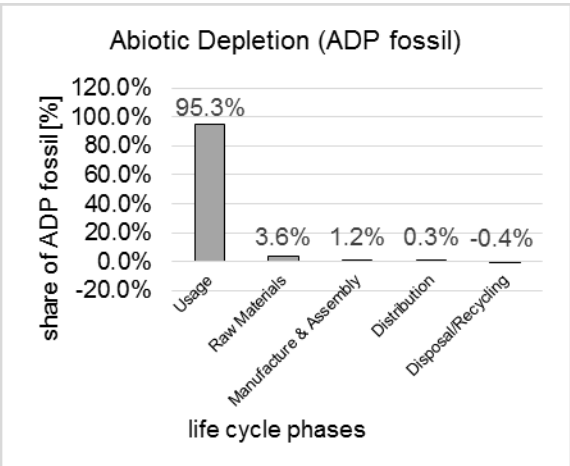
Following the "usage" phase as the main contributor for negative impacts on the environment the "raw material" phase is in all impact categories the second biggest contributor. Besides the impact categories "abiotic depletion of resources", "human toxicity", "freshwater toxicity" and "terrestrial ecotoxicity" the "raw material" phase represents a share of between 2.2 % and 3.8 % of the environmental impacts. For the toxicity categories the impact share increases up to 13 %. Further details about the raw materials are described in chapter 3.2.1.

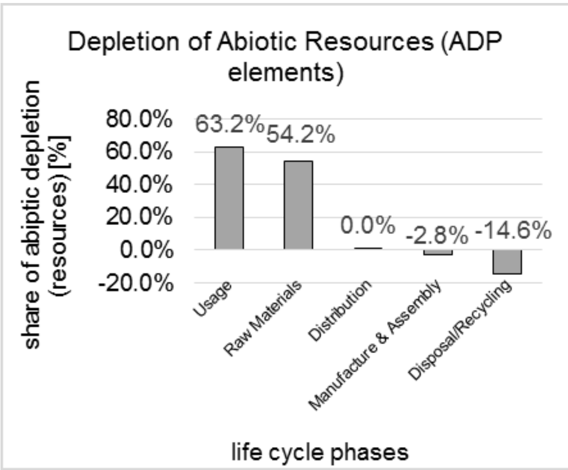
The “manufacturing and assembly” phase is on the third place regarding contribution to the environmental impacts, with the exception of the categories “depletion of abiotic resources (elements)”, the “acidification and eutrophication potential”. Regarding the “depletion of abiotic resources (elements)” the impact is negative because it contains the recycling processes of the metallic scrap and chips. Details about the environmental impacts and contributors in the manufacturing and assembly phase are explained in chapter 3.3.3.

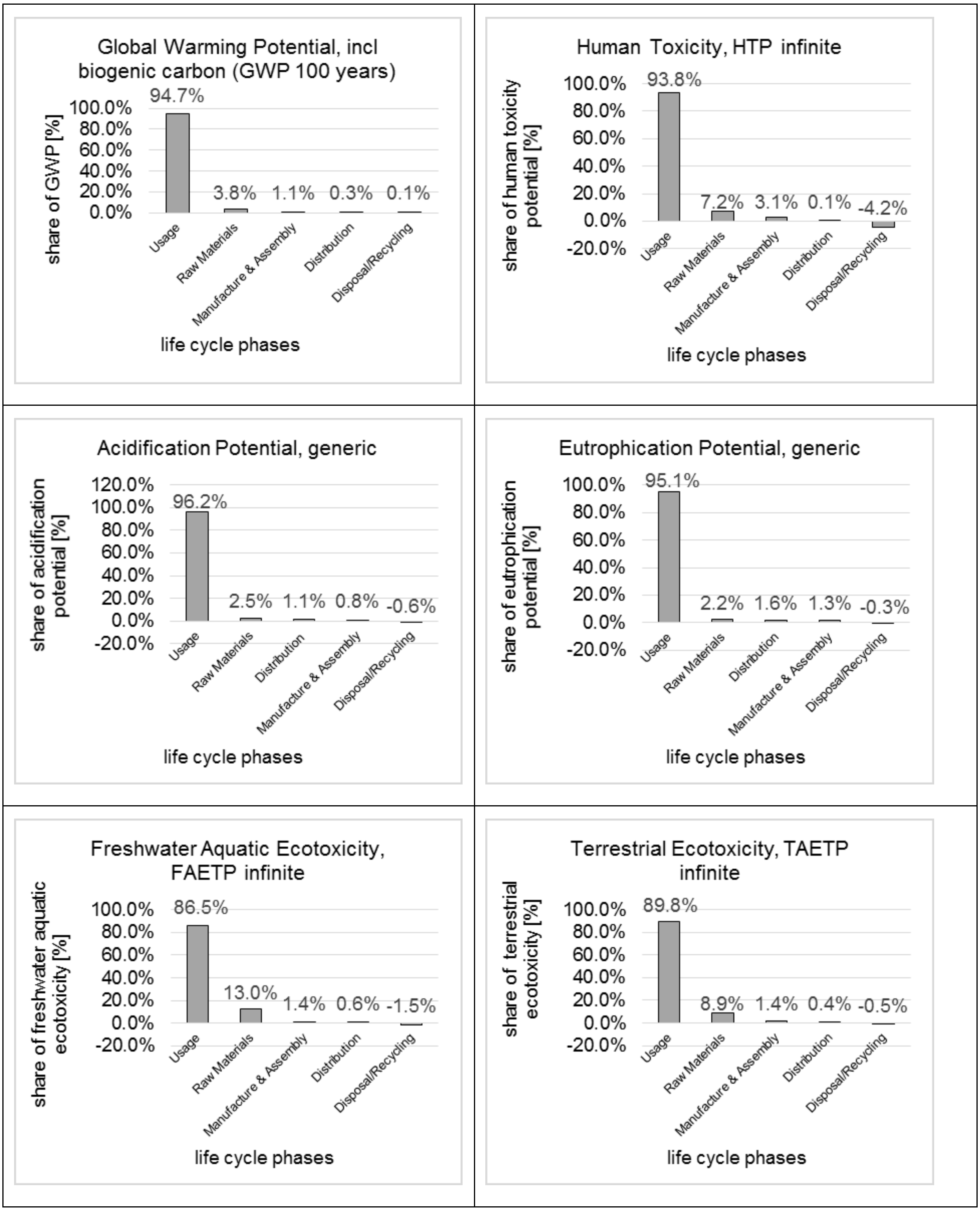
It has to be pointed out that there is a negative environmental impact within the disposal and recycling phase for all impact categories except the global warming potential. This means that the recycled resources can be used as a credit for the other phases. Especially in the abiotic depletion of resources the credit for disposal and recycling is relatively big in comparison with the other categories because this category outlines the usage of resources.

With regard to the total life time of the MB650, the distribution of the product from Austria to Australia has a share of 0 to 1.6 % of the environmental impacts. In the “abiotic depletion of resources” category the distribution does not cause any environmental impacts. The reason therefore is that the simulation only considers the fossil fuels required for the transport and no infrastructure or wear of the transport system, as described in system boundaries in chapter 3.1.2.

Table 18: Impact assessment of the basic scenario



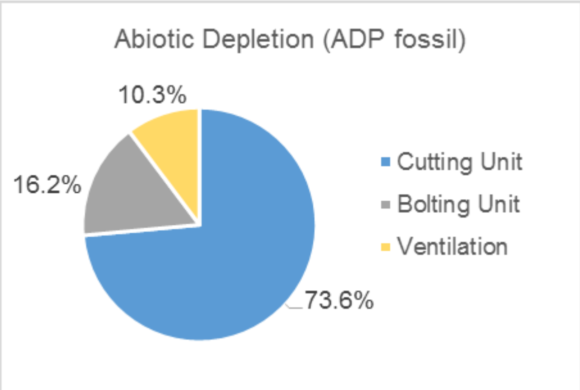


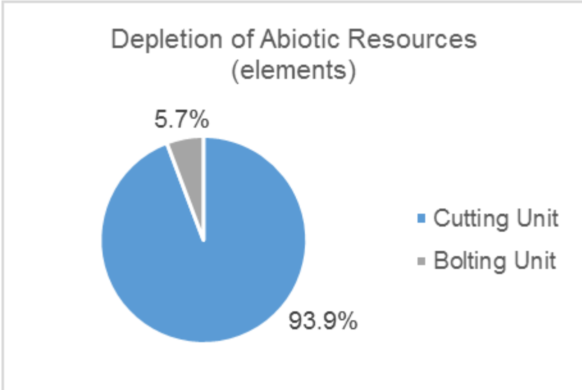


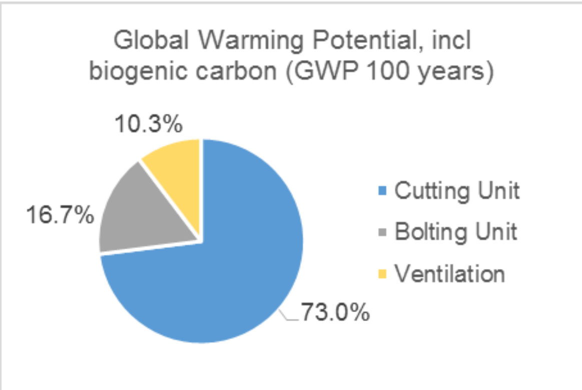
Besides the impact distribution of the different life cycle phases it is also interesting to analyse the share of the impact considering the two different modules and the external ventilation. The results are shown in Table 19. Clearly identifiably are the similar impact distributions among the different categories. Next to the category “depletion of abiotic resources (elements)” the cutting unit is responsible for approximately 73 % to 77.5 % of the overall environmental impacts. It is followed by the bolting unit with an impact share of 13.9 % to 16.2 %. Depending on the analysed category the external ventilation is responsible for between 8.6 % and 10.3 %.

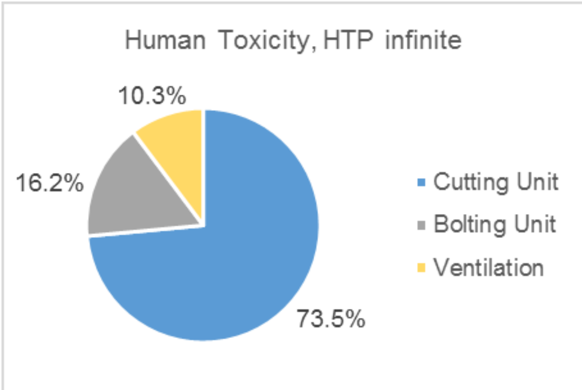
The only exception is the impact category “depletion of abiotic resources (elements)”. As explained in the system boundaries in chapter 3.1.2 the raw materials and manufacturing of the ventilation system were not considered in this LCA. Only the electrical power consumption was calculated, modelled in Umberto and considered in the impact assessment.

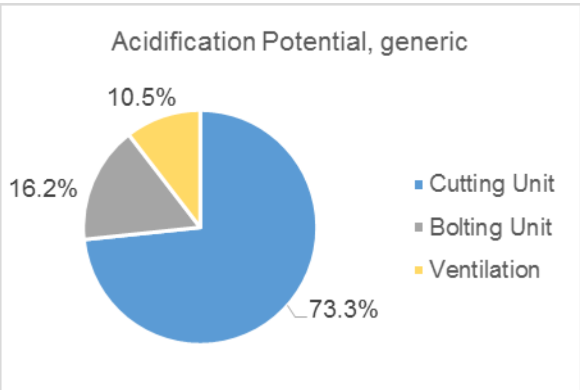
Table 19: Environmental impact distribution referring the cutting unit, bolting unit and the external ventilation

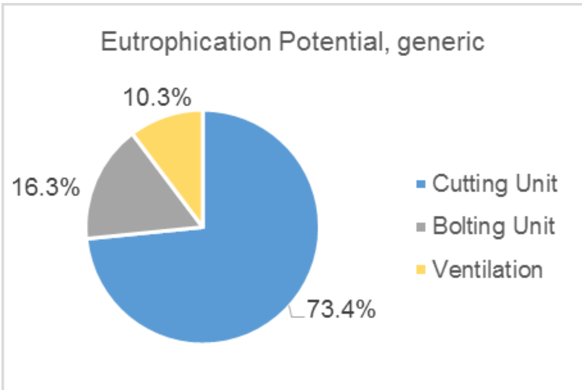


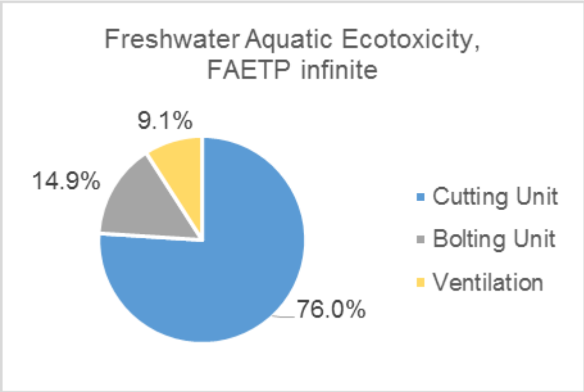


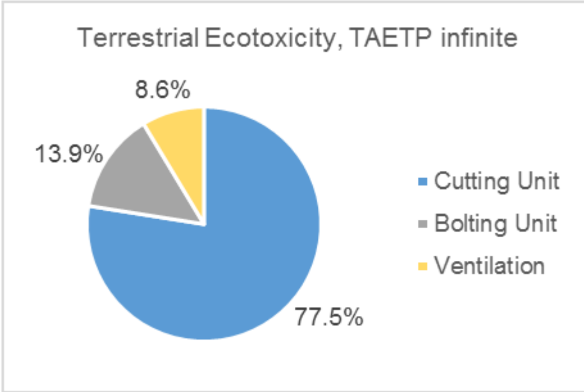












The next step of the life cycle impact assessment is the analysis of the various alternative overall scenarios. The first basic scenario, as already analyzed in Table 18 and Table 19, was defined with a recyclability rate (RR) of 95 % and an Australian grid mix as defined by the GaBi database of 2014.

The alternative scenarios were split into changes in the energy supply during the usage phase and changes of the recyclability rate. As already explained in detail in the introduction of chapter 3.3, the alternative energy scenarios assume changes in the share of renewables regarding the energy supply. The recyclability rate in these alternative energy scenarios is the same as for the basic scenario, which is a recyclability rate of 95 %.

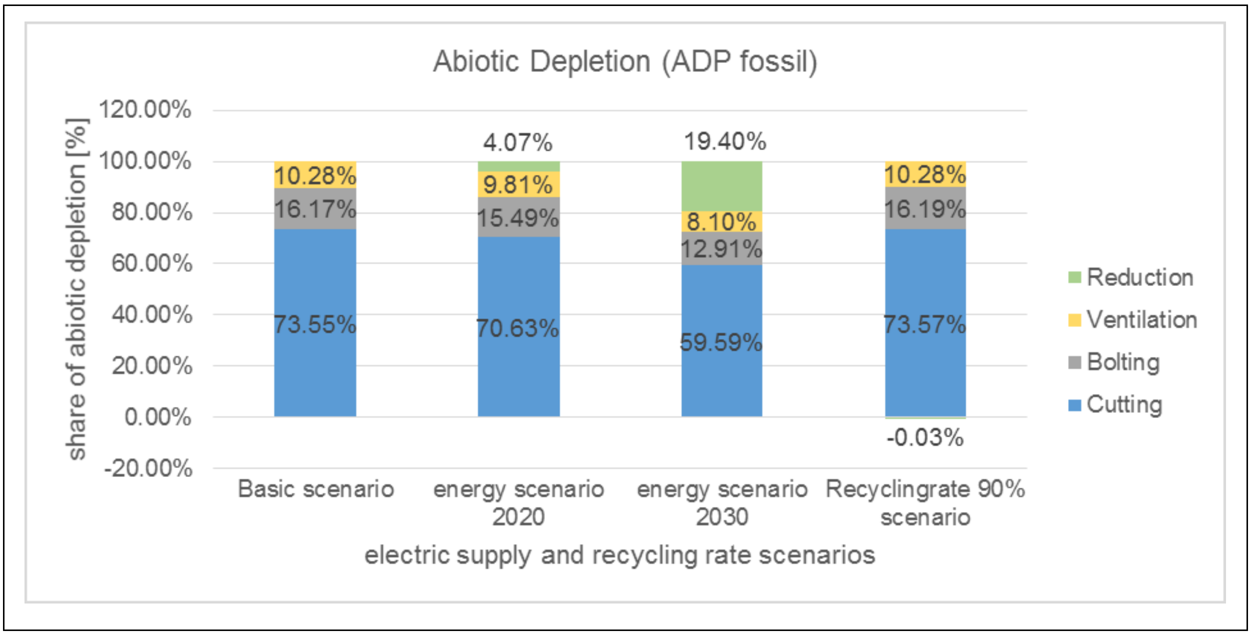
The first alternative energy scenario is called “energy scenario 2020” and it assumes a share of renewable power generation of 23.5 %. The results of the energy scenario 2020 are shown in Table 20. Except for the impact category “depletion of abiotic resources (elements)” in all other categories a significant decrease of the overall environmental impacts of 2.6 % to 4.08 % is visible. The overall life time reduction in the results is indicated by the green part in the diagram referred to as “reduction”. In addition, the results also represent the module depending share.

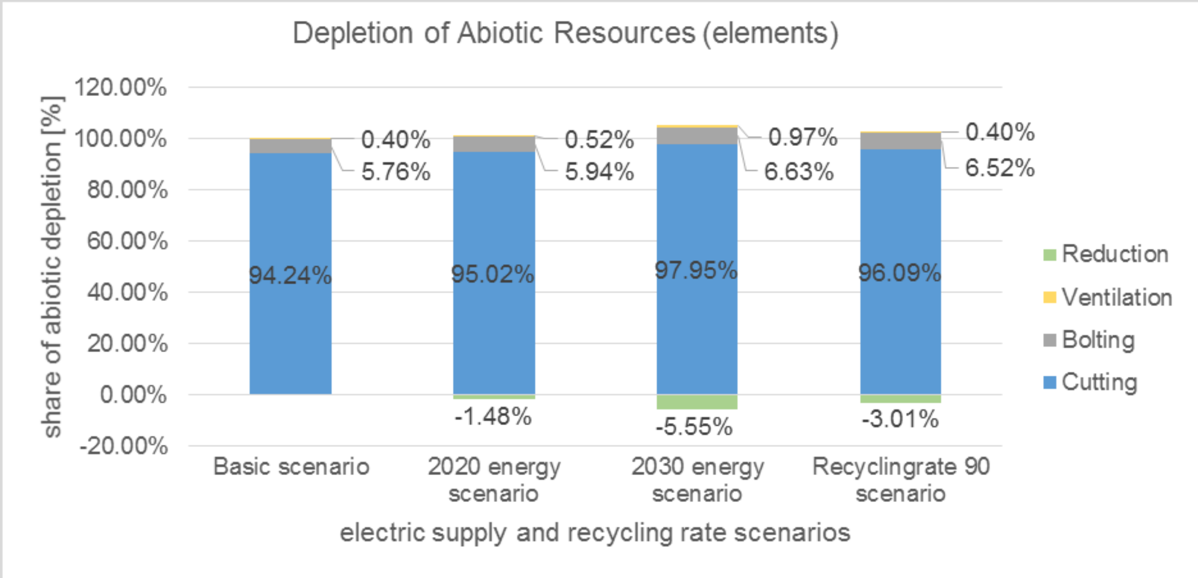
The module depending share shows that it is possible to analyse what module is more affected by the alternative scenario and it makes the exact impact noticeable. Concerning the first alternative energy scenario the major impact savings come from the cutting unit. Interesting is the impact category “depletion of abiotic resources (elements)” with a negative reduction.This means the overall environmental impacts are growing by increasing the share of renewable power generation. The “depletion of abiotic resources (elements)” is increasing by 1.48 % compared to the basic scenario. A reason for this increased consumption of resources could be that hydropower plants, photovoltaic plants and wind energy plants require more resources per generated MWh.

The second alternative energy supply scenario is called “energy scenario 2030” listed in Table 20. The share of renewable power generation is 37 %. Except for the category “depletion of abiotic resources (elements)” the reduced environmental impacts are significant. In the other categories the overall impacts are reduced by 12.4 % to 19.44 %. Interesting is the comparison of the 2030 scenario with the 2020 scenario. The share of renewable energy sources increases from 23.5 % to 37 % and the environmental impact reduction from the 2030 scenario compared to the 2020 scenario is enormous. Based on the 100% of the basic scenario the savings are up to 15 % higher than for the 2020 scenario. Remarkable again are the "depletion of abiotic resources (elements)". The overall impacts are approximately 5.5 % higher because of the higher share of renewables in the power generation.

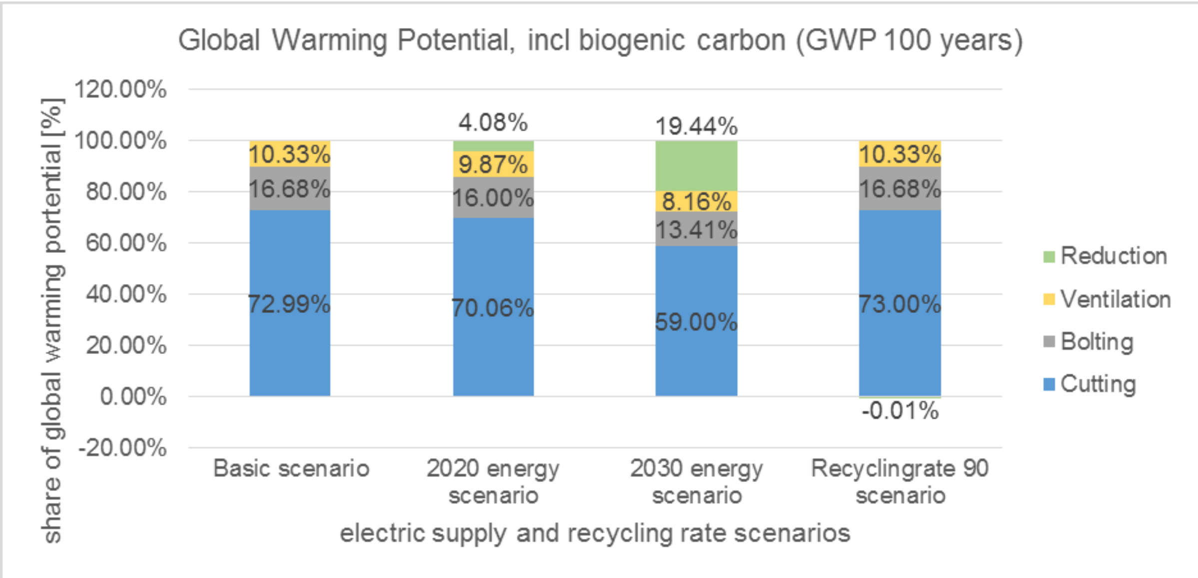
The alternative scenario regarding the recyclability rate shows a decrease of up to 90% and the disposal rate for landfill results in 10 % and not 5 %. The energy supply is the same as for the basic scenario. Details about the recycling scenario are explained in chapter 3.2.5 and the results of decreased recyclability rate are shown in Table 20. The reduced recyclability rate does not affect the impact of the external ventilation module because the materials and the end-of-life of this module is not considered in the LCA. The overall environmental impact is higher because the material credit is lower and the impact of the disposal processes increase. Nevertheless, the increased impacts are not significant. Except in the "depletion of abiotic resources (elements)" category the impacts are 0.01 % up to 0.4 % higher than in the basic scenario with a recyclability rate of 95 %.

Table 20: Life cycle impact assessment of the alternative energy scenarios

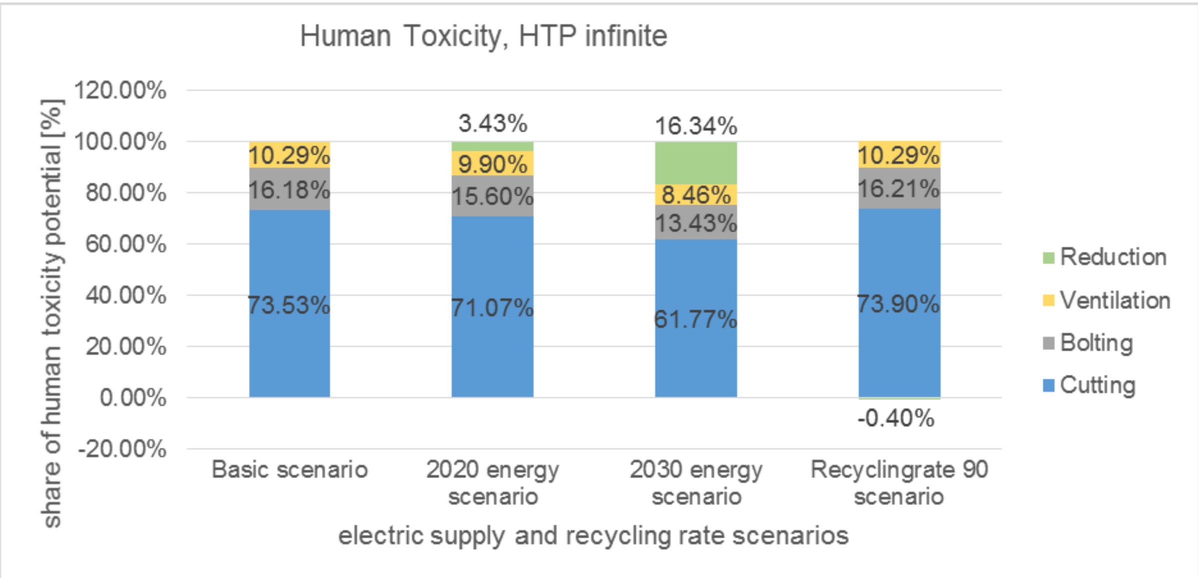




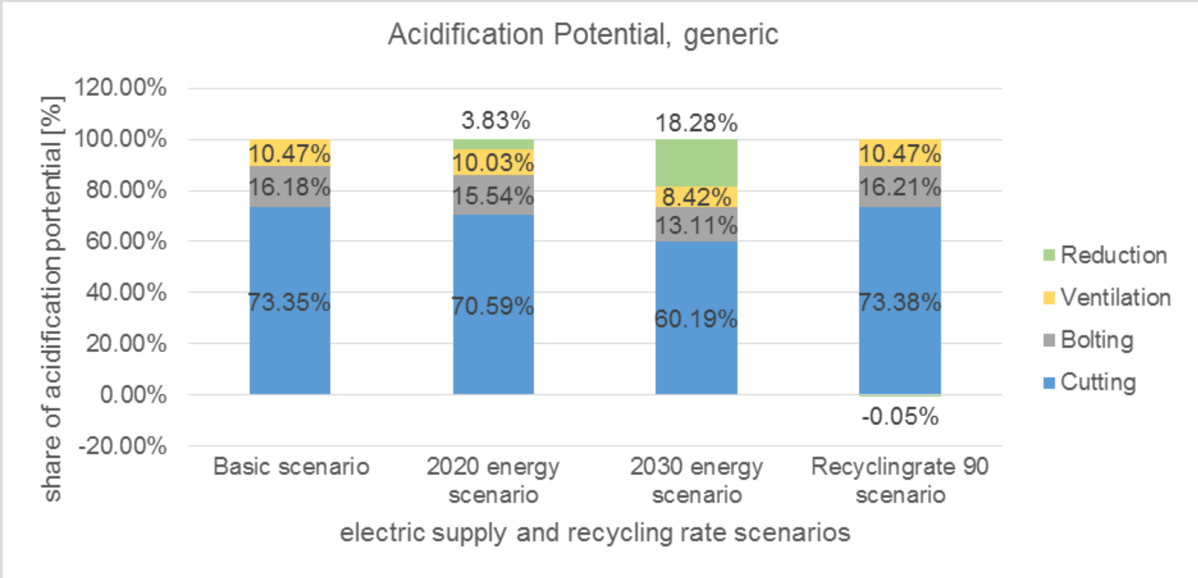
Depletion of Abiotic Resources (elements)
share of abiotic depletion [%]
120.00%
100.00%
80.00%
60.00%
40.00%
20.00%
0.00%
-20.00%
0.40%
5.76%
94.24%
0.52%
5.94%
95.02%
-1.48%
0.97%
6.63%
97.95%
-5.55%
0.40%
6.52%
96.09%
-3.01%
Basic scenario
2020 energy scenario
2030 energy scenario
Recyclingrate 90 scenario
electric supply and recycling rate scenarios
Reduction
Ventilation
Bolting
Cutting

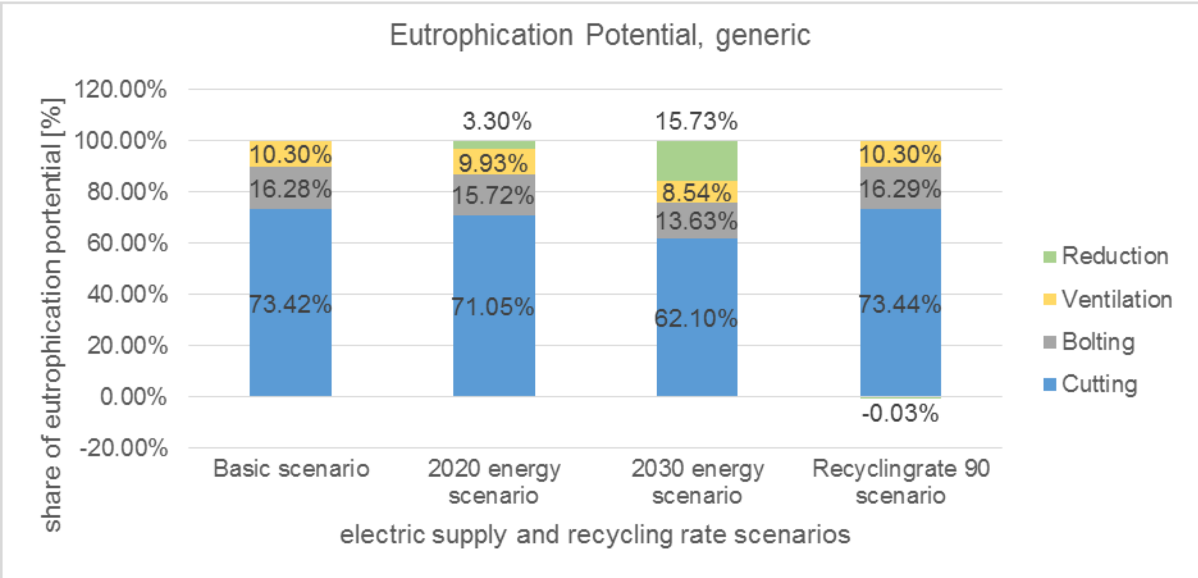


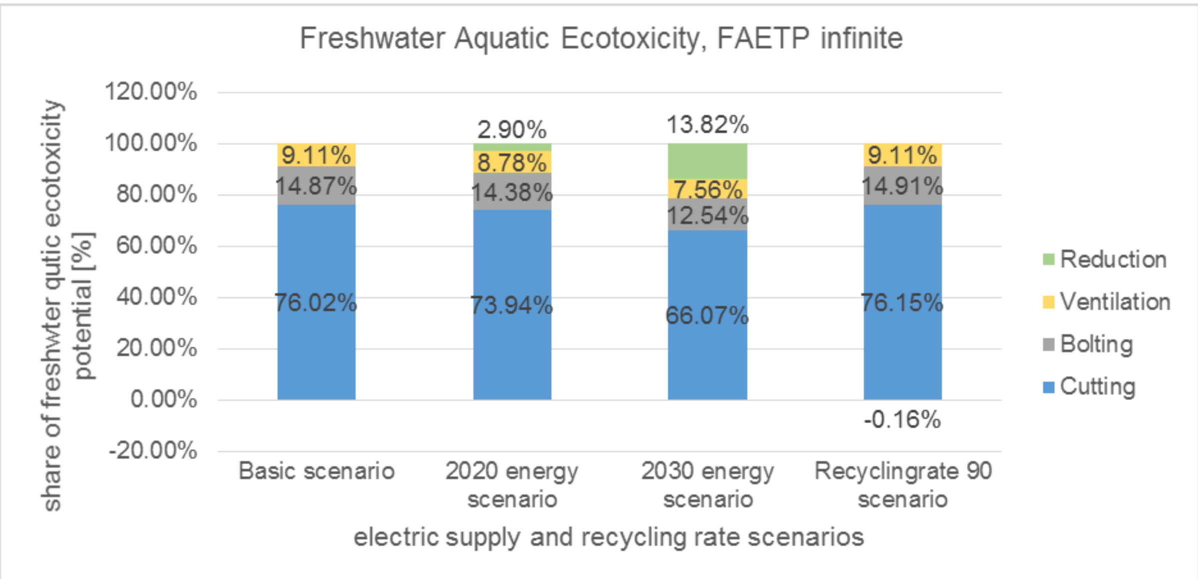
Global Warming Potential, incl biogenic carbon (GWP 100 years)
share of global warming potential [%]
120.00%
100.00%
80.00%
60.00%
40.00%
20.00%
0.00%
-20.00%
10.33%
16.68%
72.99%
4.08%
9.87%
16.00%
70.06%
19.44%
8.16%
13.41%
59.00%
10.33%
16.68%
73.00%
-0.01%
Basic scenario
2020 energy scenario
2030 energy scenario
Recyclingrate 90 scenario
electric supply and recycling rate scenarios
Reduction
Ventilation
Bolting
Cutting

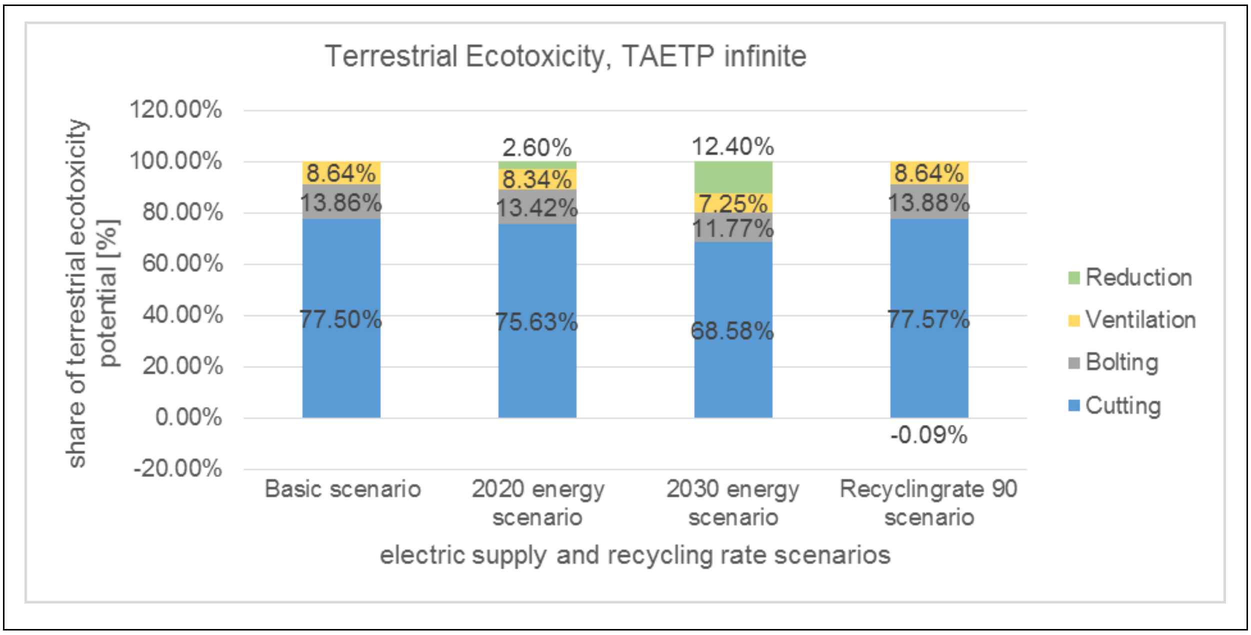


Human Toxicity, HTP infinite
share of human toxicity potential [%]
120.00%
100.00%
80.00%
60.00%
40.00%
20.00%
0.00%
-20.00%
10.29%
16.18%
73.53%
3.43%
9.90%
15.60%
71.07%
16.34%
8.46%
13.43%
61.77%
10.29%
16.21%
73.90%
-0.40%
Basic scenario
2020 energy scenario
2030 energy scenario
Recyclingrate 90 scenario
electric supply and recycling rate scenarios
Reduction
Ventilation
Bolting
Cutting


Acidification Potential, generic
share of acidification portential [%]
120.00%
100.00%
80.00%
60.00%
40.00%
20.00%
0.00%
-20.00%
10.47%
16.18%
73.35%
3.83%
10.03%
15.54%
70.59%
18.28%
8.42%
13.11%
60.19%
10.47%
16.21%
73.38%
-0.05%
Basic scenario
2020 energy scenario
2030 energy scenario
Recyclingrate 90 scenario
electric supply and recycling rate scenarios
Reduction
Ventilation
Bolting
Cutting


Eutrophication Potential, generic
share of eutrophication portential [%]
120.00%
100.00%
80.00%
60.00%
40.00%
20.00%
0.00%
-20.00%
10.30%
16.28%
73.42%
3.30%
9.93%
15.72%
71.05%
15.73%
8.54%
13.63%
62.10%
10.30%
16.29%
73.44%
-0.03%
Basic scenario
2020 energy scenario
2030 energy scenario
Recyclingrate 90 scenario
electric supply and recycling rate scenarios
Reduction
Ventilation
Bolting
Cutting


Freshwater Aquatic Ecotoxicity, FAETP infinite
share of freshwter qutic ecotoxicity potential [%]
120.00%
100.00%
80.00%
60.00%
40.00%
20.00%
0.00%
-20.00%
9.11%
14.87%
76.02%
2.90%
8.78%
14.38%
73.94%
13.82%
7.56%
12.54%
66.07%
9.11%
14.91%
76.15%
-0.16%
Basic scenario
2020 energy scenario
2030 energy scenario
Recyclingrate 90 scenario
electric supply and recycling rate scenarios
Reduction
Ventilation
Bolting
Cutting



3.3.2 IA - Raw materials

The raw material production phase is, as explained in chapter 3.3.1, in most categories the second biggest contributor to the environmental impacts. This chapter analyses in detail which material group is responsible for the impacts.

There are more than fifty different materials and alloys used to manufacture a MB650. In order to maintain a clear overview the materials are summed up in four different material groups: (1) cast Iron, (2) non-metal, (3) non-ferrous metal and (4) steel.

The (2) non-metal group contains materials like synthetic rubber, PVC, glass and impregnation resin. Aluminium, copper and copper containing alloys like CuSn12 are summed up in the (3) non-ferrous metal group. All different steel alloys such as 34Cr4 but also highly alloyed steel for example X5CrNiMo18-10 are summed up in the (4) steel group. Referring to one MB650 the proportional weight of the material groups is shown in Figure 34. The material group (4) steel counts for 87.7 % of the total weight of a MB650 followed by (1) cast iron with 9.7 % and the (2) non-metal group with 2 %. The (3) non-ferrous metal group contributes less than 1 % to the total weight of a MB650.

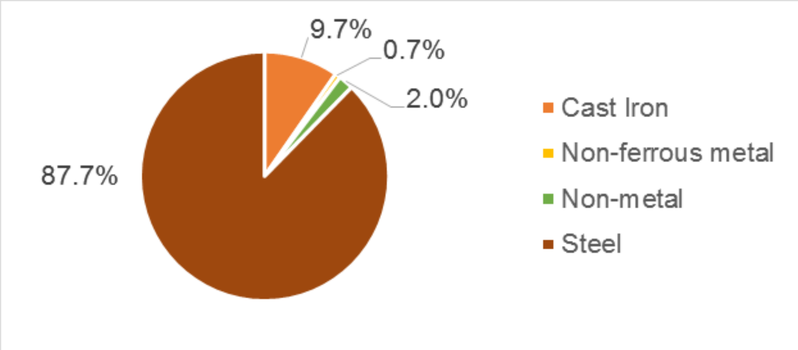


Figure 34: Proportional weight of the material groups (MB650) [87]

Detailed results of the impact assessment of the “raw material” phase are shown in Table 21. The proportional contribution of the various material groups regarding the impact categories “abiotic depletion of fossils”, “global warming potential”, “acidification potential” and “eutrophication potential” are similar to the proportional weight of the material groups. This means that the environmental impact is proportional to the weight of the according material group.

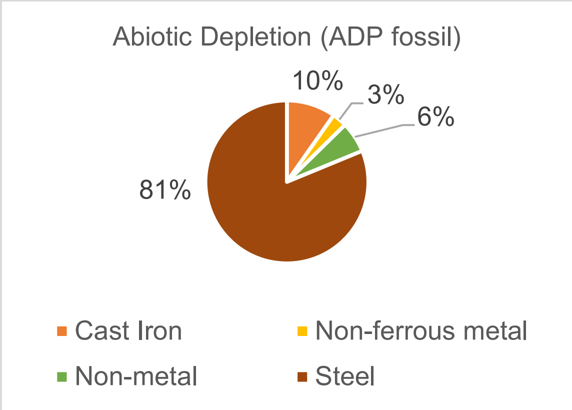
Interesting are the results of the category “depletion of abiotic resources (elements)” and the “human toxicity”. The (3) non-ferrous metal contribute only 0.7 % to the total weight yet it is responsible for major environmental impacts regarding these categories. A reason for this disproportional contribution is copper which is allocated to this material group.

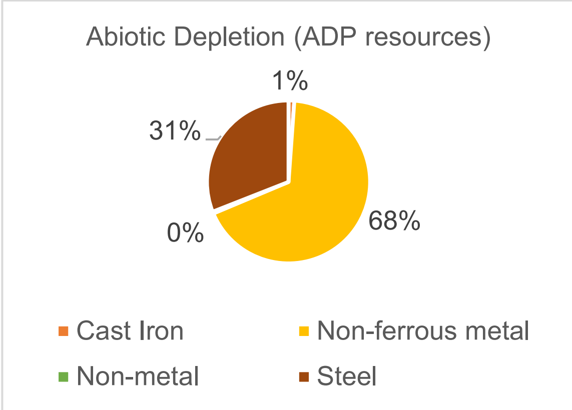
To analyse the high impact about the abiotic depletion of resources (elements) and why copper stresses such high amounts of resources, the required input to produce 1 kg copper and 1 kg steel plate are listed in the appendix. There are more than hundreds of different input and output entries for both materials and not all of them are listed. However, the list is ranked by their value. Important to highlight is the amount of required “inert rock”. For 1 kg copper 157.02 kg “inert Rock” are required. In contrast, for 1 kg steel plate 5.08 kg “inert rock” are necessary. This means that for the production of steel plates 31 times less material is required than for copper. Another interesting result is the higher water consumption for the copper production which is approximately 5,400kg compared to the water demand for the steel plate which sums up to approximately 15 kg. Still, these numbers have to be treated with care because the required water amount for 1 kg steel plate seems to be quite small.

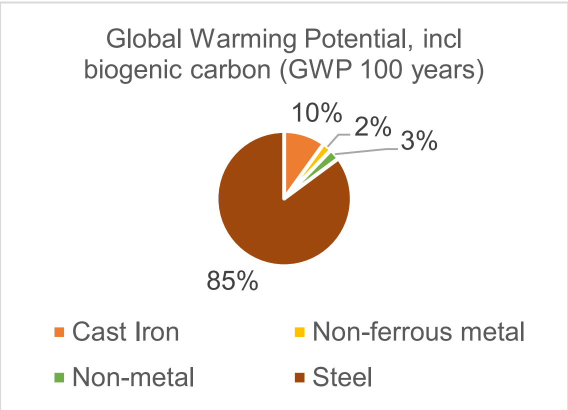
The results of the categories “freshwater aquatic ecotoxicity” and “terrestrial ecotoxicity” show the following: The (2) non-metal group is responsible for a disproportional contribution towards the FAETP but weights merely 2 % of a MB650. Main impact source is the raw material process “Polyvinylcloride injection moulding part (PVC) [technology mix]”. Regarding the “terrestrial ecotoxicity” category the cast iron is responsible for a high share of the overall environmental impact. The main impact of the cast iron group is caused by the processes “Cast iron part (automotive) [EAF route] [production mix, at plant]”.

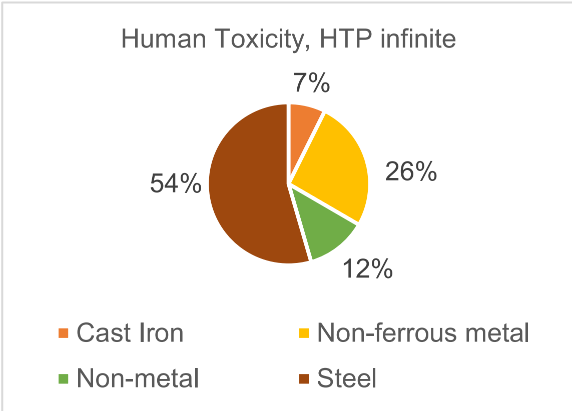
[87] Source: own figure

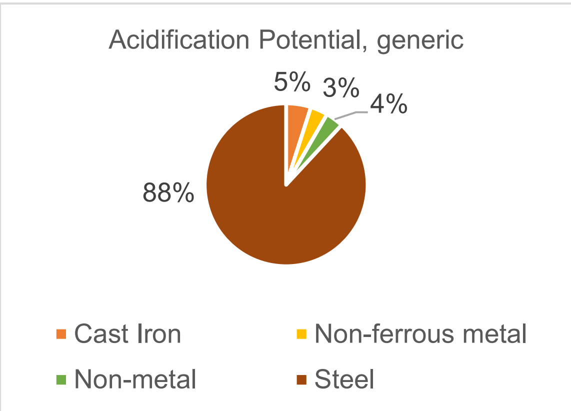
Table 21: Detailed impact assessment of the raw material phase

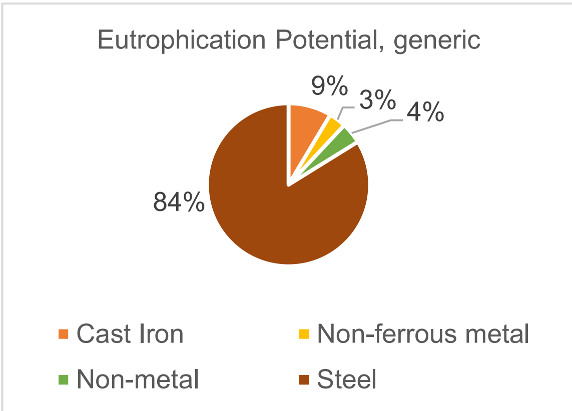


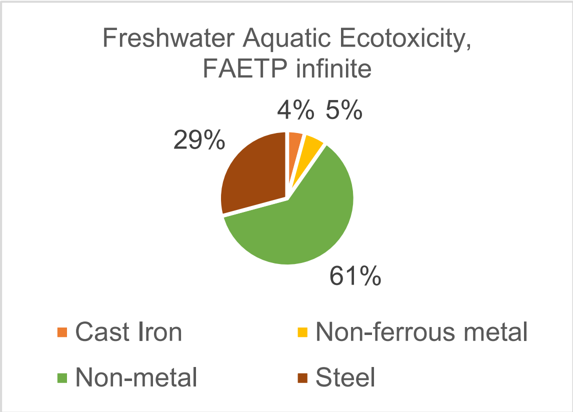


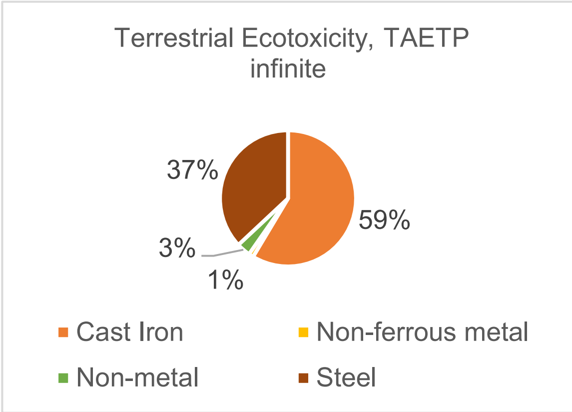












3.3.3 IA - Manufacturing and assembly phase

The processes in this phase are pooled together in various process groups. There is a group for the 'electrical supply', 'heating, waste', 'distribution' and 'others'. The 'electrical supply' group contains the process of electrical power generation and the 'heating' group the process to produce the heating power. The 'waste' group contains the disposal and recycling processes including recycling of aluminium and copper but also processes like waste incineration of untreated wood and plastic. The environmental impact of this group is mainly of negative value because they result in a resource credit.

A negative percentage in the figure means it is responsible for a credit in this category. Only in the global warming potential the 'waste' group is contributing in a negative way to the environmental impacts. Reason for this impact in the 'waste' group is the process "Waste incineration of untreated wood". The process group 'others' contains the production of operating and auxiliary material like cardboard, lubricants and paint. There are several reasons why the 'manufacturing and assembly phase' was analysed in this level of detail.

The first reason is because Sandvik Mining and Construction can use the results of this detailed impact assessment as a basis for further LCA analyses and for environmental improvements in their assembly plant. They cannot influence the grid mix composition in Australia but they can offer valuable information for decreasing for example their energy consumption in their workshops. The results of the detailed impact assessment are shown in Table 22 and the basic scenario is illustrated by the '300km transport scenario'.

This basic scenario shows that the 'electrical supply' process and the 'heating supply' process are in most categories responsible for a high share of the environmental impacts. Exceptions are the categories "abiotic depletion (fossils)" and "human toxicity".

In the "abiotic depletion (fossils)" category the process group 'others' takes over 24.5 % of the environmental impact. One reason for this high number is the material process "Lubricants at refinery [from crude oil]". The lubricants are made of crude oil and the impact category measures the consumption of fuels. As in the other categories electric supply is with 68 % and heating with 11 % responsible for the major impact in this category. The process group 'others' is responsible for 30.6 % of the environmental impacts in the category "freshwater aquatic ecotoxicity". As for the abiotic depletion category the lubricants are responsible for this high impact share. Within the basic scenario the impact category "human toxicity" shows unequal to the other categories that the heating process is dominating the "human toxicity" category.

Another reason for examining the "manufacturing and assembly" phase more closely was that the electric supply process and the heating process are dominating the environmental impacts in this phase. Therefore, an additional scenario was assumed. The additional scenario adopts an annual reduction of the power consumption and the heating consumption of 2 % for the following 5 years based on the consumption of 2014. This results in an overall decrease of these values of 10 %. In the results this scenario is called 'reduction scenario', shown in Table 22.

If this reduction scenario is applied, it results in a minimal environmental impact reduction of 7.9% in the category "abiotic depletion of fuels" and in a maximum impact reduction of 12.6 % in the category "human toxicity". The reductions are indicated with a positive value in the figure for the reduction category.

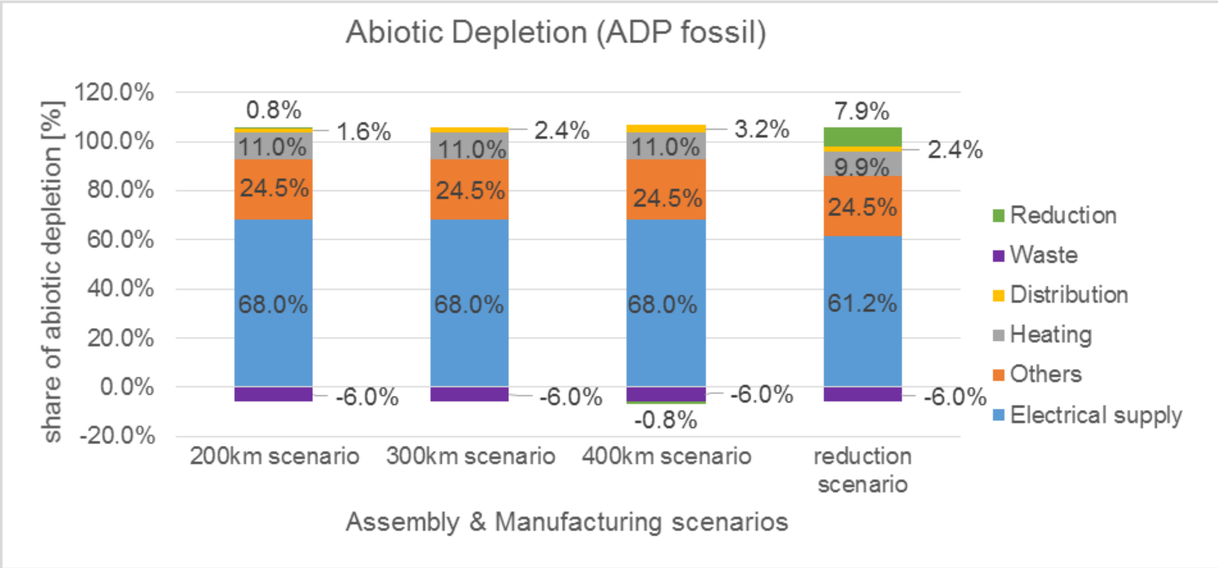
The third reason for a detailed analysis was, as explained in chapter 3.2.2, the sub-item "transport". The limited information available for the origin of manufacturing locations of many pre-assembled and purchased parts were responsible that assumptions were necessary. The detailed analysis of the "manufacturing and assembly" phase offered the chance to identify the environmental impact of the transport process compared to other processes in this phase. If the impact of the transport were significant in relation to the other processes it would be necessary to invest more time to get the exact transport data.

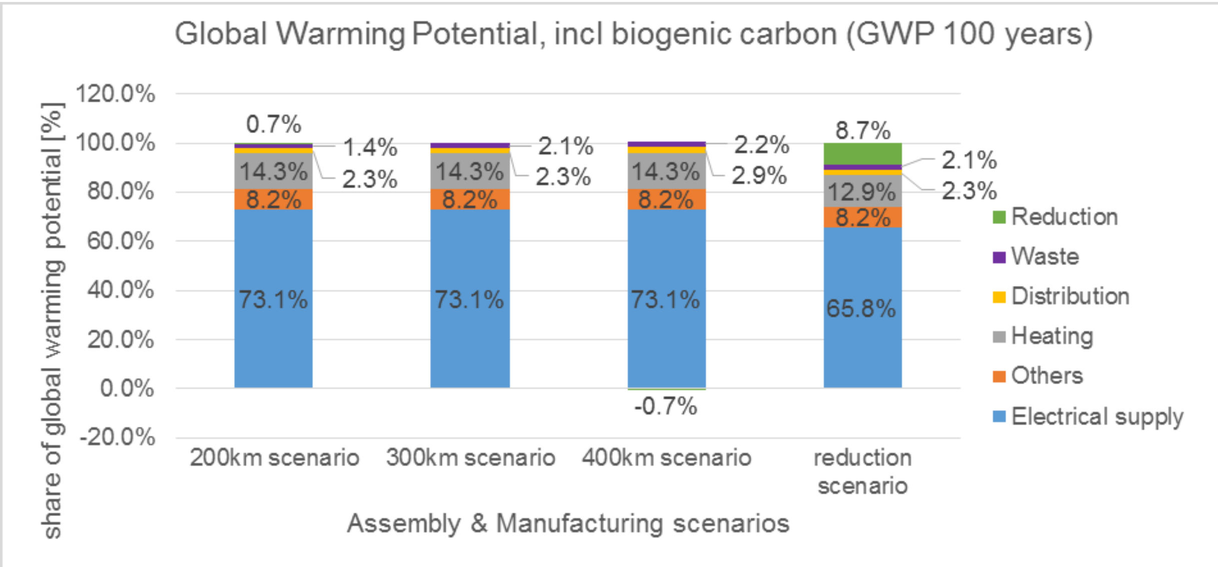
The basic scenario assumes a transport distance of 300km. The results are displayed in Table 22. Depending on the considered impact category the distribution in the 'basic scenario' is responsible for 0.3 % to 7.6 % of the overall environmental impacts. In the impact category "human toxicity" the distribution contributes 0.3 % to the environmental impacts. The highest environmental impacts concerning the distribution accumulates in the category "eutrophication".

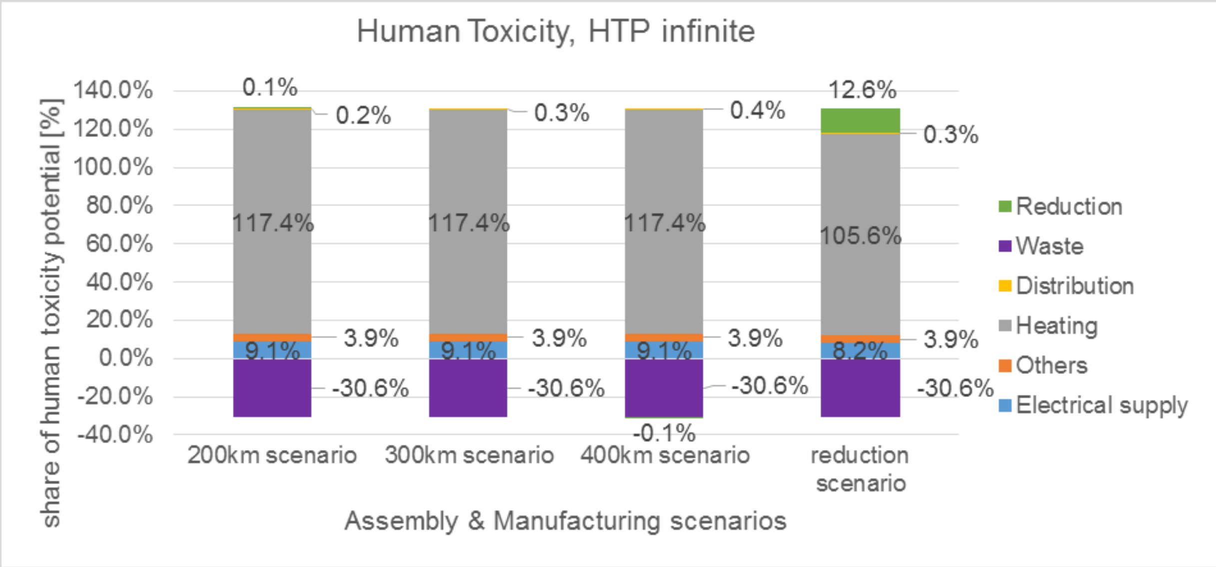
The fourth reason to analyse the "manufacturing and assembly" phase in greater detail are the two alternative transport distance scenarios of the raw materials and parts from the manufacturing location to the assembly plant in Zeltweg. Details about the scenarios are explained in chapter 3.2.2, in the sub-item "transport" and in the introductions of chapter 3.3. The results of the two alternative scenarios are shown in Table 22.

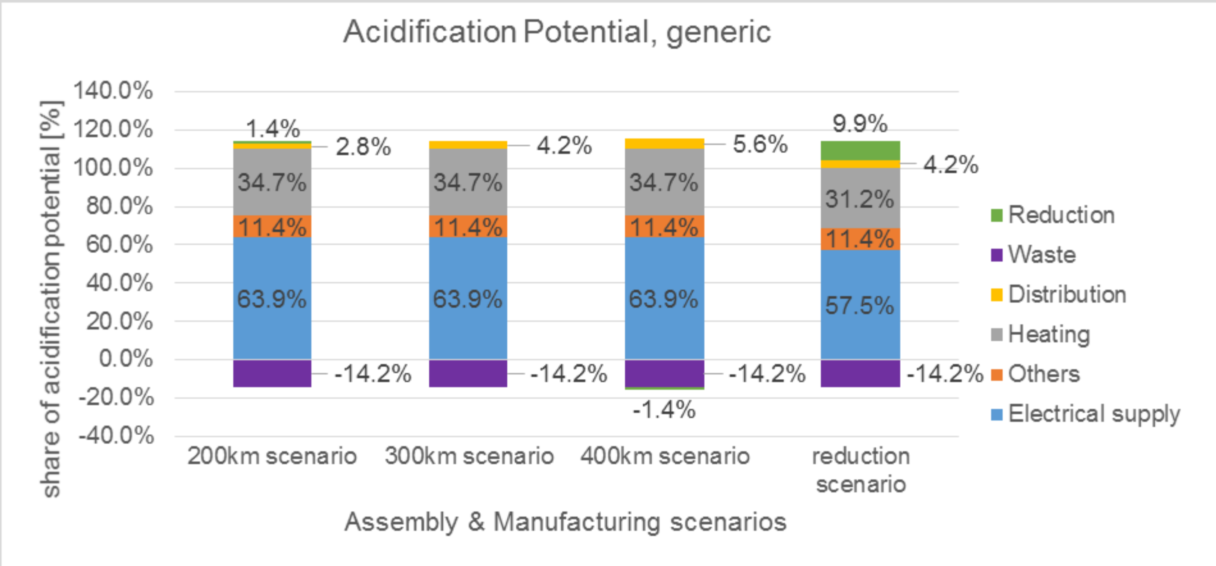
These alternative scenarios are called '200km scenario' and '400km scenario'. The distance of the scenarios is 33.3 % higher or lower than the basic scenario and the environmental impacts change with the same ratio. This means that the impacts are proportional to the distance. Maximum environmental impact contribution is caused by the '400km scenario' in the category "eutrophication potential" with a share of 9.7 %. The other categories are significantly lower in the worst case scenario and range between 0.4 % and 6.9 %. Referring to the overall environmental impacts of this phase the impacts would increase by 0.1 % in the category "human toxicity" and up to 2.5 % in the "eutrophication potential" category. This is shown in the results by a negative value for the reduction entry, displayed in green. Yet if the real transport distance corresponds more to the '200km scenario' the overall environmental impacts would decrease by only 0.1 % up to 2.5 %.

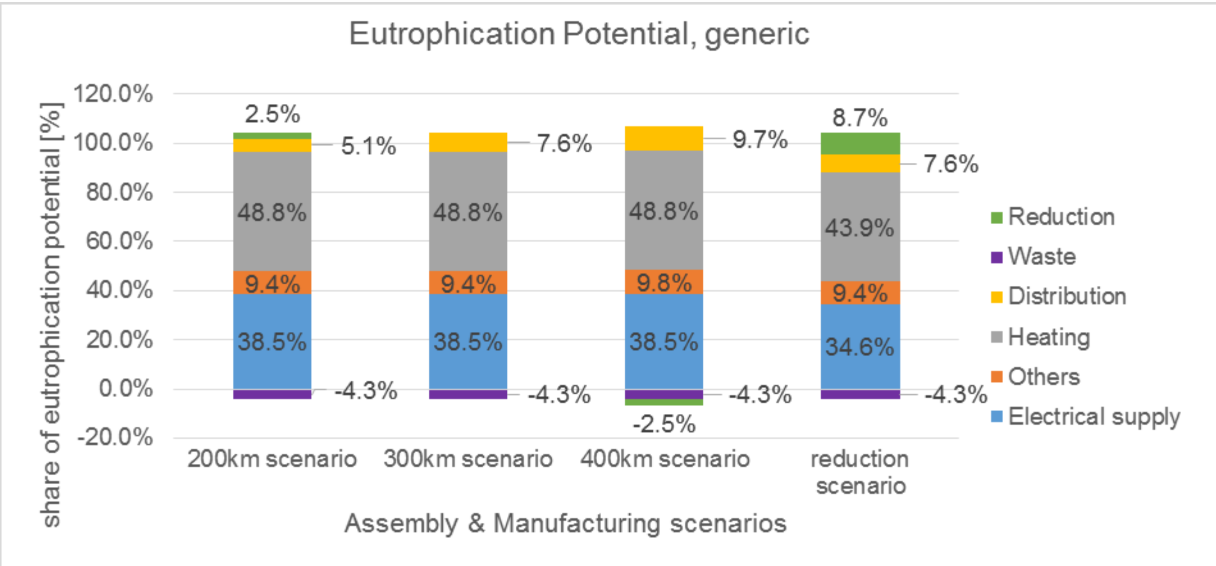
Table 22: Detailed impact assessment of the manufacturing and assembly phase and alternative transport scenarios

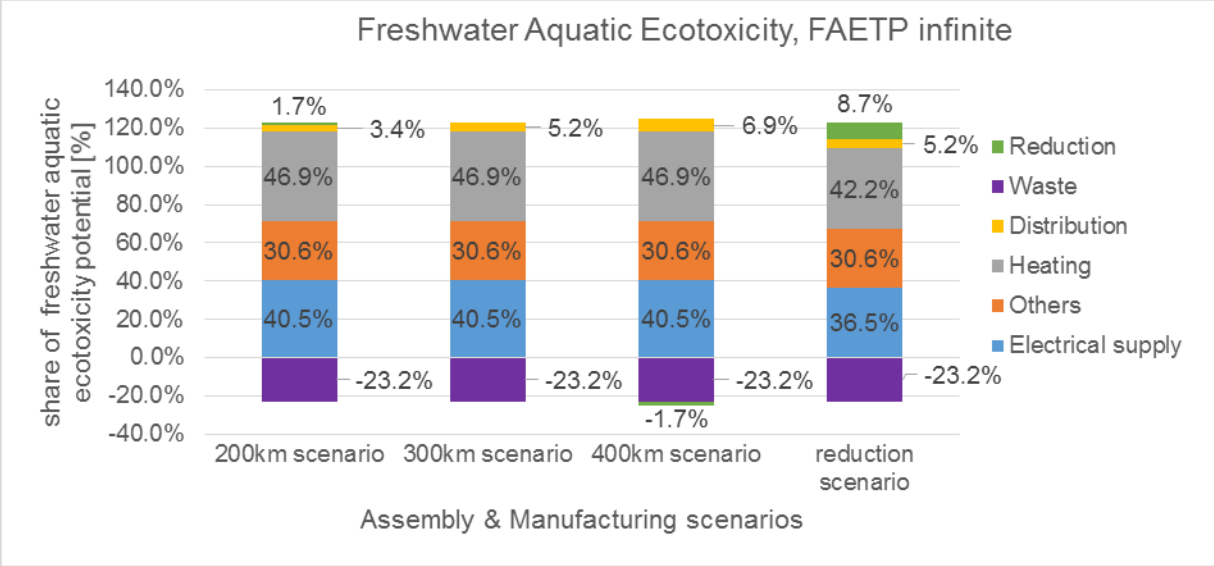


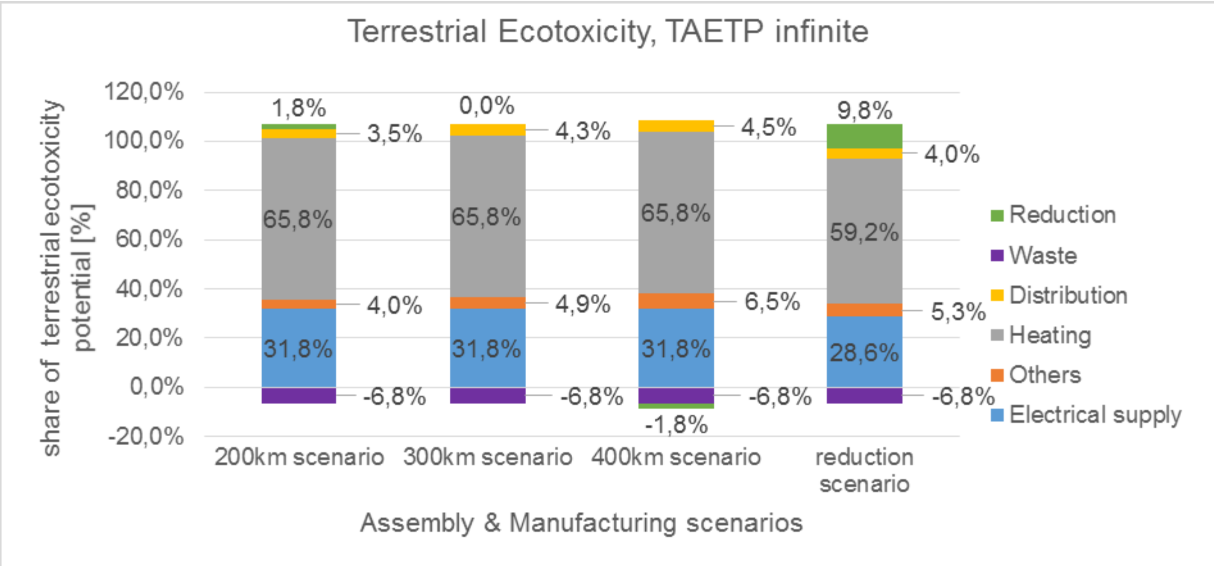



Human Toxicity, HTP infinite
share of human toxicity potential [%]
140.0%
120.0%
100.0%
80.0%
60.0%
40.0%
20.0%
0.0%
-20.0%
-40.0%
0.1%
0.2%
117.4%
9.1%
3.9%
-30.6%
0.3%
117.4%
9.1%
3.9%
-30.6%
0.4%
117.4%
9.1%
3.9%
-30.6%
-0.1%
12.6%
0.3%
105.6%
8.2%
3.9%
-30.6%
200km scenario
300km scenario
400km scenario
reduction scenario
Assembly & Manufacturing scenarios
Reduction
Waste
Distribution
Heating
Others
Electrical supply


Acidification Potential, generic
share of acidification potential [%]
140.0%
120.0%
100.0%
80.0%
60.0%
40.0%
20.0%
0.0%
-20.0%
-40.0%
1.4%
2.8%
34.7%
11.4%
63.9%
-14.2%
4.2%
34.7%
11.4%
63.9%
-14.2%
5.6%
34.7%
11.4%
63.9%
-14.2%
-1.4%
9.9%
4.2%
31.2%
11.4%
57.5%
-14.2%
200km scenario
300km scenario
400km scenario
reduction scenario
Assembly & Manufacturing scenarios
Reduction
Waste
Distribution
Heating
Others
Electrical supply


Eutrophication Potential, generic
share of eutrophication potential [%]
120.0%
100.0%
80.0%
60.0%
40.0%
20.0%
0.0%
-20.0%
2.5%
5.1%
48.8%
9.4%
38.5%
-4.3%
7.6%
48.8%
9.4%
38.5%
-4.3%
9.7%
48.8%
9.8%
38.5%
-4.3%
-2.5%
8.7%
7.6%
43.9%
9.4%
34.6%
-4.3%
200km scenario
300km scenario
400km scenario
reduction scenario
Assembly & Manufacturing scenarios
Reduction
Waste
Distribution
Heating
Others
Electrical supply





3.3.4 IA - Usage Phase

Referring to Table 18 in chapter 3.3.1 the usage phase is responsible for the major contribution to the environmental impacts. This is the reason why it is interesting to look at it more closely and analyse what processes or process groups are responsible for all impacts together. As for the manufacturing and assembly impact analysis in chapter 3.3.3, the high number of different processes in the usage phase makes it necessary to cluster them into process groups.

The first process group is named ‘electrical supply’ and includes the electric power generation processes. The second process group comprises the manufacturing of the spare parts but also the production of the lubricants and the hydraulic oil. This second process group is referred to as ‘spare parts’. The next group “distribution” contains the distribution of the spare parts from Austria to Australia. It has to be mentioned that only the spare parts are transported from Austria to Australia and not the operating material like hydraulic oil and hydraulic fluid. It can be assumed that these materials are also offered and purchased on the Australian local market.

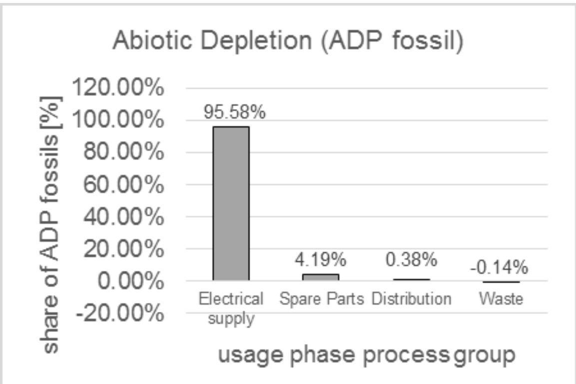
The fourth process group, “waste”, contains the recycling and disposal of all worn out materials and spare parts during the usage and rebuild phases. The results of this impact assessment are shown in Table 23 and refer to the basic scenario. This means the recyclability rate is 95 % and thus the energy supply is equal to the GaBi database entry of 2014.

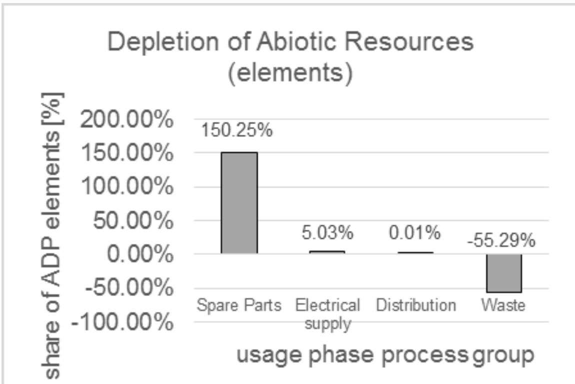
Excepting the category “depletion of abiotic resources (elements)” the results show that the process group ‘electrical supply’ effects the environmental impacts massively. Depending on the impact category its influence ranges from 83.79 % for the category “terrestrial ecotoxicity potential” to 97.25 % in the “human toxicity” category.

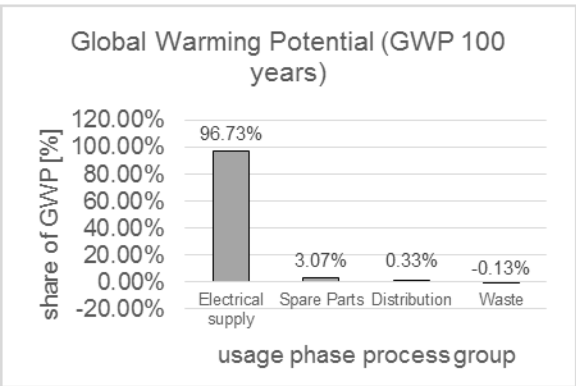
In the “depletion of abiotic resources (elements)” the ‘spare parts’ group exceeds with 150.25 % the overall environmental impact followed by merely 5.03 % of the ‘electrical supply’ group. In contrast the recycling processes in the ‘waste’ group compensate 55.25 % of the impacts in this category. The numbers of the ‘electrical supply’ group are relatively low because most required resources of this phase are fuels and they do not count for the ‘abiotic depletion of resources (elements)’.

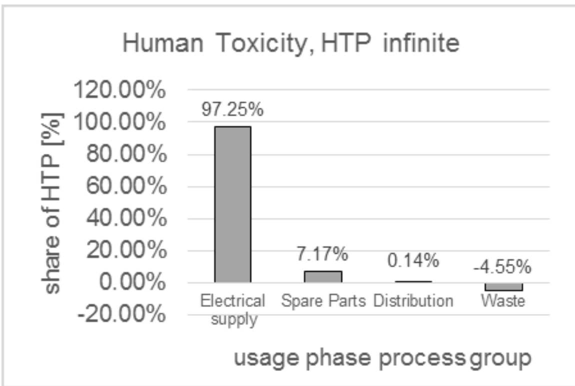
The credit of the “waste” process makes sure that the added up impacts reach 100 %. In the other categories the ‘spare parts’ are responsible for an impact share of 2.16 % to 16.21 %. The latter refers to the “terrestrial ecotoxicity potential” category. In detail the main contributor in the ‘spare part’ group regarding the “terrestrial ecotoxicity potential” is the process “Cast iron part (automotive)”. This is in line with the high impact in the ‘raw material impact assessment’ in chapter 3.3.2. “depletion of abiotic resources (elements)”

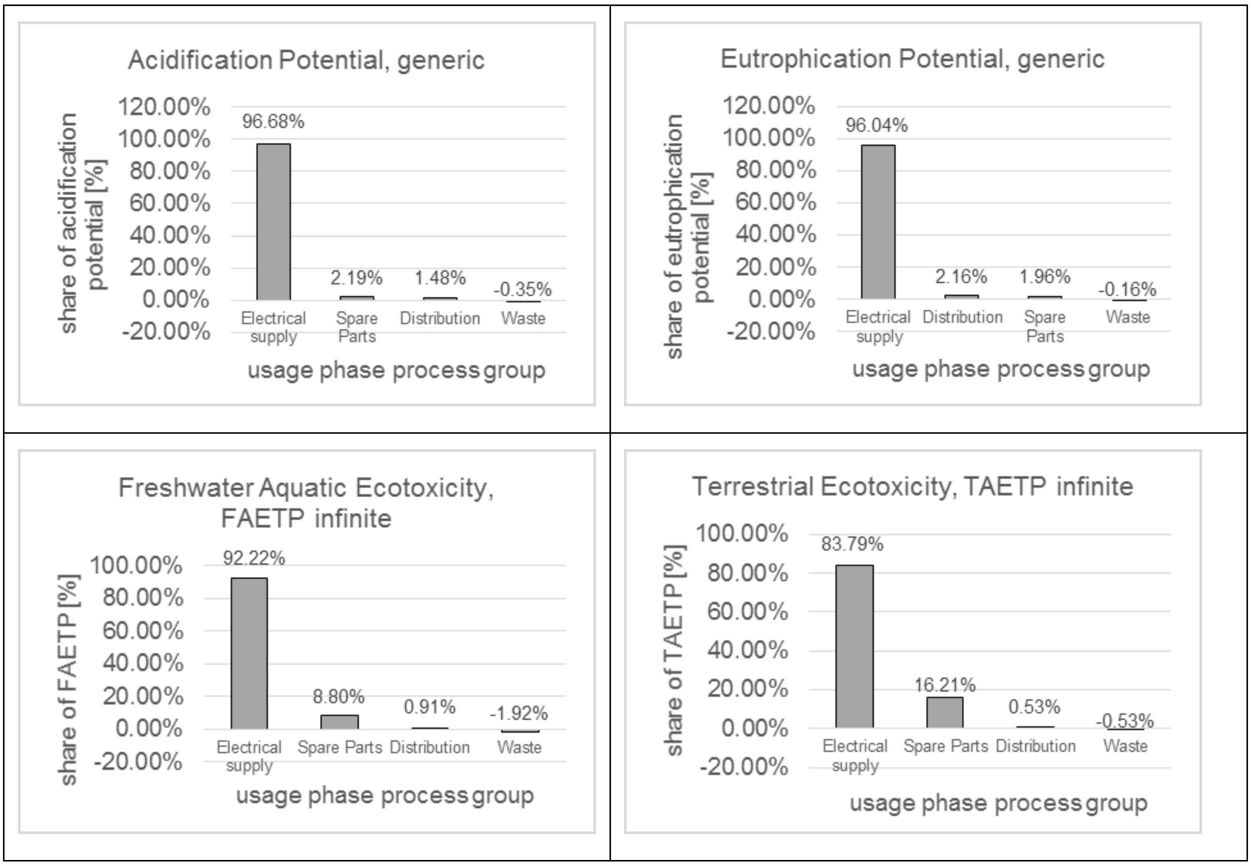
Table 23: Detailed impact assessment of the usage phase











3.4 Results and Interpretation

Detailed graphs of the analysed life cycle phases of the MB560 with its impact results are shown in chapter 3.3. The first interpretations and results of the graphs has already been conducted after the detailed impact assessments. This chapter will sum up the results and give suggestions regarding activities to decrease the environmental impacts.

The “usage” phase is responsible for the major environmental impacts in most categories with a share from 86.5 % to 96.2 % which is discussed in more detail in chapter 3.3.1 in Table 18. The only exception is the category “depletion of abiotic resources (elements)”. In this category the “usage” phase reaches 62.5 % and the “raw material” phase comes up to 54.2 %. The negative values of the “disposal and recycling” phase mean that the resource credits and energy credits can balance and compensate some of the statistical impacts caused by other phases. The “manufacturing and assembly” phase is just a minor contributor to the environmental impacts in all categories with an impact share between 0.6 % and 1.3 %. Also, the “distribution” phase is only responsible for a minimal share of 0.3 % to 1.6 %.

Following the first overall impact assessment a detailed assessment of the various phases was conducted.

The analysis of the “usage” phase, as the main contributor to the environmental impacts in the most categories, is examined in more detail. The thorough assessment shows that the process group ‘electric supply’ is responsible for the major impact share in all impact categories except the categories “depletion of abiotic resources (elements)” and “terrestrial ecotoxicity potential”.

In the other categories the 'electric supply' group is responsible for up to 92.22 % to 97.25 % of the impacts. The second influential contributor is the 'spare parts' group. This group takes up between 2.16% up to 8.8% except in the category "terrestrial ecotoxicity" and "depletion of abiotic resources (elements)". In the "terrestrial ecotoxicity" group the material manufacturing process of cast iron parts is pushing the 'spare part' group up to 16.21%. The impacts in the abiotic depletion category is caused by the spare parts because they require most of the resources (elements) in their usage phase.

As mentioned above, the 'electric supply' process group has the highest impact rate. The environmental impacts caused by the electric supply is strongly depending of the way the electric power is generated. On one hand there is electric power generation by fossil fuels and on the other hand it is possible to generate electric power by renewables. Therefore possible future energy supply scenarios are assumed. The alternative energy supply scenarios are discussed in chapter 3.3 and simulate an eventual future Australian grid mix for the years 2020 and 2030. The results of these alternative scenarios are shown in Table 20. The overall life time impact reduction for both alternative scenarios are significant. For the 2020 scenario the reductions are up to 4.08 % regarding the impacts of the product life time. The possible reduction in the 2030 scenario are even higher and the product life time impacts might decrease up to 19.4 %, depending on which category is analysed.

Details about the potential energy supply reductions are described in chapter 3.3.1. The disadvantage of these prediction scenarios is that Sandvik Mining cannot influence the Australian grid mix. This means if the Australian government decided that they no longer want to follow their energy targets, as a result the share of renewables in the power generation will no longer increase and the environmental impact reduction would not occur.

Sandvik also might offer, for example, additional photovoltaic modules and battery packs to ensure the mine site operators can increase their share of renewables. However, photovoltaic modules are not a field of Sandvik's activity and the high price pressure in the energy sector would pose an economic risk at the moment. This underlines the fact that increasing the share of renewable energy sources lies only to a small amount in Sandvik's hands.

Another LCA variable which cannot be influenced by Sandvik is the applied recyclability rate. There is a difference between the planned and calculated recyclability rate and the applied recyclability rate. According to the directive 2000/53/EG of the European Parliament and the Council of the European Union the end-of-life vehicle recoverability rate has to reach 95 % in 2015.[88] Because this directive is a European decree it is not ensured that this is also applied in Australia.

For the case that Australia decides on other laws an alternative recyclability scenario is assumed. The alternative scenario adopts a recyclability rate of 90 % and a landfill rate of 10 %. Details about the recyclability and the end-of-life are explained in chapter 3.2.5. The scenario results are shown in Table 20 and are indicated as 'recycling rate 90 % scenario'. This includes the lowering of the recycling rate, the increasing of the material landfill percentage and the

[88] Cf. European Parliament; Council of the European Union (2000), p. 38

decreasing of the credits for resources and energy. Following this reasoning, the phase cannot longer compensate the same percentage of the other phases and the overall impacts are higher than in the basic scenario.

Since the value for the reduction of the environmental factors in the graphs is negative this means the overall impact increases by this amount. Especially affected is the category “depletion of abiotic resources (elements)” by an overall increase of 3.01 %. The effect of the other categories is only increasing by 0.01 % to 0.4 %. Thus it can be assumed that the recyclability rate is not quite as essential for the overall impacts.

On one hand Sandvik can increase their design efforts to improve the recyclability rate of the MB650. On the other hand it is also important to motivate and make the operator aware of a proper end-of-life-treatment. One possible way would be if the purchase contract provides the option for Sandvik to take over the MB650 after the “usage” phase and undertake a correct recycling treatment. One disadvantage of such an end-of-life takeover might be the economic costs. Further investigations about the actual applied end-of-life-treatment in Australia and their economic effect for the operator and for Sandvik would be an interesting case for future research.

It has to be pointed out that the recycling of steel scrap does not reduce the environmental impacts directly. As explained in chapter 3.2.5 the recycled steel is going to be used as a credit for the input. This means the credit recycled steel scrap is just subtracted from the required steel scrap to manufacture the various types of steel alloys. Finally the amount of recycled steel is higher than the required steel scrap in the raw material phase and the spare parts in the usage phase. This result in a positive steel scrap credit of 74,555 kg.

Another part of the detailed impact assessment is the analysis of the “raw material” phase. As explained in chapter 3.3.1 this phase is the second biggest environmental impact contributor regarding the total life time of an MB650. In the detailed impact assessment in chapter 3.3.2 the environmental impact is divided into four different groups: (1) cast Iron, (2) non-metal, (3) non-ferrous metal and (4) steel. Furthermore, the proportional share of their weight of one MB650 is shown in Figure 34. The results of the detailed impact assessment are shown in Table 21.

The material group (4) steel is, regarding the material and the impact category, the major contributor in most groups. Also, the impact in most categories is proportional to the weight of (4) steel within the material groups. Exceptions are the impact categories “depletion of abiotic resources (elements)”, “human toxicity”, “freshwater aquatic ecotoxicity” and “terrestrial ecotoxicity”. Details and reasons for the deviant impact behaviour are also explained in chapter 3.2.1. It is difficult to reduce the environmental impacts of the “raw material” phase. Copper as a major contributor in some categories is mainly used in the electric motors. Yet a substitution is not that easily possible because copper is an essential part within a motor.

Maybe the most interesting life cycle phase and detailed analysis target for Sandvik is the impact assessment of the “manufacturing and assembly” phase. This phase is possibly the most controllable and influenceable part of the life cycle for reducing environmental impacts of an MB650. The processes in this phase are clustered in five process groups termed as (1) electrical supply, (2) heating, (3) distribution, (4) waste and (5) others. The process group ‘others’ contain auxiliary and operation material like lubricants. Furthermore this process group also includes the production pre-processes of the known waste like the manufacturing of cardboard required and consumed in the “manufacturing and assembly” phase.

Noteworthy is that some materials and emissions were left out of the analysis because the available databases did not contain information about pre-processes or waste treatments. Details about not considered material flows are explained in the inventory analysis of the “manufacturing and assembly” phase in chapter 3.2.2.

Additionally, a few alternative manufacturing and assembly scenarios were modelled and simulated. These include a basic LCA scenario, two alternative transport scenarios and a heating/electricity reduction scenario. The transport scenarios are explained in further detail in chapter 3.2.3 and the reduction scenario is elaborated on in chapter 3.3.3. The results of the impact assessments are shown in Table 22. The alternative transport scenarios are referred to as ‘200 km scenario’ and ‘400 km scenario’ meanwhile the basic scenario is indicated as ‘300 km scenario’.

The alternative scenario concerning the heating and electric power reduction is named ‘reduction scenario’. In all impact categories the electric supply and heating process groups are dominating in the overall impact share. Depending on the category, they are together responsible for between 79 % and 126.5 % of the environmental impacts. This high contribution of the heating and the electricity are the reason for the alternative reduction scenario. The additional scenario assumes an annual reduction of the power consumption and the heating consumption of 2 % for the following 5 years referencing the consumption of 2014. This results in an overall decrease of this values of 10 %. Concerning the impact categories, the environmental impacts would decrease by 7.9 % to 12 %.

A recommendation for further steps would be a detailed gate to gate LCA referring only to the “manufacturing and assembly” phase. This would allow to allocate the electric energy consumption to the different processes such as the hardening oven, the lighting or the mechanical processing machines. As a result of this detailed LCA it would be easier to increase the energy efficiency during the ‘manufacturing and assembly’ phase. Nevertheless, Sandvik Mining and Construction in Zeltweg is already decreasing their electric as well as heating consumption by several activities. For example between 2013 and 2014 following activities were implemented:

- Power analysis of the main production machines
- Step-by-step replacement of illuminates by energy saving lamps
- Partial renewal of the workshop glazing
- Monitoring of the air-conditioning system (consumption, power-on time,…)

Concluding this chapter, the theory of an active and passive product can be verified. The Miner Bolter 650 is an active product and the main environmental impacts are caused by the usage phase.

4 Summary and Outlook

The life cycle assessment methodology is a valuable way to visualize environmental impacts and it enables companies to handle large amounts of data and compromise them to meaningful results. Furthermore, it increases their overall environmental awareness and their responsibility for products from the cradle to the grave. This means especially environmental impacts which are not caused directly by themselves by manufacturing the products but by the usage and end-of-life of their product.

The research question led to a case study about the interdependency of the “design” phase, “manufacturing” phase and the “usage” phase. By changing details in the “design” phase the environmental impacts of the “manufacturing” phase increased. Nevertheless, the overall results decreased because the impacts of the “usage” phase were disproportionally lower. This means it is important that manufacturers and designers take responsibility for the whole life cycle of their product and not just about the impacts during the manufacturing process.

Major objective of this master thesis was to identify the environmental impacts and allocate the impacts to the various life cycle phases. Moreover, alternative scenarios were assumed and simulated to identify potential for environmental improvements.

One of the results emphasizes that the “usage” phase is responsible for the major environmental impacts regarding all environmental impact categories. In detail the impact assessment of the “usage” phase showed that the electrical supply is the main impact contributor of this phase. Various alternative energy supply scenarios made it clear that changes in the grid mix in favour of power generation by renewable energy sources will lead to a significant impact decrease. Disadvantage of this impact decrease is that Sandvik cannot influence the Australian grid mix. It is recommended to share the overall results of the LCA but also the detailed results of the usage phase with the MB650 mine site operator. The mine site operator might as well be interested in decreasing its ecological footprint and consequently invest in a positive image for the coal mining industry. It would be also interesting to get direct feedback from the operator.

Identifying potential for environmental improvement in the “raw material” phase is difficult because direct material substitutes are quite hard to apply. Nevertheless, this phase was analysed to see if the environmental impacts of used material groups are proportional to their weight. Result of this analysis is that the impacts are not always directly proportional to the weight. This is especially true for the material copper, PVC and the cast iron parts which are responsible for a disproportional share of impacts.

Uncertainties about the distribution process during the “manufacturing and assembly” phase were faced by implementing two alternative transport scenarios and analysing their effects. The detailed results of this phase show that the distribution is not really essential regarding the environmental impacts. Furthermore, also the modifications of the alternative transport scenarios effect the results to only a low degree since the impacts of the electrical supply and heating are dominating this phase. A recommendation for further LCA activities would be a detailed gate-to-gate LCA of the ‘manufacturing and assembly’ phase. Although this phase has only an impact rate of 0.8 % - 3.1 % it can be influenced by Sandvik directly.

Through this LCA ‘Umberto NXT Universal’ can be confirmed as a proper program to model LCAs and is recommended for further analyses. Nevertheless, a few disadvantages and problems were identified. When the models are more complex and many material flows are used the program it becomes RAM intensive. The separation of the two modules was advantageous because it was possible to split the modelling into distinct files. Otherwise the used computer would not be able to model and simulate the LCA.

The LCA model is structured modular and it is possible to use the model for other roadheaders. If using the model in future LCAs is planned it would be worth to increase the level of connectivity with the excel files which contain all the required data. This would heighten the level of modularity and allow quick changes regarding the type of roadheader.

The used database for the environmental impacts and pre-processes ‘GaBi’ is already extensive. Nonetheless, it was not always possible to consider all material flows and provided data because there were no database entries or the pre-processes were not included in the basic database. Many material flows and emissions could be modelled but the impacts were not considered. Should additional extensional databases be acquired the possibility to implement them into the existing model and increase the accuracy and level of detail exist.

The LCA method is a proper method to identify and allocate environmental impacts caused by a product. Especially the compact impact indicators are a powerful advantage because they combine different emissions to straightforward results which are easy to understand. Disadvantage of the LCA based on ISO14040 and 14044 is the sheer quantity of data required to perform a detailed LCA. Without any experience in performing a LCA it is easy to getting lost in details. Nevertheless, the LCA method is a powerful method and provides companies or governments with informative results if they are applied correctly.

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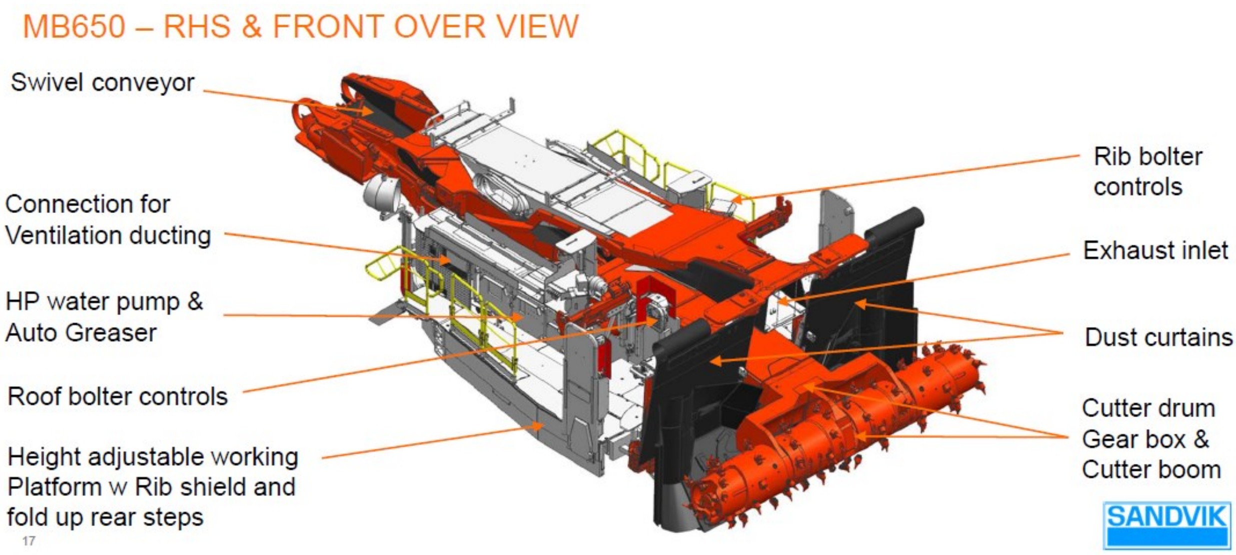
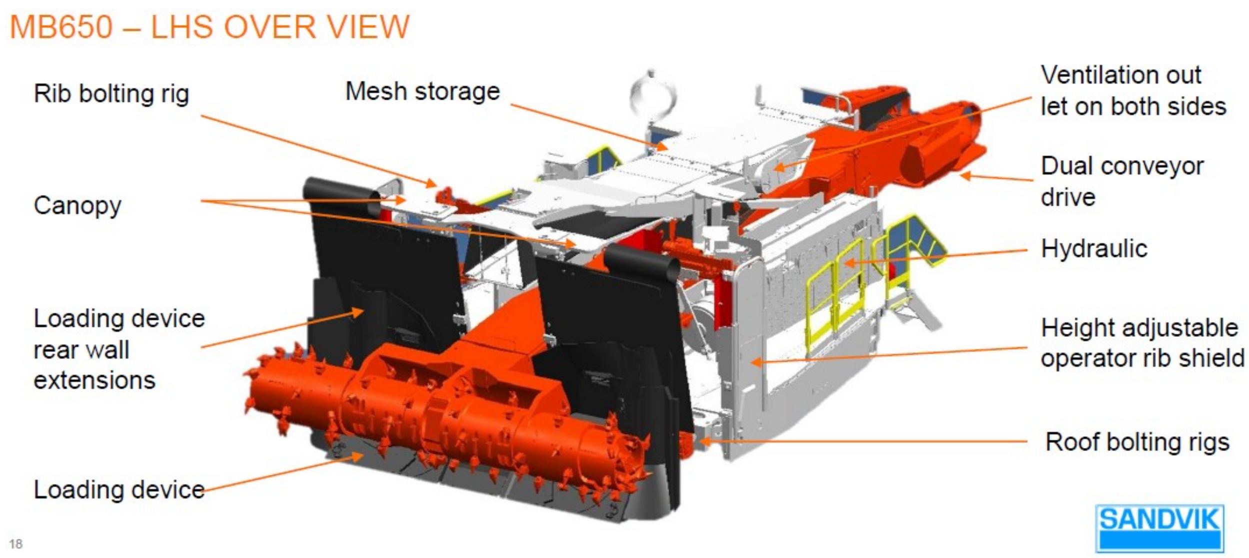
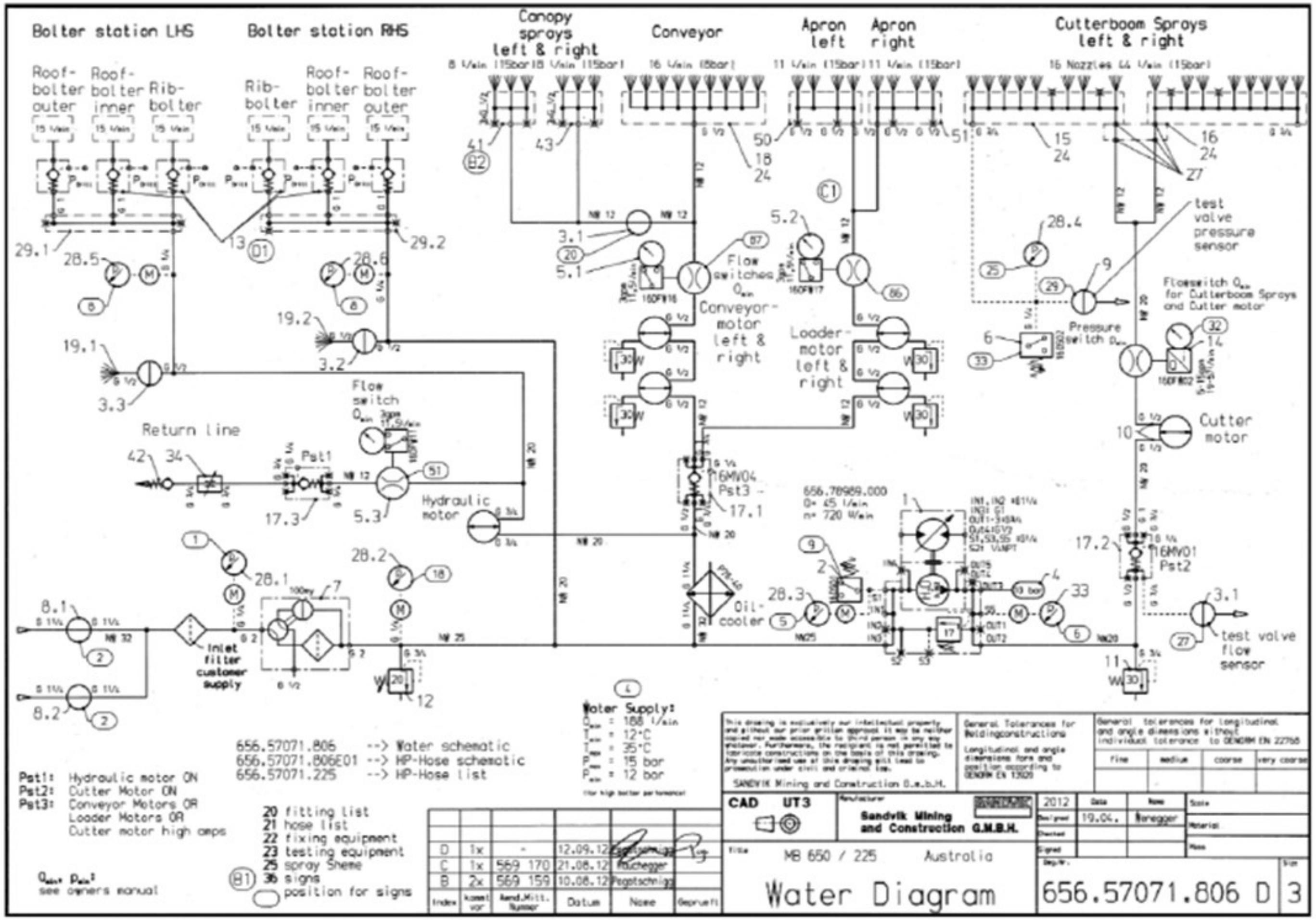
Appendixes

Appendix 1 – MB650 RHS, LHS & FRONT OVER VIEW





Appendix 2 – MB650 WATER SPRAY & COOLING CIRCUITS



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Appendix 3 – Simplified Inventory Analysis of Cutting Unit

Aggregated Input / Output of the Cutting Unit					
Input			**Output**		
Material	**Quantity**	**Unit**	**Material**	**Quantity**	**Unit**
Water (ground water)	70,741,412	kg	Water [Other emissions to fresh water]	70,668,000	kg
Electrical consumption	21,977,778	MJ	Waste heat [Other emissions to air]	704,527	MJ
heating	704,527	MJ	Steel scrap [Waste for recovery] - CREDIT	51,894	kg
S355JO	66,293.70	kg	Water (waste water, untreated)	73,412.48	kg
Cutting-Bit material	48,699.77	kg	Metals (unspecified) [Particles to fresh water]	14,515.2	kg
St	24,774.11	kg	Landfill of ferro metals	9,626.57	kg
Hydraulic oil	21,648	kg	Waste incineration of untreated wood	3,265.02	kg
G-42CrMo4	20,633.91	kg	Used oil (without water) [Waste for recovery]	2,194.88	kg
42CrMo4	18,106.43	kg	Plastic (unspecified) [Waste for recovery]	1,663.09	kg
G-26CrMo4	13,349.92	kg	Copper scrap [Waste for recovery]	1,371.67	kg
Electrical Steel	5,391.97	kg	Waste incineration of plastics (rigid PVC)	965.14	kg
17CrNiMo6	5,334.87	kg	Aluminium scrap [Waste for recovery]	753.33	kg
Getriebeöl	5,324.4	kg	Oil [Waste for disposal]	499.99	kg
X5CrNi18-10	4,363.59	kg	Waste incineration of paper fraction in municipal solid waste	365.52	kg
18CrNiMo7-6	3,923.55	kg	Landfill of plastic waste	332.02	kg
Cast Iron for the electrical motor	3,583.52	kg	Used oil (with water. to treatment) [Waste for recovery]	248.97	kg
X17CrNi16-2	3,123.63	kg	Waste incineration of plastics (PE. PP. PS. PB)	110.90	kg
Lubricating oil	3,119.02	kg	Oil sludge [Hazardous waste for recovery]	108.10	kg
EN-GJL-500	2,478.74	kg	Dust (PM2.5 - PM10) [Particles to air]	0.066096	kg
Böhler U-N700	2,039.99	kg			
34Cr4	1,934.78	kg			
G-24Mn6	1,199.99	kg			
Cu	1,105.66	kg			

E335	1,102.16	kg	
PVC	1,054.38	kg	
Synthetic Rubber	1,045.88	kg	
Hardox 400	952.262	kg	
GS-18NiMoCr35	860.695	kg	
Aluminium	730.413	kg	
X6CrNiMoTi17-12-2	704.266	kg	
34CrNiMo6	679.307	kg	
GS-42CrMo4	670.979	kg	
S235JO	517.041	kg	
GI - Silicon rubber	400.908	kg	
Paper for corrugated board	365.524	kg	
Paint	383.857	kg	
A514F/1300	347.014	kg	
E295	334.602	kg	
K340	303.753	kg	
20MnV6	292.999	kg	
VSF- Viscose Staple Fibre	258.091	kg	
CuSn12	214.557	kg	
GS-52	210.722	kg	
34CrAlNi7	152.999	kg	
X46Cr13	137.399	kg	
X5CrNiMo18-10	133.199	kg	
Polyethylene low density granulate	110.908	kg	
X90CrMoV18	110.688	kg	
G-20Mn5	103.198	kg	
NBR	97.8983	kg	
Inpregnation resin	93.0394	kg	

X20Cr13	87.2396	kg	
X38CrMoV5-1	77.3995	kg	
EN-GJL-250	48.2594	kg	
23MnNiCrMo6-4	37.4706	kg	
Polyester	31.5539	kg	
2C45	19.8498	kg	
PTFE	17.2997	kg	
X12CrMoS17	16.5925	kg	
X12CrNi18-8	14.6997	kg	
Insulation material	10.9499	kg	
35S20	9.76983	kg	
Wood. soft. standing	7.25543	m3	
Glas	6.30534	kg	
EN-GJL-400	4.59992	kg	
P235TR2	4.55992	kg	
EN-GJL-200	2.69995	kg	
9SMn28	0.64059	kg	
CuZn40Pb3	0.15302	kg	

Appendix 4 – Section of input- and output- flows to manufacture 1kg copper and 1kg steel plate referring to GaBi database

Section of input and output Flows to manufacture 1kg copper					
Input	**Value**	**Unit**	**Output**	**Value**	**Unit**
Water [river water)	5,278.45	kg	Radon (RN222)	7,526.53	Bq
Mechanical Filtration	2,218.91	c	Water	6,149.4	kg
Water (lake water)	1,039.02	kg	Hydrogen-3 Tritium	2,387.77	Bq
Inert rock	157.02	kg	Hydrogen-3 Tritium	837.55	Bq
Water (ground water)	75.22	kg	Xenon (Xe135)	159.54	Bq
Air (renewable resources)	26.03	kg	Water	143.49	kg
Crude oil	22.77	MJ	Radium (Ra226)	137.98	Bq
Water (rain water)	14.47	kg	Xenon (Xe133)	115.19	Bq
Natural gas (in MJ)	11.11	MJ	Overburdon (deposited)	97.32	kg
Groundwater Replenishment	10.98	MJ	Tailings (deposited)	51.59	kg
Water (sea water)	6.3	kg	Water vapour	51.16	kg
Hard coal (in MJ)	5.05	MJ			
Uranium natural (in MJ)	4.58	MJ			
Primary energy from hydro power	4.08	MJ			
Lignite (in MJ)	2.8	MJ			
Oil sand	2.17	MJ			
Oil sand (100% bitumen)	1.89	MJ			
Primary energy form solar energy	1.79	MJ			
Zinc	1.62	kg			
Copper	1.23	kg			
Erosion Resistance (Occupation)	0.99	kg			

Section of input and output Flows to manufacture 1kg steel plate					
Input	**Value**	**Unit**	**Output**	**Value**	**Unit**
Water (fresh water)	11.70	kg	Krypton (KR85)	1,942.95	Bq
Inert rock (Non renewable resources)	5.08	kg	Radon (Rn222)	366.77	Bq
Water (surface water)	1.71	kg	Hydrogen-3 Tritium	76.79	Bq
Water (ground water)	1.70	kg	Radium (Ra226)	11.11	Bq
Air (renewable resources)	1.60	kg	Waste Water	9.86	kg
Iron ore (56.86%)	1.59	kg	Overburden	5.11	kg
Water (sea water)	1.48	kg	Water (river water)	3.12	kg
Hard coal China	0.32	kg	Carbon dioxide	2.32	kg
Uranium natural (in MJ)	0.32	MJ	Exhaust	1.28	kg
Primary energy form hydro power	0.15	MJ	Waste heat	1.02	MJ
Primary energy from solare energy	0.14	MJ			
Hard coal Australia	0.14	kg			
Steel scrap (St)	0.11	kg			
Hard coal	0.10	kg			