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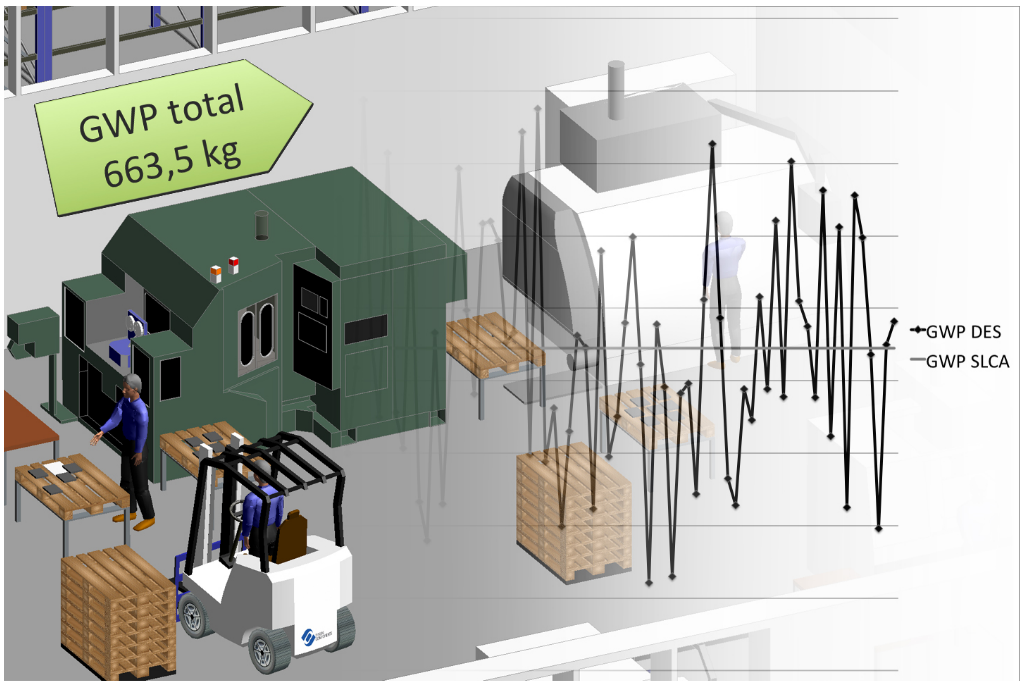

Environmental Product Footprint Assessment using Discrete Event Simulation

Proposed Method based on a Case Study at NMW

MASTER OF SCIENCE THESIS IN THE MASTER DEGREE PROGRAMME, PRODUCTION ENGINEERING

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Preface

This report is the result of a master thesis project performed at the Swedish production company NMW during the first half of 2011. The master thesis project has been the final compulsory part in the master's degree programme Production Engineering provided by the department of Product and Production Development at Chalmers University of Technology.

We would like to express our gratitude to:

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- For all the help and support during the course of this master thesis.

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- For all the help within the environmental area in this project and creation of the LCA.

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- For the support in environmental analysis and software applications for LCA.

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- For data management automation solutions and support through this project.

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- For his leading role in the EcoProIT project.

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Erik Lindskog & Linus Lundh
Göteborg, June 14, 2011

Abstract

Companies today are becoming increasingly interested in tracing and measuring the environmental footprint of their products. This interest is driven by both marketing possibilities and pressure from society. Discrete Event Simulation (DES) is one tool for acquiring the dynamics of the real world for determining a product's environmental footprint. There are static methods for analyzing the environmental impact of products that do not consider dynamical aspects of production systems. Life Cycle Assessment (LCA) is one of the most adopted static methods. In this master thesis a method for the process of obtaining a valid simulation model with the output of an environmental label is proposed.

This master thesis work is a part of the research project EcoProIT. The project's aim is to develop a new method for labeling products with their environmental footprint using DES. This master thesis is considered to be a pre-study and the focus will be directed towards the manufacturing process of a product in a job shop production facility. As a benchmark for evaluating the proposed method a Simplified Life Cycle Assessment (SLCA) is carried out on the same system using the same input data.

Evaluating the dynamics of production with DES, variations of environmental footprints can be determined. The results from this study will be used as a framework for future research of developing a standardized method or tool within the area. The study has shown upon several important steps that should be included in such a method and factors that could be included in environmental labeling of products. Based on this project the authors are proposing a method consisting of three major steps for determining the environmental product footprint.

Shortcomings of the method that needs to be addressed in further research have also been found. The importance of what type of production system that is studied has impact on the dynamic results. Due to the focus of just a small part in the total life cycle the total results from benchmarking the proposed method with the SLCA is not differing much. When focusing and benchmarking only the manufacturing process, the dynamics derived from the proposed method appears. A complex production system such as a job shop with many products and components will lead to simplification and assumptions that can decrease the dynamics of the result. The allocation of overhead energy and resource consumption would need to be addressed in further research to incorporate dynamics of the real world.

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List of abbreviations

AP	Acidification Potential
CEO	Chief executive officer
CNC	Computer Numerical Control
CO	Carbon monoxide
CO_2	Carbon dioxide
CSV	Comma-separated values
DES	Discrete Event Simulation
ELCD	European reference Life Cycle Database
ERP	Enterprise Resource Planning
ERPA	Environmentally Responsible Product Assessment
GWP	Global-warming Potential
ILCD	International reference Life Cycle Database
ISO	International Organization of Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
NIST	National Institute of Standards and Technology
NMW	Norrahammars Mekaniska Werkstad
NO_X	Mono-nitrogen oxides
SLCA	Simplified Life Cycle Assessment
SO_X	Sulfur oxide
WSC	Winter Simulation Conference

1 Introduction

Consumers are today aware of the negative environmental impact of our daily used products. Media are continuously reporting about problems connected to environmental issues and environmental parameters are used when marketing new products. To increase the product marketing value for consumers a product labeling of the environmental footprint is desired. The product's environmental footprint can be seen as the amount of greenhouse gases, acidification gases and other pollutants affecting the environment during its life cycle. Today there is no standardized method for determining the environmental footprint that takes the dynamics of production into consideration.

Using Discrete Event Simulations (DES) for determination a product's environmental footprint makes it possible to include dynamical factors from the production that static methods will not consider. The dynamics generated by a DES model will make it possible to analyze the production and evaluate different solution for how to reduce the environmental footprint. It will become possible to examine the production system's stability in the aspects of environmental and productivity. DES makes it possible to follow each product through the production to evaluate where events occurs that will have environmental impact. There exist toolkits and add-ons to some of the DES software´s that can determine emissions related to the production.

This master thesis will be a part of the research project EcoProIT with the aim to develop a new method for labeling products with their environmental footprint using DES. The involved parties in the research project are Norrahammars Mekaniska Werkstad (NMW), Volvo Cars Floby, Stena Metall, National Institute of Standards and Technology (NIST) and Chalmers University of Technology. In this thesis work a case study at NMW will be undertaken as a first and initial study within EcoProIT. The focus will be directed toward the manufacturing process of a product in the job shop facility at NMW. The studied product is one of several products produced at the company and consists of in-house produced parts and bought components.

The result from this case study will be compared with the results of a Simplified Life Cycle Assessment (SLCA). Life Cycle Assessment (LCA) is a well-known method for studying the product's life cycle and SLCA is a more compact version made for faster execution. Traditional LCA methods are mostly using static data in calculations, which take no consideration to the dynamical factors in the manufacturing process. The dynamical aspects of using DES make studies more open for the possibility to evaluate changes within the process. A proposed method base on this case will be presented and used as for future studies in EcoProIT.

1.1 Purpose and goals

The purpose of this project is to analyze parts of the production at NMW and determine one of their product's environmental footprint in order to make them more competitive on the market. The projects results will also benefit the future work and research in EcoProIT.

The goals of this thesis are to produce:

- A validated simulation model of the production at NMW in a DES environment. The model will use environmental parameters from an established Life Cycle Inventory (LCI) database. It should also be graphically representative for presentation purposes.
- A user interface for handling model parameters and calculations that are machine or system specific.
- A proposal for how to generalize what types of parameters that are important to include in a simulation model with the aim of determine and/or reduce the environmental product footprint.
- A proposal for a project method specific to this case that aims to determine the product footprint with simulation and supports the goals of EcoProIT.
- A comparison between a SLCA and the project results.

1.2 Project questions

How should a method be constructed in order to dynamically determine and improve the product footprint? To answer the question the following sub questions must be answered:

1. What types of result could be expected from an environmental product footprint study?
    a. What parts of the result could be dynamic?
    b. What should a labeling of an environmental footprint contain?
    c. How should the label be made at NMW for their products?
2. How should an initial method be structured for determining the environmental footprint based on the case at NMW?
    a. How should an environmental product footprint study be made?
    b. How should allocation of resources and overhead functions be distributed among the products?

c. What considerations have to be made before using DES in an environmental footprint study?
d. Is the methodology compatible with analyzing job shops?

1.3 Delimitations

Following limits will be applied for focusing the thesis work:

- The thesis work will be made in 20 weeks and cover 30 hec.
- The most common environmental factors related to the production at NMW should only be used.
- The proposed methodology will be designed and evaluated solely regarding production circumstances given by the case study.
- The simulation will focus on producing two products that combines to a set of 12 products.
- The simulation model will be reduced in its complexity compared to the real world system to a degree that is found to be proficient to not lose the validity of the model.
- The LCA will be made by NIST according to the ISO 14040 and will not be evaluated in this project.
- Only LCI databases that can be accessed at Chalmers will be used.

1.4 Factory description

NWM is a producing company based in Jönköping with around 20 employees who produce machined metal parts for Swedish industries. One of their main areas is the production of components to forklift manufacturers. The produced products are varying from standard components to special orders. Due to the variation of components the shop floor is built around standalone machines. The flow through the factory is changed based on the products and available machines. The production flow could therefore be different from the last time the product was produced. In this project the standard flow is only taken into consideration.

1.4.1 The factory

The factory is separated into two large areas, one hall for CNC machines and another one for cutting, assembly and welding. Some of the machines have manual loading of new products and needs to be attended almost the whole time. A couple of the machines can though be loaded with a whole batch and run unsupervised. This means that some machines can be left running with enough raw materials for the entire night or at least for a couple of hours. That possibility is used for some of the machines when the company has a high order stock. The layout of the factory can be seen in Figure 1.

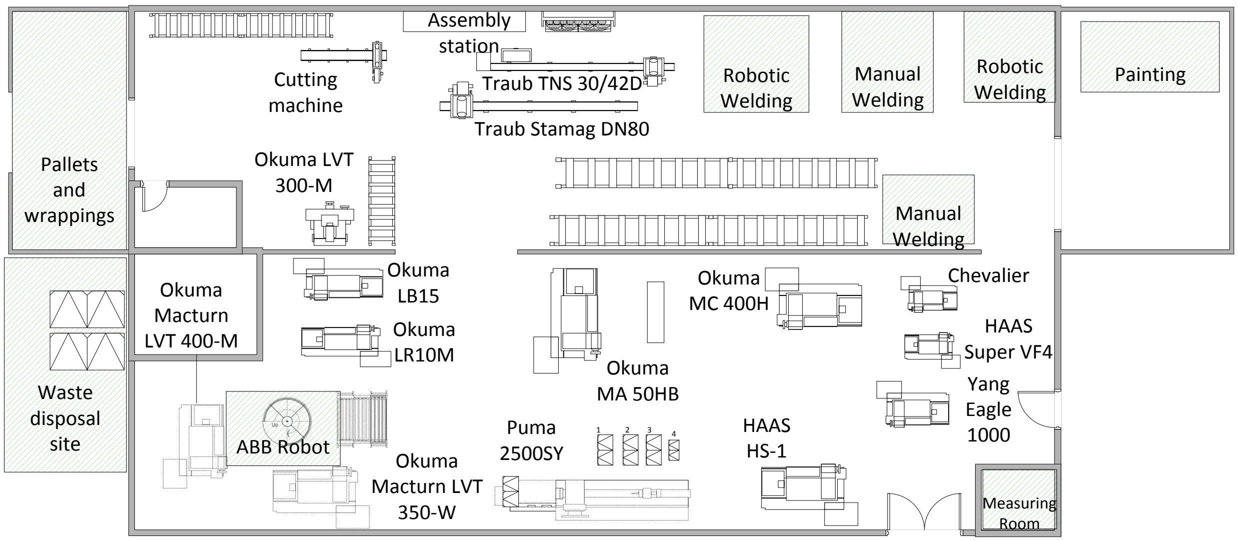

Figure 1 - Factory layout over the production area.

1.4.2 Production constraints

Normal work hours for the operators are between 07:00 to 16:00 with one break of 15 minutes in the morning and one break of 25 minutes for lunch. This schedule allows them to end at 13:00 each Friday.

The company uses an Enterprise Resource Planning (ERP) system called MONITOR for production planning, ordering points and economics. Through this system the logistics manager and the production planner can plan the work that is going to be carried out each week. The purchasing manager and the sales manager are also using this system to keep track of when and from whom materials and finished products are being bought and sold to.

1.4.3 The studied product

The studied product in this project will be a set of 12 products of two product models. “Länkhjul” and “Vridhjul” are the names of the two products in this set but from this point they will be named as Product A and Product B. In Appendix A the flow of the own produced components are described from the delivery into, and through, the factory.

Table 1 - Number of components in each product.

	Bought components	Produced components
Product A	22	6
Product B	37	8

The assembly is made in the factory of all the components in the data sheet of Appendix B. In some cases the components can be preassembled in order to shorten the assembly time. Normal time for assembling the whole set of 12 products are one working day. When components are preassembled the assembly time is shortened down to five hours. If some of the parts are missing however the time could extend to several days.

Figure 2 describes the production chain for produced components from the raw material producer to the customer. In this case study the focus has been at the "In house production" box, which includes all processes inside the factory. Environmental data for the raw material production has been assumed to include processes at the supplier and transportation between raw material producer and supplier. The transport between the supplier and NMW is not assumed to be included in the given data. The "External treatment" is considered to be part of the "In house production" since the event is happening in between processes within the factory. The last part included in the production chain is the transportation to the costumer.

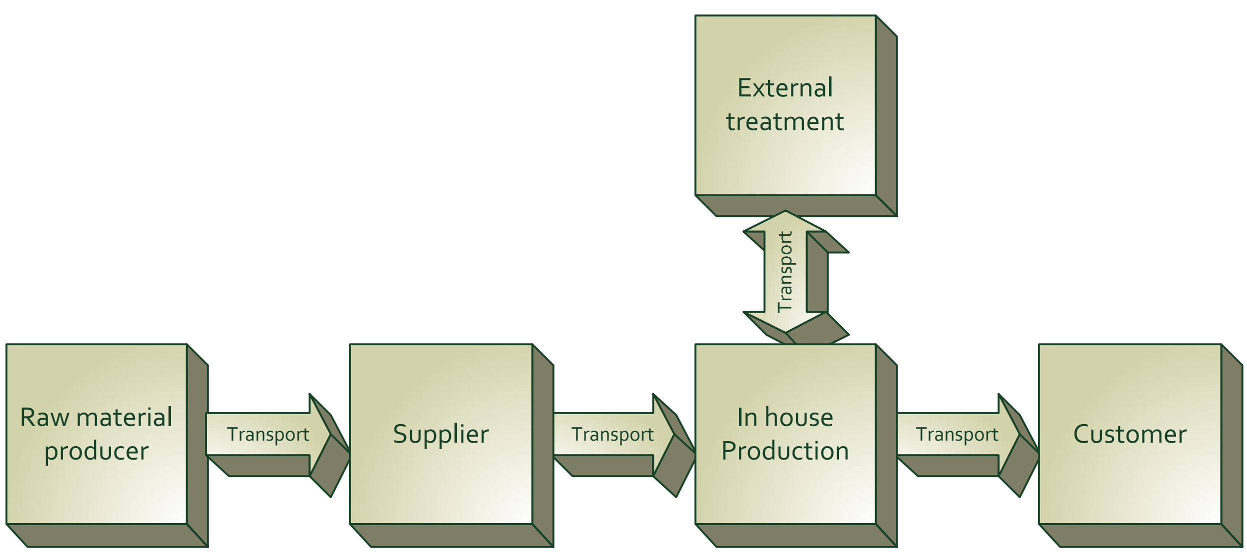

Figure 2 - The production chain from cradle to gate.

2 Frame of reference

This chapter will describe the knowledge and concepts used within this project. The presented theories have a central part in the project and are used to validate the outcome.

2.1 Life Cycle Assessment

LCA is a standardized method for determining all relevant emissions and consumed resources connected to a product or service. The method is controlled by the ISO standards 14040 and 14044, which defines the general framework. (Institute for Environment and Sustainability, 2010) International reference Life Cycle Database system (ILCD) is one of the main guides for creating LCA analyzes and SLCA methods supported by the above mentioned standards (Institute for Environment and Sustainability, 2010).

2.1.1 SLCA

For most studies a complete quantitative LCA will not be efficient, the amount of data that is needed would not be beneficial for the assessment and the involved parties, in other words the result would not justify the means. Qualitative data, calculations and estimations are therefore needed in order to create a useful assessment, today a variety of SLCA methods exist. (Finnveden & Hochschorner, 2003) SLCA methods such as the ERPA and the SLCD are good at highlighting what link in the product's chain is causing the most environmental emissions. Simplified studies are less time consuming but they do neglect some of the parts in the process that could be important to include in a study. A decision of what is going to be achieved and what data that is going to be needed for the study has to be considered in order to choose the right method. (Lee, Kim, Kwon, & Hur, 2003)

2.1.2 LCI databases

There exist several databases for LCA studies, some of them are open and free to use, such as the European reference Life Cycle Database (ELCD) (Institute for Environment and Sustainability, 2010). Commercial databases exist but are licensed. The ecoinvent database can be considered to be one of the leading commercial databases (Swiss Centre for Life Cycle Inventories, 2011). Depending on the level of detail and the scope of the study, databases can be a good tool in order to access the core data of emissions. Due to the level of detail that is required in an LCA it is preferable that a database is used in order to make the data acquisition more time efficient. (Tivander, 2011)

2.2 Simulation

Simulation could be used in widely spread areas to make virtual studies. In this project the focus is towards DES.

2.2.1 Discrete Event Simulation

Making an analysis of a production system usually has the goal of finding elements that could improve the overall performance. Banks Model is a widely spread method for how to structure an analysis within DES projects. The method describes the necessary steps in order to create, verify and validate a simulation model so it can be used to experiment and analyze the present and future improvements. (Banks, Handbook of Simulation, 1998)

DES requires a lot of input data and the more detailed data the better. Depending on the data the model will be reacting differently and if the data is incorrect the model will not assimilate the real system. (Balci, 1990) DES is an efficient method for analyzing complex production systems. In some cases the production system might not be complex enough to put down the effort of modeling it, easier methods or common sense might be more useful. These and other reasons when simulation with DES is not preferable are best concluded by a list made by Banks and Gibson (Banks & Gibson, 1997). If the 10 rules in that list are not broken in a project that aims to use DES as a method then the outcome will probably be successful. The result might however not satisfy the needs or hopes of the involved parties but the simulation model can be made correct and useful.

2.2.2 Existing solutions for environmental applications

There are existing solutions that could be applied on a simulation model in order to obtain values of the environmental impact of a product (Zhou & Kuhl, 2010; Heilala, et al., 2008). The most straightforward solution is to implement the data and calculations in the simulation logic. This will though require a strategy and knowledge of coding in order to obtain objective and useful results.

Simter is a software add-on for Visual Components 3DCreate that will let the user to implement calculations of energy and materials usage during the production. Simter will though not include the environmental overhead costs. The add-on module is taking ergonomics and Levels of Automation (LoA) into consideration, which completes the sustainability circle of the social, economic, and environment aspects. (Heilala, et al., 2008)

A simulation toolkit has also been developed for the simulation software Arena that incorporates simulation of logistics with environmental parameters. The toolkit will help the user to include environmental calculations into the normal DES environment much like Simter. (Zhou & Kuhl, 2010)

The above mentioned add-ons for simulation software are producing data tied to processes or products as outputs. That data can be used to determine and improve the existing situation for the producing facility. The benefit of an add-on module or toolkit is the simplicity of letting the software's perform calculations for the user. (Zhou & Kuhl, 2010; Heilala, et al., 2008) The approach may however decrease the control and understanding for the user when the calculation process is made in the background with less transparency. Neither of these methods is however compared to another static method for validity purposes or is specified for labeling products with an environmental product footprint (Heilala, et al., 2008; Zhou & Kuhl, 2010).

2.3 Input data

Input data collection is one of the most time-consuming tasks in a DES study and the need for correct data is profound (Skoogh & Johansson, 2008). Using existing sources of data might not be enough in order to create a validated model, estimations and measurements might be needed. In a normal productivity improvement simulation study the machines' specifications, cycle times, stop times etc. needs to be included (Heilala, et al., 2008). This is also the case when including environmental factors. The input data will be a more challenging job when assessing productivity and environmental impact, the input data management is therefore an extremely important task during the study that will require structure (Skoogh & Johansson, 2008).

To gather data for a simulation model an automatic data collection system can be beneficial for extracting large amounts of events and times from the system. Automatic data collection systems are though not always present at all parts of a production chain or not present at all. This will demand manual logging of cycle times, breakdowns and so on. If such logs do not exist a study of the actual production has to be made and if that is not available or it will require too much time the data has to be estimated. Traditional data gathering techniques can also be used to produce input to a simulation model. These gatherings are often done with stop watches, Mean Time Measurements or video recordings of the work process. Other data that are not available and cannot be collectable have to be estimated. Using similar processes or sources for comparison is often a good base for the estimation. In normal situations all of these data collection methods have to be applied in order to create a validated model. (Skoogh & Johansson, 2008)

The data can be classified in one of three categories; A (Available), B (Not available but collectable) and C (Not available and not collectable) (Skoogh & Johansson, 2008). Each of the categorizations will be present in most cases of DES cases, and the quality of the simulation might depend on how the data is distributed among them. If a data set belongs to category C, then the practitioner will have to estimate the value. It will then be practical to compare with other similar processes or materials to get an accurate estimation (Sargent, 1999).

2.4 Environmental communication methods

Existing types of product declarations that are based on Life Cycle data can be useful to communicate the environmental effects of a product. Environmental Product Declaration (EPD) and the Carbon Footprint are two well spread methods that can be communicated to the stakeholders of the product's environmental performance. (The International EPDsystem, 2010) (Institute for Environment and Sustainability, 2010) Carbon Footprint is though a method that only considers greenhouse gases, which might not be enough for everybody (Institute for Environment and Sustainability, 2010) (Tivander, 2011). The Carbon Footprint is measured in Global Warming Potential (GWP) where the carbon dioxide is considered to be the base value of 1 and other gases such as methane and nitrous oxide has a higher value due to higher effect on the environment (Institute for Environment and Sustainability, 2010). GWP is a measurement of which several emissions are combined into the equivalent CO_2 with respect to an optional specified lifetime. The measurement itself is only considering the emission substances that are proven to be affecting the global warming. (Solomon, et al., 2007)

Acidification Potential (AP) is a congregated single index indicator of acidification. Two of the main subsets of AP is nitrogen oxides and sulfur oxides. The idea of AP is generally the same as what is behind GWP but instead of CO_2 equivalents the Acidification Potential is measured in hydrogen-ion equivalents. The environmental effect is however not the same since acidification depends on the surroundings. (Metz, et al., 2005)

ECO Indicator 99 is a method for determining the damages made to human health, the environment and natural resources (Dreyer, Niemann, & Hauschild, 2003). The method itself is designed to present a single point value that will represent the damages made by the company or product. Since this method is considered to be nontransparent it is not recommended for communicating the results commercially. (Goedkoop & Spriensma, 2001)

A practical example of communicating the environmental product footprint comes from a Swedish fast-food company called Max. They present a carbon dioxide equivalent (CO_2e or GWP) label on all of their products. In this way the customer get a number and a unit to relate to each of their products. (Max, 2009)

3 Method

As mentioned in the introduction, the project was implemented through a case study at the company NMW. The case study in this project is used as a pre-study in the area of labeling products with environmental footprint data. The work process was including several phases for reaching the goals.

3.1 Work process

The case study was performed with different methods dependent on what type of interim target that should be reached. While gathering information such as input data for the simulation model the aim was to use as much existing data as possible.

At the initiation meeting with the CEO of NWM the project structure and scope was discussed to come up with a joint goal that fitted in to NMW's and EcoProIT's expectations. In the beginning of the project, factory visits were made to get a good understanding about the production system. Data was gathered from several different sources, which are all described in section 3.2. In some areas expert knowledge were needed to get help with input data and to get better understanding in some areas. In this case help from external resources has been used for LCA execution and power analysis.

Components of the two products were categorized into two categories described as "bought component" and "own produced component". Bought components are delivered ready for assembly to the factory and have no direct environmental impact in the production. The own produced components are manufactured at NMW from raw material delivered to the facility.

From the gathered information about the production system a DES model was created. Parallel to the creation of the DES model, Jonatan Berglund at NIST made an LCA with the same scope but for only "Product A". Both studies were using the same production data and environmental data to make them comparable. A comparison between the results for the studied product was made to benchmark the proposed initial DES method.

The project result is presented with a report and a presentation. Besides them a conference article to the Winter Simulation Conference (WSC) 2011 was made with the focus towards the comparison between the LCA and the proposed method. The outcome from the case study and recommendations for future research should be presented to the members in EcoProIT at a project meeting in June 2011. The work has been in close connection to other project members in

EcoProIT by several meetings during the period and meeting with the supervisor every Friday. The work process of this case study is described in Figure 3.

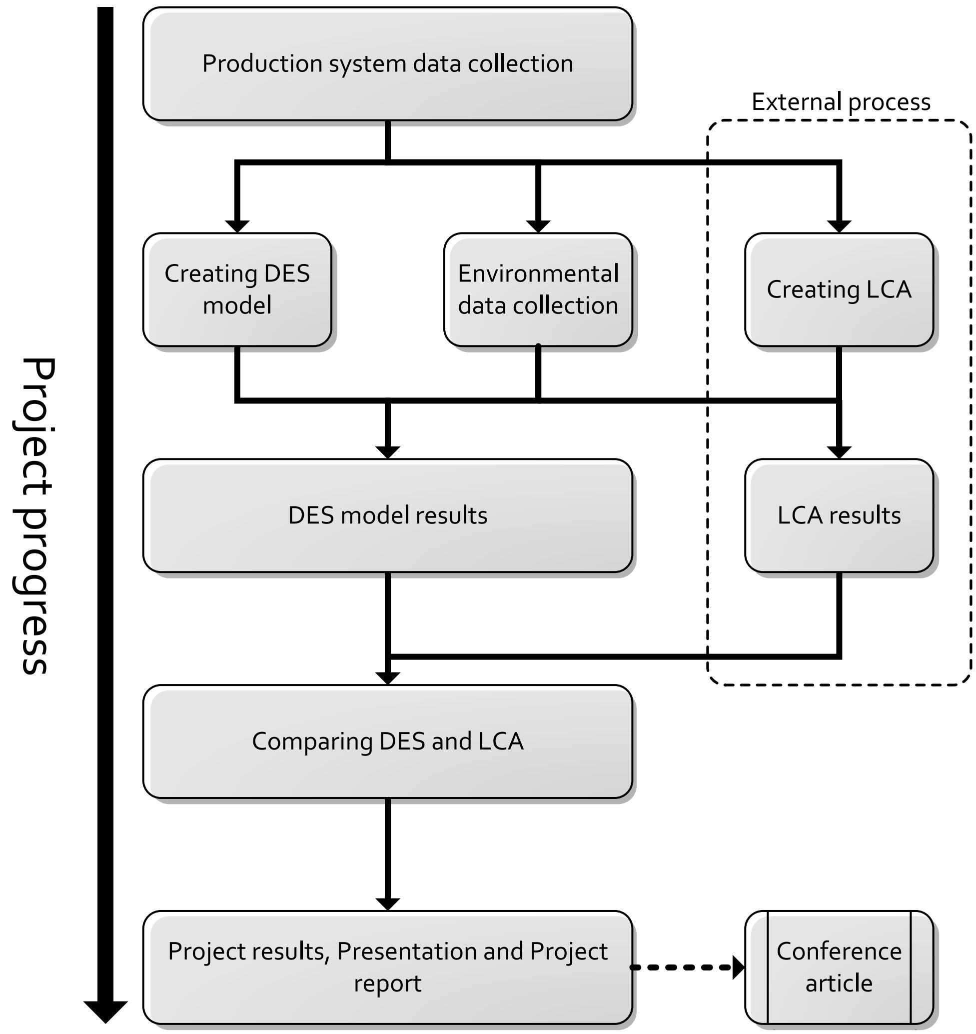

Figure 3 - Project progress and main tasks.

3.2 Data collection

The data collection process is a time consuming and very important phase in these kinds of studies. Before a simulation model could be created all input data should have been collected and the person creating the model should have a great understanding about the production system. In Table 2 sources for all input data and production system data is presented.

Table 2 - Data sources.

Data type	Source
Material quantity	Invoices
Supplier data	Invoices/ERP system/Company contact
Electrical power utilization	Measured
Production flows	ERP system/Interviews
Component data	ERP system/Measured
Raw material data	ERP system/Company contact
Breakdowns	Interviews/Observations
LCI data	ELCD/Ecoinvent

3.2.1 Invoices

General material data such as material quantity and supplier information was collected through the company's invoices from 2010. The material quantity and the price of material have been collected from a minimum of three months invoices to get sufficient correct average values. The total turnover from suppliers has been used as a factor to get the whole amount of material that has been bought from each supplier during 2010. Delivery distances from all suppliers to NMW have been calculated for each material by using common route finding web applications.

3.2.2 Measurements

The electrical power utilization for machines was analyzed by connecting a power quality monitoring instrument at the incoming three-phase system electricity feed. Data from at least four cycles of machining products was collected from each machine to get qualitative values. The sample time was set to 1 point per second. Collected data was categorized into idle and busy states. Average values of each stage were calculated to be get used in the simulation model. All machines used in the simulation model except the Okuma LB15 and the cutting machine were analyzed due to inactivity when the equipment and competence were available. Data measured for LR10M was estimated to be the same for the Okuma LB15 because of similarities of machine properties. The measurements were made with products that were available at the time of the study.

The weights of each component were measured when components were available with a scale at the resolution of 0,001 kg. Two components were missing when the measurement was made but similar products were available so a qualified approximation has been made with respect to these components. The components that are machined within NMW have been measured as finished components and raw materials. In the case where no raw material was available, the distributor's product information was used together with the raw material measurements to get the original weight of the raw material pieces.

3.2.3 ERP system

The product structure and the flow within the factory of the own produced products were collected through internal documents at the company and their ERP system. The flows consists of the most frequently used machines for sub products but from time to time the flow can vary depending on the workload and the fact that many machines can perform the same operations.

The ERP system also contains information about which suppliers that are used for which components. The raw materials size and in which quantities they are ordered have also been extracted from the same software. Since the ERP system also logs the customer orders, information about deliveries of products and turnover directed to the customers have been used from this source.

3.2.4 Interviews

Interviews with production workers were made at NMW in order to gathered data about production problem such as breakdowns and repair times. The interviews also answered questions about the production system in general and how the operators handled exceptions in the production system. The interviews were made in conversational form (Schober & Conrad, 1997) in order to get accurate answers that will benefit the project.

3.2.5 LCI databases

The majority of the LCI data has been extracted from LCA software that uses the ecoinvent database. The raw data has been used with regard to the functional unit of the process or material. When LCI data has been gathered no consideration has been taken to the specification of where production has been taken place. The database contains a large number of emission factors for most processes and materials. In this study only a select few have been extracted (CO_2, SO_x, NO_x, CO and CH_4). Through calculations these have then been turned in to GWP and AP. The selections of factors were made due to familiarity and comparison with existing product labels.

3.3 Assumptions and estimations

In order to make the data gathering less complex some assumptions have been made. Estimations have been made only when no data was available and when not enough data points were available in order to assimilate the dynamics of the real system.

The distance that components, raw material and the finished products are transported is the shortest possible way the delivery trucks can take. Stops and detours are not included in the calculations since no general method has been found that takes this into consideration. NMW and their suppliers use several logistic services for their deliveries, which add unnecessary complexity. An assumption has been made that all transportations are done with the same type of truck.

Raw material used for the own produced components are considered to be just enough for the amount of products that is being used for the component before machining. Leftover scrap or recycled material will only effect the total consumption for the factory and will not be added directly to the product.

Cycle times and setup times extracted from NMW's ERP system does not include any variations. Variations were discussed with the operators and distributions parameters were estimated as a percentage of the extracted value. The extracted value will therefore be considered as the mean value.

The energy consumption for general factory equipment such as heat, light, computers and machines in standby mode can be concluded from the below equation. In the calculation energy consumption for June and August were used. June month consisted of full production in 2010 and with almost the same average temperature as August. In August there was one week of vacation with no production, which contributed to lower energy consumption. The variation in energy consumption makes it possible to calculate the overhead energy consumption for the whole factory by using equation 2. Equation 3 is used to calculate the overhead consumption for one set of products.

$X_{month}; Energy\ consumed\ during\ one\ month$
$X_{tot}; Energy\ consumed\ during\ 2010$
$X_{pw}; Energy\ needed\ for\ production\ during\ one\ week$
$E_o; Energy\ overhead$
$O_p; Overhead\ percentage\ affecting\ a\ set\ of\ products$
$E_k; Energy\ affecting\ a\ set\ of\ products$

$$X_{June} - X_{August} = X_{pw} \tag{1}$$

$$X_{tot} - 12 * 4 * X_{pw} = E_o \tag{2}$$

$$E_o * O_p / 19 = E_k \tag{3}$$

3.4 Simulation modeling

In order to create a dynamic analysis of the product's environmental footprint the method will incorporate a DES model. A simulation model was built with respect to Banks Methodology (Banks, Handbook of Simulation, 1998). All of the data was cleaned and sorted in order to make it possible to use as input data for the simulation model.

3.4.1 Modeling method

In this study, five steps described in the Banks Methodology have shown to be most critical for reaching the project's goals. Two of the first steps described in the methodology are the data collection and conceptual model. A conceptual model was created parallel to the data collection process when the production system information was collected. Gathered information about the layout and the production flows was used to create the conceptual mode. The model was used as a base for creating the simulation model, which is the next main step described in the methodology. Verification of the simulation model was made continuously by making new studies of critical parts in the production and comparing them to the simulation model. The validation process was done in two steps. Firstly, production data such as lead times from the simulation model was compared with lead times from the production. Second, a comparison between results from the DES and LCA, described in section 3.6, were used as a validation of the environmental properties of the simulation model.

3.4.2 Simulation software

The simulation model was created in 3DCreate from Visual Components. The software has been chosen in order to maximize the usage of the model after its completion in the studied case. The software has the possibility to use "plug and play" models of machines and other equipment. To use the capability of fitting manufacturing equipment together the actual models have to be predefined and compatible with each other. If the system that is going to be modeled differs in some of the logic or have special attributes, these have to be added manually. A job shop styled manufacturing with several product flows and is going to simulate it through discrete events. In order to simulate the production at NMW all of the machines have to be created or modified in their logic code to create all the flows that are present and also adding the environmental approach.

3.4.3 Data management interface

The relevant input data is accumulated in a Microsoft Excel spreadsheet and converted to csv-files in order to easily import the data to the model. Importing the data into the model before it starts will not slow the simulation down during commissioning and will be less power consuming than continuously reading from the data-files during the simulation. The output from the simulation will be saved into another csv-file, which will be imported into an output spreadsheet through a macro. The output spreadsheet will consist of production data from the model, raw material, overhead and transport data which all are connected with the environmental data. The result is presented in both tables and diagram over the different environmental factors.

3.5 SLCA

The SLCA uses the same input data and most of the same assumptions as the DES analyze, which make them comparable. The LCA standard series ISO 14040 is used as a framework for the study and in accordance to the standard; all resource allocations are based on product weight. The total weight of material for Product A during one year of production is compared with the total weight of all materials delivered to the company during the same year. The given factor is used to calculate how much of the production that is occupied by Product A, for example the amount of electricity and coolant used from producing Product A. All internal processes are combined into one category and are seen as one black box. External process emissions are treated separately and calculated using LCI data found in the ecoinvent database.

3.6 Comparison

When validating a simulation model the normal proceeding is to compare the model results towards the real system often done by the simulation team. In this project that is focusing on the environmental performances of the system, validation will be done in a different form but using the same techniques that are proposed to be used for validation of simulation models (Sargent, 1999). In order to validate and evaluate the results of the DES model it has been compared with the LCA study. This comparison has also highlighted the differences in how data is treated and calculated. The comparison of the methods has been done through meetings and phone conferences with Jonatan Berglund focused on how the methods are separated through calculations. The results the different methods have produced are central in the comparison but also how they are presented. Basis for the evaluations have been focused towards one of the end-products of this project, the labeling of a product. Essentially the “Comparison to Other Models” validating method has been used for the purpose of validating the results (Sargent, 1999).

4 Results

The outcome from the DES study consists of two parts. In the first section the environmental product footprint for the studied product is presented. Secondly, a proposed method for how to make similar studies in the future is thrown out.

4.1 Case study results

The results of the case study are presented by exemplifying some of the most important parts of the study that affects the end result. The end result is considered to be the labeling of the products environmental product footprint.

4.1.1 Simulation model

In the simulation model only resources used for producing components to Product A and B was included. Other machines and equipment were left out for the model. This results in that the model only can handle the components produced by those resources. If the model should be possible to run other products resources and logics needs to be added. Some 3D-models of unused resources were included as static objects in the model for better graphical representation, which are presented in as a screenshot in Figure 4. Logic for all resources was created with the same ground, which make it relatively easy to adapt new products and flows to the system. Because of the focus towards determining the environmental footprint, functions for productivity evaluations were left out from the model. This part could be included in the future if needed.

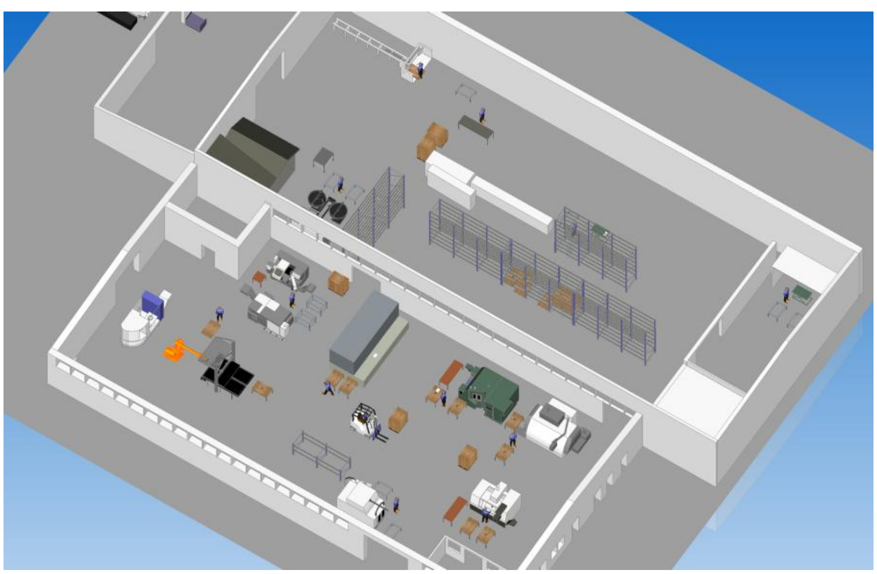

Figure 4 - Factory layout during a simulation run.

Output data from the simulation model consist of environmental emission affecting parameters such as idle electricity consumption, busy electricity consumption, transportation, steel thread and shield gas used for producing each product. All produced products are presented one by one to be able to calculate standard deviation of the production. From the output data calculations were made for the different emission drivers, which are summarized in Table 3. The internal processes are the only one directly affected by the output from the simulation model and it is to that emission driver the standard deviation is belonging to. As presented in the table most of the environmental emissions from producing Product A and Product B are taking place before the material comes to the actual production facility. One of the main reasons for this is that raw material extraction and processing have high electricity consumption (Norgate, 2002).

Table 3 - CO_2, GWP and AP emissions in kg for a set of products (standard deviation is in grey since it is not included in the total).

	Emission driver	**CO2**	**GWP**	**AP**
Before production	Bought components	286,779	291,149	64,968
	Raw material	368,618	368,711	79,207
During production	Internal processes	1,873	1,874	0,513
	Standard deviation	0,102	0,102	0,030
	External processes	0,690	0,715	0,585
	Overhead	1,005	1,006	0,192
Transport	Before production	0,0007	0,0007	0,0001
	Production transport	0,0001	0,0001	0,00002
	Post production	0,0009	0,0009	0,0001
	Total	**658,967**	**663,457**	**145,466**

When the study was made the electricity source was according to the contract with the electricity distributor containing of 99% hydroelectricity, which is good from an emission perspective. In electricity calculations the hydroelectric source was compared against a normal contract of the Swedish electricity mix, which represents a year when the import of electricity is at its highest levels. In Figure 5 the GWP emissions are presented for the main emission driver during production with hydroelectricity.

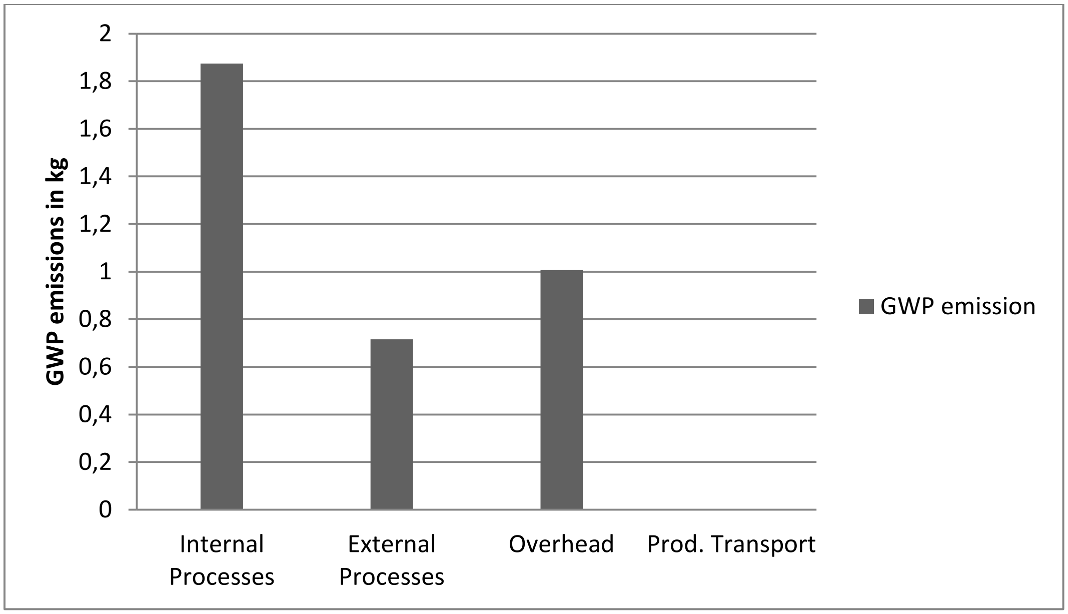

Figure 5 - GWP emissions of hydroelectric power and overhead calculations by material weight.

Changing the electricity source to Swedish electricity mix, this will affect the proportion of the emissions will change. In Figure 6 the emissions for example overhead emissions will be much higher since electricity consumption constitutes a large part of the overhead factors. Processes including high parts of direct electricity consumption will be affected the most of the change.

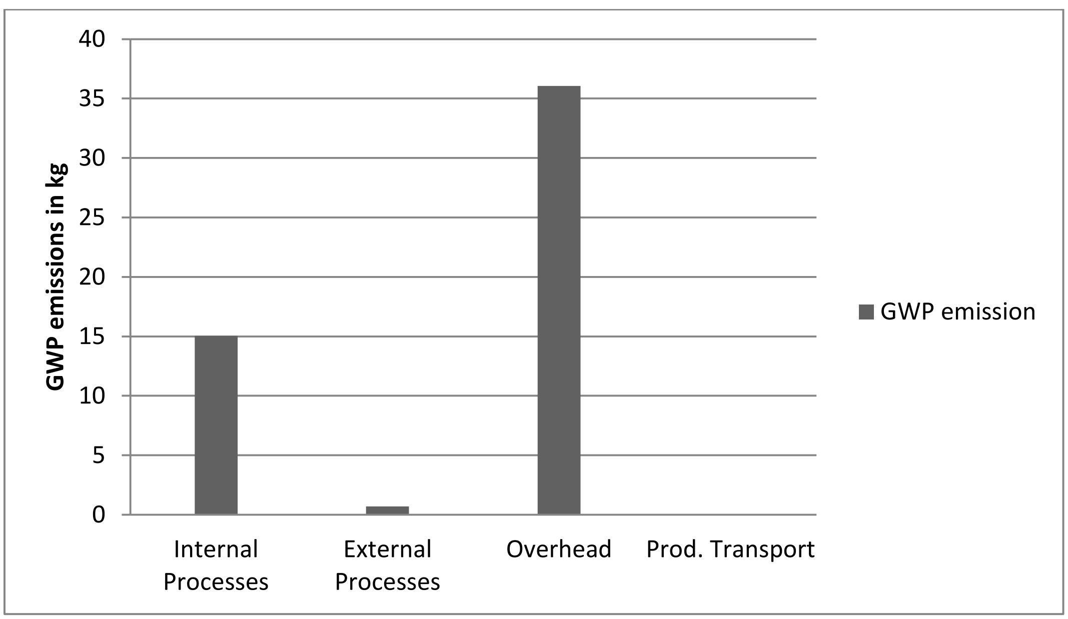

Figure 6 - GWP emissions of Swedish mix electric power and overhead calculations by material weight.

4.1.2 Overhead allocations and electrical power utilization

Overhead calculations of production allocations to the studied products are depending on how the allocations are extracted. In general the allocation method will give a percentage that can be multiplied with whatever resource that is supposed to be affecting one year production of Product A and Product B as a set. In this study allocation methods have been compared and are presented in Table 4. The 80% fill rate for storage space describes the current situation when the study was made.

Table 4 - Overhead calculation base.

Type	Calculation base	Overhead percentage
Economical	Value of invoices	6,79 %
Storage space	Storage rack	6,27 %
	Storage rack 80% filled	7,84 %
	Pallet capacity	3,43 %
	Pallet capacity 80% filled	4,28 %
Deliveries	Amount of outgoing parcels	3,61 %
Working hours	Dedicated working hours	6,05 %
Incoming material weight	Dedicated incoming material	4,93 %

As could been seen in the table above the calculated allocation values differ between 3,61% and 7,84%. The large variance affects the result to some extend because the overhead factor is a large part of the total emissions in the factory, which is presented in section 4.1.1 . Figure 7 is presenting the GWP emissions for the different overhead calculations.

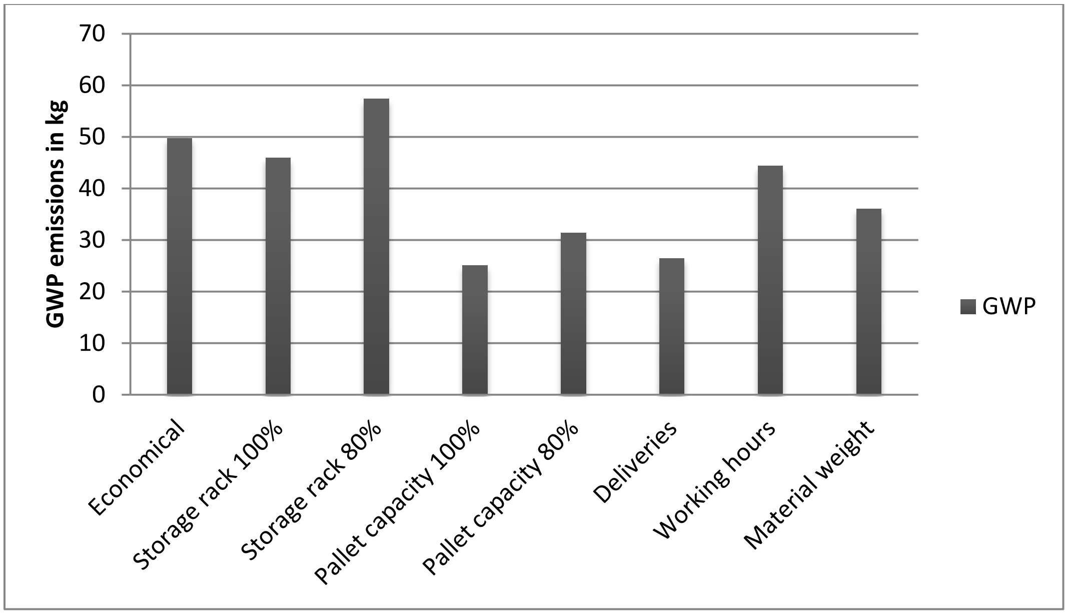

Figure 7 - GWP emissions for different overhead factors for one set of products.

The electrical power utilization study resulted in values of power consumption for all machines except the Okuma LB15 and the cutting machine. The full table of power consumption for each machine is presented in Appendix C. The used monitoring instrument generated graphs of the power consumption. Figure 8 presents one section of the graph for the Okuma MC400H. In the graph two pointed cycles can be seen, which represent the busy state of the machine. In the period between the two cycles the machine waits for new material and is representing the idle state. The line above in the graph describes the average value of the busy state and the lower the calculated value for the idle consumption. The measurements also showed that some machines were consuming reactive power when they were in standby mode.

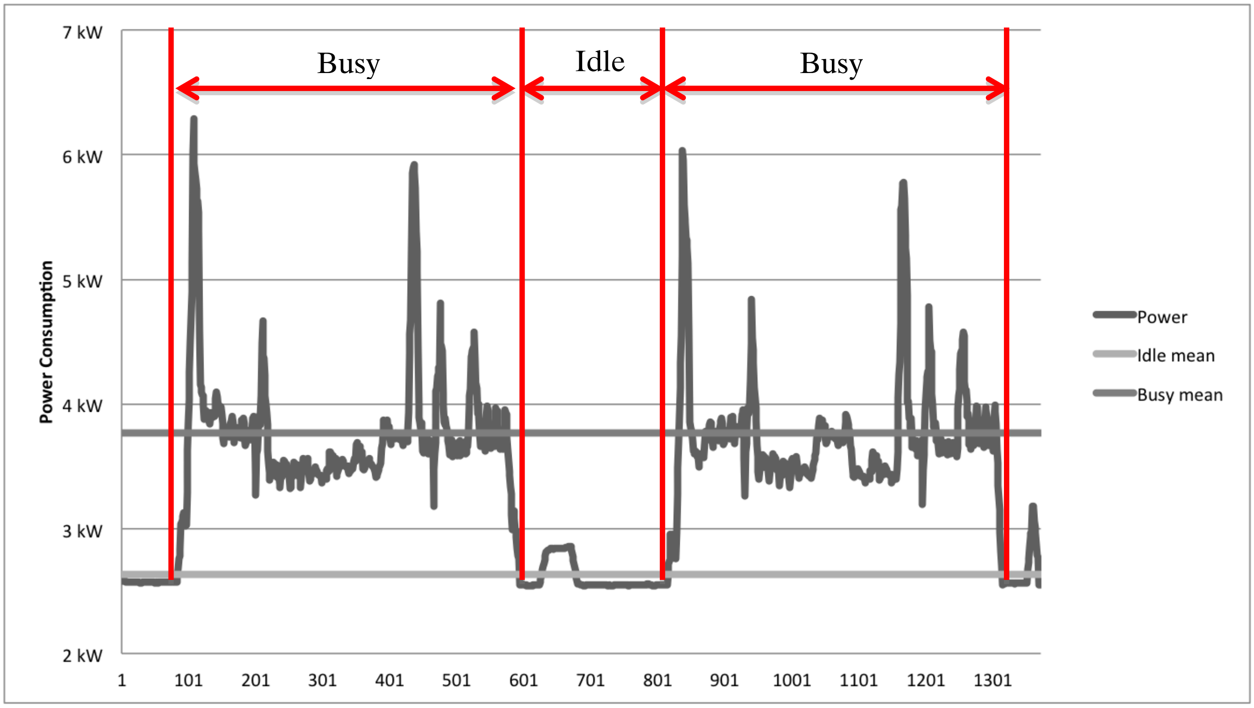

Figure 8 - Energy consumption for Okuma MC400H.

4.1.3 Environmental product footprint labeling

The internal label should contain at what stages of the life cycle that the emissions are emitted. This label could contain all of the desired environmental factors but it would be recommended in order to ease the absorption of information that one factor such as GWP is at main focus. The standard deviations of "Internal Processes" are an important factor for analyzing the stability of the production system. For NMW their product labeling of their set would be as pictured in Figure 9.

Life cycle stage	Emission driver	CO2	SOx	NOx	CO	CH4	GWP	AP
Before production	Bought components	286,77885479 kg	0,39193807 kg	1,12542328 kg	5,76726693 kg	0,17481956 kg	291,14934370 kg	64,96848271 kg
	Raw mataterial	368,61767736 kg	0,36368074 kg	1,51687153 kg	8,48384879 kg	0,00375160 kg	368,71146734 kg	79,20688090 kg
	Transport	0,00071702 kg	0,00000007 kg	0,00000268 kg	0,00000096 kg	0,00000001 kg	0,00071720 kg	0,00011090 kg
During production	**Internal processes**	**1,87307914 kg**	**0,00222960 kg**	**0,00999154 kg**	**0,04966155 kg**	**0,00002737 kg**	**1,87376327 kg**	**0,51330272 kg**
	Standard deviation	*0,10183208 kg*	*0,00013536 kg*	*0,00056831 kg*	*0,00314834 kg*	*0,00000143 kg*	*0,10186770 kg*	*0,02962430 kg*
	External processes	**0,68983599 kg**	**0,00190750 kg**	**0,01219357 kg**	**0,00388548 kg**	**0,00101868 kg**	**0,71530287 kg**	**0,58511233 kg**
	Overhead	**1,00542006 kg**	**0,00050829 kg**	**0,00413818 kg**	**0,00554825 kg**	**0,00001733 kg**	**1,00585323 kg**	**0,19150881 kg**
	Component transport	**0,00011015 kg**	**0,00000001 kg**	**0,00000041 kg**	**0,00000015 kg**	**0,00000000 kg**	**0,00011018 kg**	**0,00001704 kg**
Post production	Delivery to customer	0,00090088 kg	0,00000009 kg	0,00000336 kg	0,00000120 kg	0,00000001 kg	0,00090110 kg	0,00013933 kg
Production at NMW	*End product*	**3,568 kg**	**0,005 kg**	**0,026 kg**	**0,059 kg**	**0,001 kg**	**3,595 kg**	**1,290 kg**
Total	*End product*	**658,967 kg**	**0,760 kg**	**2,669 kg**	**14,310 kg**	**0,180 kg**	**663,457 kg**	**145,466 kg**

Figure 9 - Screenshot of the internal environmental product footprint label from the datasheet.

The external label however shall consist of less information than the internal label since the knowledge of what stage the emissions is produced is not of interest for the customers. A similar presentation that a known Swedish restaurant group has done of only a single value of GWP is therefore recommended. This projects label would then be pictured as in Figure 10.

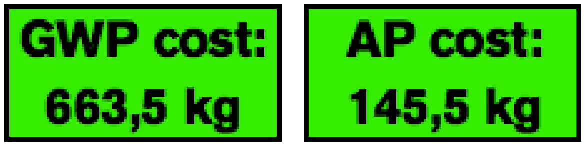

Figure 10 - External environmental product footprint label.

This small amount of information only constitutes the information that is derived from the environmental product footprint study and does not explain anything other than the result.

4.2 Proposed method for determining environmental footprint

During the course of this case three parts of the project have been present that can apply for similar projects of this nature. Firstly, the managing of data that is the foundation for the study and its results. Secondly, the determining of the environmental impact or product footprint should be made through a DES analysis. When the environmental product footprint has been determined the results can be communicated both internally within the company and externally towards customers. The main phases of the proposed initial method are pictured in Figure 11.

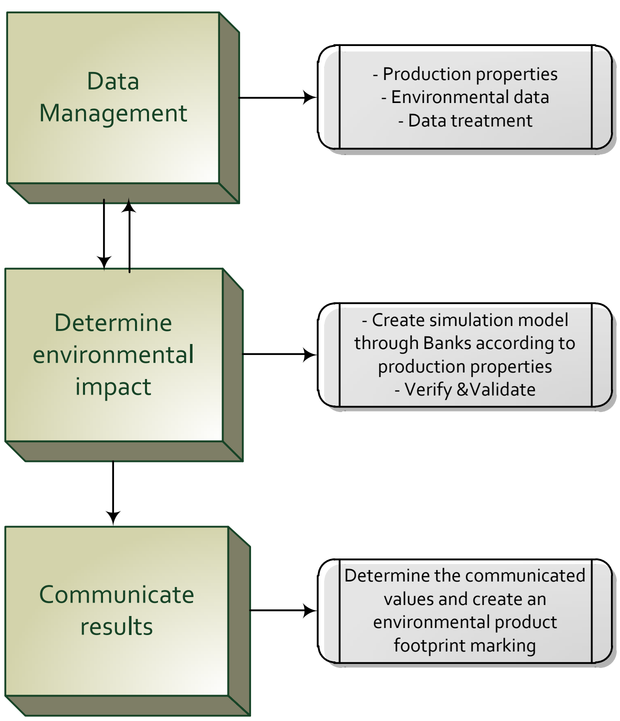

Figure 11 - Three steps of analyzing the environmental product footprint.

4.2.1 Data management

Creating an analysis for determining the environmental footprint for a product dynamically requires a lot of data to be managed. Firstly the process data needs to be gathered, since this data will carry the dynamics of the production. In the sheet below, questions and data points are gathered under its respective area. By following the list and if all data is present then the base for the model is complete. Depending on what type of production that is going to be analyzed, some of the questions or data sets can be excluded or presented in a different form. Process data might also be added to create a complete model, but this is up to the practitioners of the project.

Data management

To be able to create a DES model with focus on determining the environmental product footprint the following questions and data sets needs to be answered and gathered:

Data Group 1: Before production properties

- -Components
  - How can the components be categorized?
  - What components are produced in-house?
  - What materials are used in the components?
  - What do the components weigh?
  - What batch sizes are the components and the raw material ordered in?
- -Suppliers
  - Who are the suppliers of raw material, components and media?
  - What is the distance to the suppliers?
  - Which transport services are used?

Data Group 2: During production properties

- -Machine specific data (Gather data)
  - Cycle times, setup times and stop times (MTTR, MTBF)
  - Manual work specifications
  - Use of auxiliary media and material
- -Product flow (Gather data)
  - Map the studied products flow
  - Transport options within the production area
  - Production planning strategies (Push or pull etc.)
- -External services (Optional)
  - Where is the external service?
  - What type of treatment is used?
  - What are the lead times?

Data Group 3: After production services

- -Transport
  - What transport service is used for delivering finished products?
  - How far are the products transported and to which customer?

Data Group 4: Environmental data specifications

- -Machine energy consumption during busy, idle or break down periods
- -Raw material production emissions from cradle-to-gate
- -Transport emissions for different types
- -Auxiliary media emissions for different types during production from cradle-to-gate

The material data is concerning foremost the incoming material data, its specifications and origins. The finished product data is also important in this category in order to decide how much material that is being scrapped during production.

4.2.2 Determine environmental impact

There exists a general method that has been well adopted in order to produce a verified and validated DES model; the Banks model (Banks, Handbook of Simulation, 1998). This framework for creating simulation models can also be adapted to also determine the environmental footprint for a product.

To determine the environmental impact dynamically, a simulation model has to be created. This step during the project is often software specific and the choice of software could be done with regard of the task, the data or the usability of the model for the customers. Depending on which software that is chosen there might be an available plug-in that can handle most of the environmental calculations for automatically. Using a plug-in might however reduce the control of the data calculations.

If the model is created and coded without any environmental plug-in the dynamic data should be added to each product on a machine level as exemplified in Figure 12. The static input of environmental overhead costs can be added within the simulation model or in order to simplify the model it can be included afterwards in the data sheet that represents the output of the model.

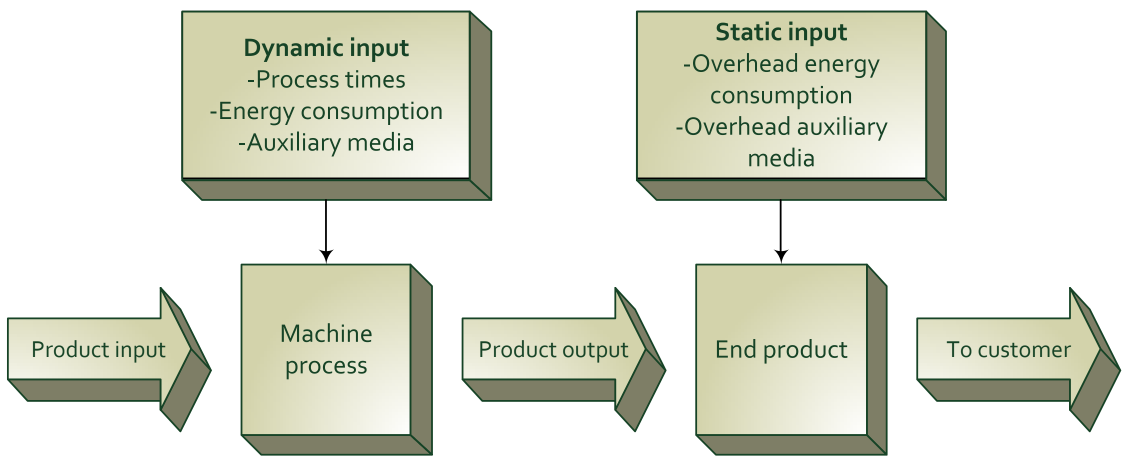

Figure 12 - Dynamic and static environmental factors and data adding to a product.

Using this way of allocating dynamic and static environmental emissions or resources will then give a total value for each product. The end product's consumption will then consist of energy, materials and media that are being used during production which all emit environmental emissions. The total from each product will not be the same for each product since the dynamics of the simulation model are taken into consideration.

Validating and verifying the simulation model can be done in a number of ways that are suitable for the project. The best possible way is if the output of products and details can be verified against the real system through known validation methods and the environmental product footprint could be validated towards another known method for determining environmental impact. (Sargent, 1999)

4.2.3 Communicate results

Depending on to who the information is directed at the communicated information amount from an environmental product footprint analysis can be different. This project has identified two main receivers of the environmental information, first the customers who and secondly the producing company itself. It is recommended that two ways of labeling the products should be used, one simple and informative for the external customers and one more detailed label for internal communication and improvement work. The information that is contained within the simulation and labels will decrease closer to the customers as in Figure 13.

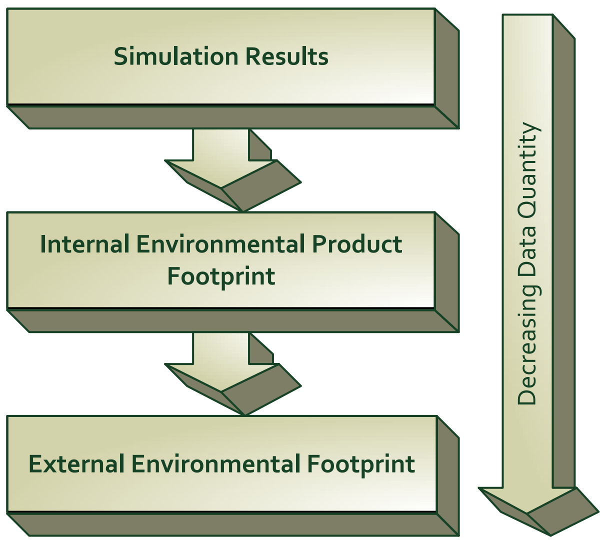

Figure 13 - Information communicated at each step.

An example of what specific environmental information that is communicated internally and externally is presented in paragraph 4.1.3.

5 Comparison

Results from the SLCA from production Product A, presented in Appendix D, compared with the DES results shows that all stages except processes inside the production at NMW (During production) have similar values. This was expected since those parts originate from the same data and static calculations. Since the SLCA was using weights of incoming material as an allocation strategy the same method was used for overhead allocations in the DES study. The results of the major emission drivers are shown in Table 5 for producing one individual Product A, which confirms the similarities of before production and transport services.

Table 5 - Product A's GWP emissions for major emission drivers with hydroelectric power.

Emission driver	DES	SLCA
Before production	49,142	49,142
During production	0,286	0,279
Transport	0,0001	0,0001
Total	**49,428**	**49,421**

The interesting parts are how the production dynamic changes the output data for processes within the factory. In the DES study each product gets an individual footprint, which resulted in a standard deviation that describes the dynamics of the system. The standard deviation can be observed in Figure 14 as a thin black bar on top of the DES results. Because of static calculations in the overhead allocations and external processes the standard deviation is only related to the internal processes result. The internal manufacturing part in the SLCA includes parameters included in both overhead and internal processes for the DES study. As could be seen the SLCA result is within one standard deviation of the DES result.

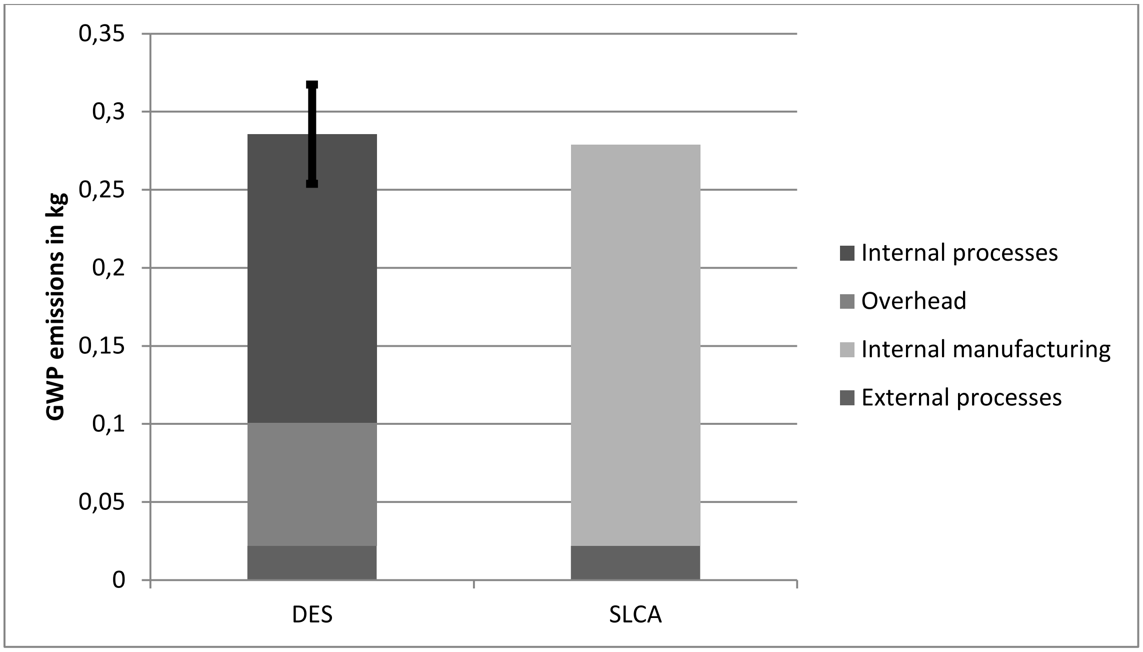

Figure 14 - During production comparison of internal processes between DES and SLCA with hydroelectric power.

The variations could have a significant effect on the result, which is shown by the standard deviation. This is something that is not accounted for in the SLCA method. In Figure 15 the GWP emission for each of all produced Product A during one year is plotted and compared with the value of the SLCA. The plot is displaying variations that are not taken into account by the SLCA.

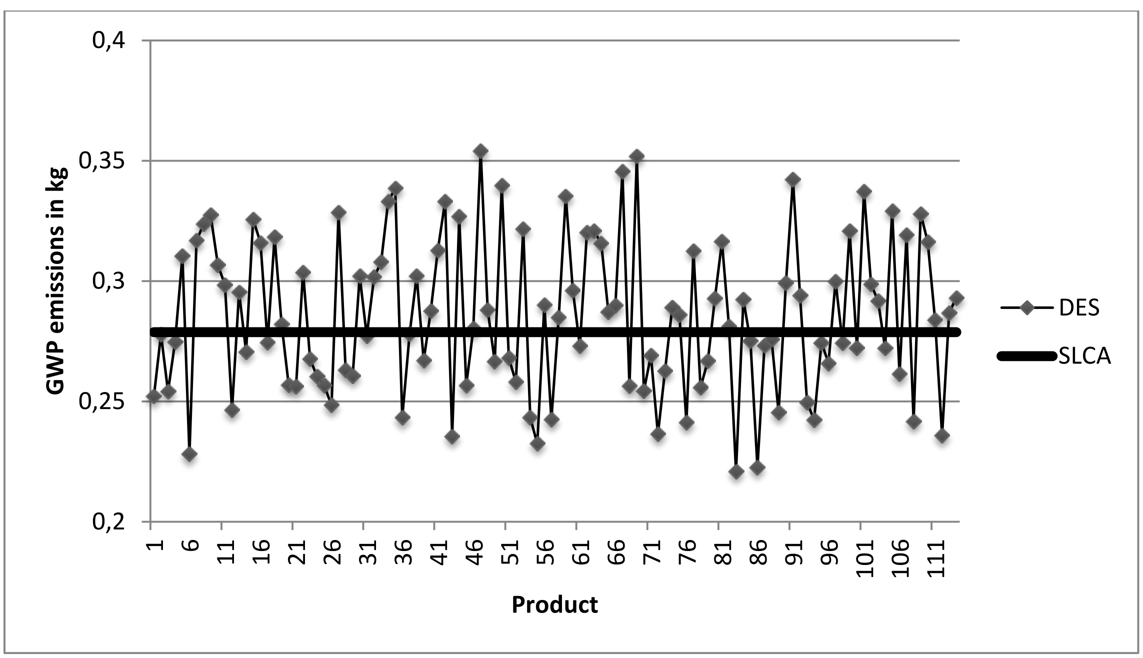

Figure 15 - The variation of product results for 114 of Product A.

In Figure 16 the “During production” emissions of GWP is presented with the use of environmental parameters that are relative to the Swedish electricity mix. When comparing Figure 14 with Figure 16 it is apparent that the SLCA is more dependent on what type of electrical source that is used since that is the only difference between the figures. In Figure 16 the SLCA value is not within a standard deviation of the DES method, which suggests that the two methods have different allocation strategies. For the DES method the variations becomes less important when static overhead emissions are a larger contributor to the products total emissions.

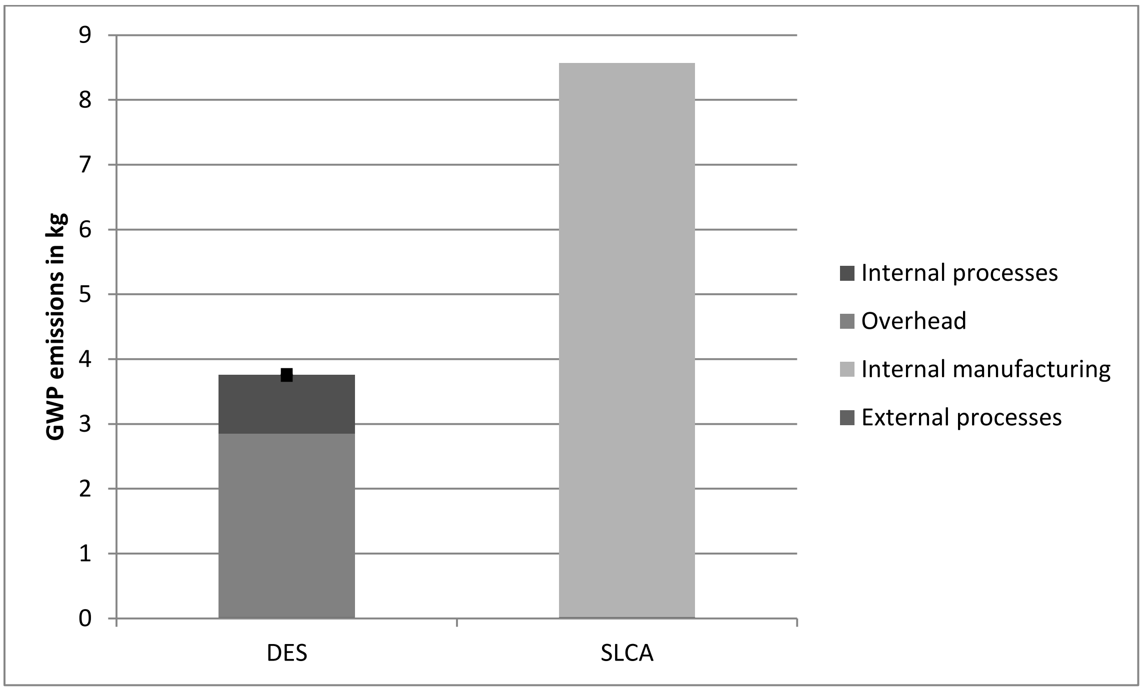

Figure 16 - During production GWP emissions for internal processes with Swedish-Mix energy.

The SLCA accounts for the whole electricity consumption of the factory and will indicate higher consumption attributed to the product. The mean electricity consumption allocated by each product for the two methods are presented in Table 6. Depending on which method and which electricity that is used the emissions will vary since the effect is increasing with higher emission values per kWh.

Table 6 - The average resource consumption during production for one individual Product A.

Product A	DES	SLCA
Electricity consumption	34,45 kWh	83,68 kWh
Welding thread	0,2353 kg	-
Shield gas	0,1041 kg	0,1866 kg
Paint	0,0318 L	0,0318 L
Thinner	0,0080 L	0,0080 L
Coolant	0,1674 L	0,1674 L
Hydraulic oil	0,1911 L	0,1911 L

The difference in electricity consumption between the methods can be one of the reasons for the higher value of GWP for the SLCA method in Figure 16. This comparison has shown that some electricity consumption might not be included in allocations for the DES method or that too much consumption is allocated to each product in the SLCA. In the DES study the missed consumption could be for instance when the machine is turned on and is consuming power in the idle state and no product is there to allocate that consumption. The weight allocation by raw material could be the reason that the electricity consumption is higher for the SLCA. The allocation method also includes the weight of the bought components which has a main part of the total production weight but do not consume as much electricity as the produced components.

The other two big differences in the table are the welding thread and shield gas. For the welding thread this part is accounted for as raw material to the production in the SLCA while it is calculated as a parameter in the DES study. Shield gas is calculated and allocated to each production in the simulation model, but in the SLCA the total amount of gas consumed during one year is divided to each product by the described allocation method. In this case the differences could be connected to those other products consumes more gas than the studied product.

Comparison summary: The average emission result from the case study has shown to be similar with the SLCA results, which make the methodology credible. System variations are stated in the methodology and described in Figure 15, which is not possible to evaluate from the SLCA. The allocation of overhead factors is crucial for the total result and a large contribution to differences between the two methods.

6 Discussion

The purpose of this thesis was to determine the environmental product footprint for a product and compare the results with an existing static method. Since the result of the external product label is presented as static values the result has a non-significant value in terms of innovativeness. The internal product label includes foremost the internal production emissions, which has a dynamical value. The dynamical value can give indication on how stable the emission contributing events within the production are. Using the simulation model for analyzing future improvements, investments within the production can be made with respect to the environment and lower the products environmental footprint.

The data collection process has shown to be one of the main phases in this project and is very important for making an accurate study. The quality of the input data will reflect the simulation results. In this study most of the data can be categorized as A (Available) and B (Not available but collectable). Data that has been classified as category C (Not available, not collectable) have not been included in some cases. (Skoogh & Johansson, 2008) The amount of data that could be gathered is in some way controlled by the available time and how much work that are needed for getting each data parameter. This limitation has most probably contributed to the vast difference of emission values between the proposed DES method and the SLCA method in Figure 16. Some of the machine properties are input data belong all of the categories A, B and C. The cycle time for some machines was available but the variation of the cycle time did not exist. In some cases they were derived from interviews with operators and in other cases they had to be estimated.

In the process with collecting environmental data from ecoinvent and ELCD it was noted that some of the parameters are differing to some extent between databases. Depending on which database is used the result will also differ. This could be seen in the example with the electricity source. The problem could be connected to what assumptions that have been made, e.g. if some data have been uncollectable in the database an assumption is made to use data for a similar material with almost the same properties.

During measurements of the machines energy power utilization it was shown that one of the machines were consuming reactive effect during the night. Since the company is small they are not billed for this effect, the energy is not included in the results but the energy has to be produced. Further research of how and if reactive and capacitive power should be included in products environmental footprint may be necessary especially when projects like this is carried out for larger companies. The measure point for this should then probably be the main feed of electricity since they are billed for the power consumption of the whole company.

The comparison of overhead percentages in 4.1.2 shows that depending on what strategy is chosen, the result can vary with more than double from the smallest to the highest value. Which strategy that is right to use is hard to tell. All of the overhead values are though giving us a set of possibilities. The overhead part could be calculated from the simulation model and will then depend on the simulation result. For instance, if the model could produce specific figures for how long each product and component has been within the factory. If this was going to be used to produce an overhead percentage for all products but it also requires every product to be simulated in the production. As a result each product would have a unique overhead percentage, which would have included more dynamics in the result. This has not been done in this case and therefore this allocation strategy for overhead emissions have not been used.

Scrap from the manufacturing process and defect products is parameters that are left out of the simulation model, this should be analyzed further in the research project. In the production some components gets damaged and have to be reproduced to substitute them, which contributes that more raw material and resources are used in the production. The interesting part is how to divide this extra material to the end product. There are several methods to allocate the material depending on where in the production the problem occurs. In this case study, extra material could have been calculated as a static overhead part, but the gathered data over scrap is not accurate enough for a good allocation. To be able to allocate the extra material in the simulation model at process level, more detailed studies in the production is required. The metal scrap from machines such as chips is already covered by the total amount of bough raw material for each product. The recycling of material is also interesting in the total life cycle but not covered in this case. The raw material is according to the supplier manufactured by recycled material for some of the raw material types and in that sense already included in some parts. By reducing the scrap and defect products it should be possible to reduce the total emission value, based on that less raw material is needed.

Using environmental data within the simulation model requires much computing power and could slow down the execution of the model. In this case no environmental data has been included in the simulation model. The environmental calculations have been made in the spreadsheet based on output data from the simulation model. This method was chosen because of the complexity to include all data in the model and to make it easier to evaluate different environmental sources based at the same output. This method is currently used by simulation software environmental add-ons, such as Simter. Having environmental parameters included in the graphical simulation could benefit the model for presentation purposes.

Creating a simulation model is a complicated and time-consuming process, especially when the production system has a high complexity and consists of human behaviors. It could be hard to simulate human behaviors because every worker argue different and uses different solutions from time to time. It is therefore hard to analyze exactly how workers are managing different situations. Excessive human behaviors and a job shop production can be too complex and might break the tenth rule of "Don't simulate when…" by Banks and Gibson (1997). The graphical representation of the simulation model in this project is high and consists of almost all machines and equipment that are present in the real world. In this case the graphical representation may have been too high. To make the process faster the graphics could have been left out. Before deciding the level of graphics in a project like this, the aim with the simulation should be decided. If the model should just be used for one analysis, it could be enough with a lower level of graphics. If the model will be used as demonstration tool or viewed by external audiences, higher effort in graphic development could be beneficial for the project.

The comparison between the DES method and the SLCA describes several similarities and differences. Most of the work done in the SLCA is also made in the DES study, for example calculations for before the production and external processes. As could be seen in comparison between the two methods the main difference is in the internal processes, where the DES study could allocate parameters to each product, which is usually not detailed in the SLCA. Detailed parameters are though demanding thorough data collection.

In a project with the main focus of only determining the products environmental footprint it might not be beneficial to use simulation since it extends the time needed for project completion. If a simulation model already exists or is supposed to be developed for other purposes the addition of environmental parameters is not that time consuming and will give more information to the stakeholders of the project. The greatest benefit with using a method based on the proposed method instead of a static method is that the dynamic in the system makes it possible to generate different emission values for different products. This makes it possible analyze the production stability and find sources in the system with high emissions that could be improved. By focusing the right efforts towards the right emission source the largest improvements can be made for the whole system.

Dynamical studies of products and production systems focused on environmental footprints can also be useful for determining the planning strategies that are most environmentally beneficial to be used. If we consider a pull flow that only produces the amount of products that the customer wants, the number of setups for products will increase which will contribute more idle electricity consumption to the products. Larger batches in a push flow will in contradiction decrease the amount of idle electricity consumption that can be added to the product. Therefore the often mentioned LEAN philosophy with pull flows will increase the electricity consumption waste.

The proposed method is specifically designed for an industrial case that is similar to the NMW production and the project goals. In order to make the method more general some parts might have to be included or excluded. For studies that are not concerning the production of products the method might not be fulfilling the needed goals but this nothing that has been of concern in this master thesis.

To be able to use the external environmental footprint label for marketing new products, it is important for consumers to understand what the label information represents. It could be easy to just present a single index value, but if the consumers can not relate the value to anything the label will have no effect. A weight based comparison scale could be something that is preferable. For companies the proposed internal label contains more information about the different emission drivers that could be important for future improvements. It may also be needed to present more details about the different parts in the production in order to evaluate and improve different steps in the production.

7 Conclusion and recommendations

Analyzing the chain of a product and determining its environmental footprint will add more complexity to a simulation model in the form of data management. The studied production facility is not the largest emission contributor in the life cycle steps of the product, but this may not be the case for other products. It is therefore important to take each life cycle step into consideration when studying the environmental footprint. If the method could be applied in several instances of the product chain a total dynamic footprint could easily be determined, analyzed and communicated.

Using a method for dynamically determine the environmental product footprint of a product will give the advantage of being able to see product variations. Using a static method will give a single point value to each emission and if the process is unstable the values will not reflect the true emissions of the product. Analyzing the DES model in our method will also give the possibility to see where and how the unstable system could be made less unstable. E.g. if an improvement is made within the production that lowers the possible value of the environmental footprint it might also increase the highest value, the effect can therefore be the opposite or unchanged. Using static methods this might not be detected since the variation of emissions between products are not included. Future product or production changes could also be evaluated regarding environmental emissions, which can become important in case environmental restrictions is introduced or the existing emission certificates becomes an issue for the company.

7.1 Expected results from an environmental product footprint study

One of the biggest problems in the study has shown to be the dynamical aspects of environmental parameters. The main focus has been to analyze the machines electrical power consumption when producing the different products. Beside the electricity, studies have been made to the welding process that includes power, shield gas and steel thread. The contribution from the overhead emissions can be varied depending on what type of calculation method that is used. This was done in order to be able to analyze different scenarios. For several parameters included in the overhead factor it should be possible to make them dynamical in the model if accurate data could be found. The different ways of allocating overhead emissions could also be dependent on the components time within the factory. This would make the overhead values dynamic and the benefits of shorter lead times could be analyzed.

In order to create an environmental product footprint labeling that is relevant for the customer and the producing company the labeling has to be simplified enough to not enhance the risk of misunderstanding but also complex enough to be useful for further studies. It is recommended to create a labeling that easily could be communicated towards the customers with widely known variables such as CO_2 or GWP. The authors of this report recommend GWP since it includes more factors and is widely spread in environmental media. The simple labeling should be an aggregated version of an internal label. The more complex internal label should only be communicated internally within the own company for benchmarking purposes and improvement analyzes. The amount of data that is presented internally within the company should be adapted to what is considered to be necessary for the ongoing environmental improvement work.

For NMW it's recommended to use only the environmental drivers that are connected directly to their own production. Since these are the drivers that they directly can influence. During their improvement work within the company the whole picture should be accessible, since changing suppliers and ordering procedures might change external factors.

7.2 Methodology for determining the environmental footprint

The proposed methodology for determining the environmental footprint is specifically designed according to the studied case in this report.

7.2.1 Design of methodology

Using the steps that are explained in section 4.2 as a basis for a study that is focusing on determining an environmental product footprint, future studies can become successful. However the whole complexity of a production facility will not be taken into consideration since each production facility has its own special characteristics and properties. Therefore the methodology steps need to be adapted towards a more general form of factors that include the ones that have been stated relevant for this case.

Allocation of environmental factors to specific products in the model makes the method dynamic. It has shown that some factors are hard to divide to the product and depends on what data that is available for the resources. In the idle state of a machine, the machine consumes energy which is one parameter that is difficult to allocate to a specific product.

7.2.2 Evaluation of methodology

Using DES to analyze the environmental footprint will require normal data gathering that is done in all DES projects and also additional environmental data. Therefore the project initiators have to consider the "Don't simulate when…" by Banks and Gibson (1997). Normal capacity, bottleneck and productivity analysis could be done with the same or less effort as just studying environmental footprint. Because of this, it is preferable to execute both types of analyzes within the same project to maximize the utilization of time and money.

7.2.3 Application of the methodology

The increased complexity of modeling a job shop factory might contradict the need for simulation and other methods could be more efficient. A job shop production facility relies heavy on the human's behavior, which is hard to model, and the component flow within the factory can be complex too. Significant simplifications have to be made in order to not prolong the time spent on building the model.

The application of the model is more suitable for production facilities with fewer component flows and less complex products in order to be time efficient. The importance of the dynamic results for the total environmental footprint will depend on the amount of available production data (Category A, (Skoogh & Johansson, 2008)). More precise data that can be used will give more accurate results.

7.3 Future development

For future research in this area and within the EcoProIT project the authors are recommending following areas of interest:

- Clearer guidelines of how to use overhead allocations dynamically in future projects using the proposed methodology.
- Further research, aiming to determine time consumption for a study using the proposed methodology at a more appropriate production facility according to 7.2.3.
- Generalizing of the proposed methodology for expanding the usefulness in other production settings or processes.
- Generalization of the environmental product footprint label for usage in commercial cases.

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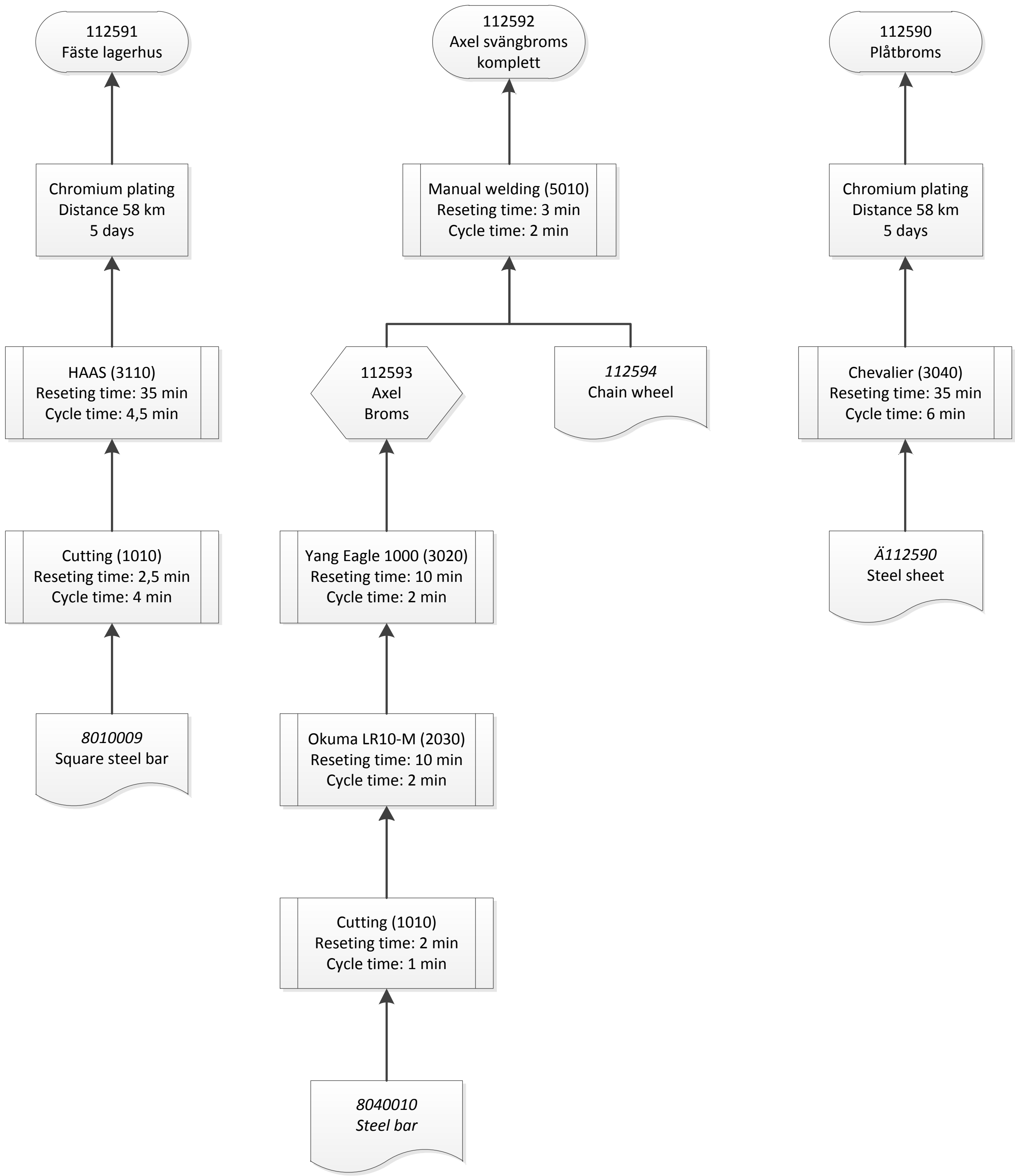
Appendix A

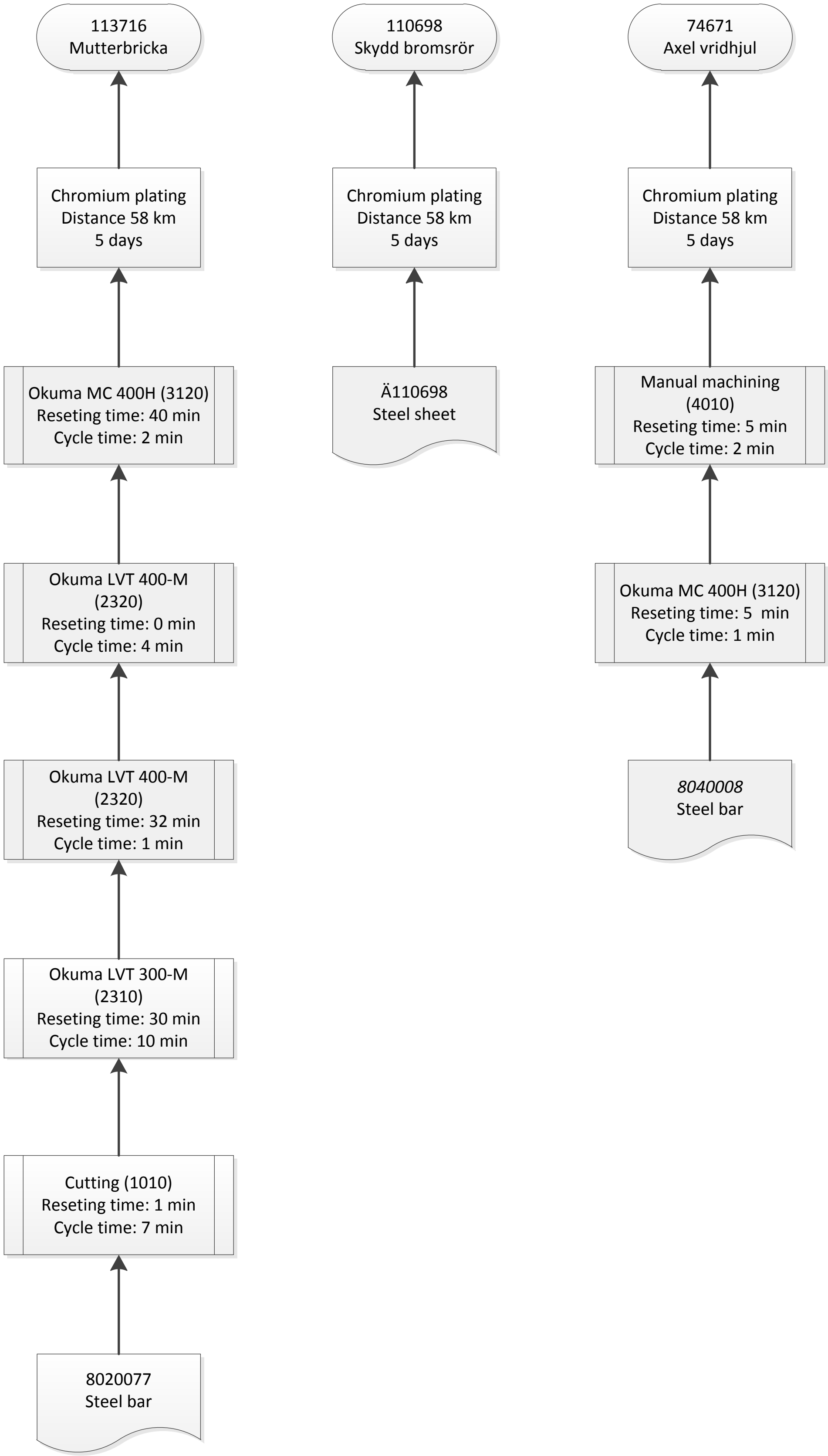
Product A – Production flows per component:

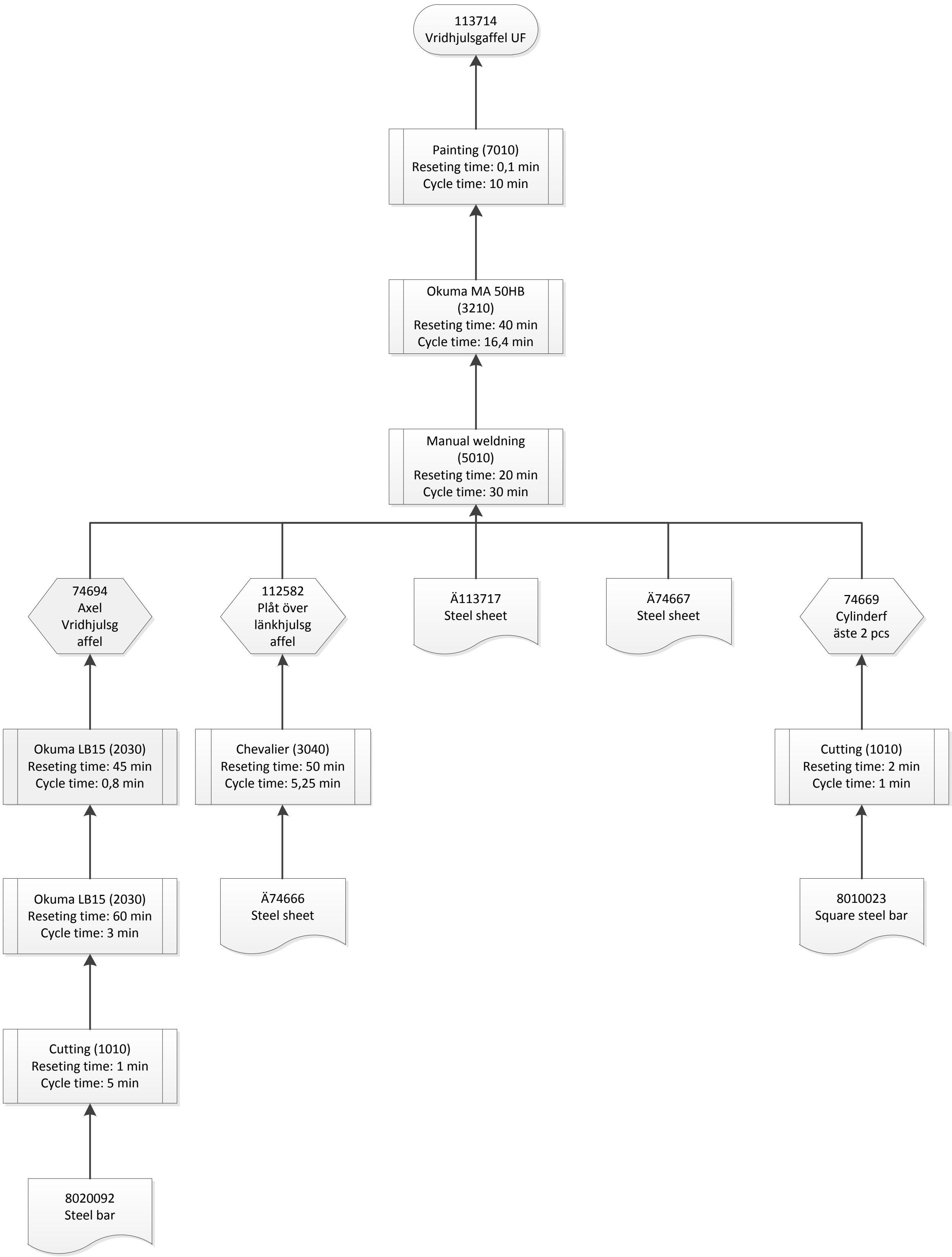



74638
Axel länkhjul
Chromium plating
Distance 58 km
5 days
Manual machining
(4010)
Reseting time: 5 min
Cycle time: 2 min
Okuma MC 400H (3120)
Reseting time: 10 min
Cycle time: 0,4 min
8040008
Steel bar
11286
Lagerhus
svängbroms
Chromium plating
Distance 58 km
5 days
Manual welding (5010)
Reseting time: 10 min
Cycle time: 5 min
112588
Kedjespä
nnare
112587
Fäste
74643
Lagerhus
R125
Chevalier (3040)
Reseting time: 30 min
Cycle time: 1,5 min
Chevalier (3040)
Reseting time: 10 min
Cycle time: 4,5 min
Okuma MC 400H (3120)
Reseting time: 15 min
Cycle time: 3 min
Cutting (1010)
Reseting time: 1 min
Cycle time: 1 min
Ä112587
Steel sheet
Okuma LVT 400-M
(2320)
Reseting time: 30 min
Cycle time: 3 min
8010059
Square steel bar
Okuma LVT 400-M
(2320)
Reseting time: 55 min
Cycle time: 8 min
Ä74643
Steel tube


112580
Länkhjulsgaffel UFS
Painting (7010)
Reseting time: 0 min
Cycle time: 12,5 min
Okuma MA 50HB
(3210)
Reseting time: 10 min
Cycle time: 8,2 min
Manual weldning
(5010)
Reseting time: 20 min
Cycle time: 25 min
112581
Axel
länkhjulsg
affel
112582
Plåt över
länkhjulsg
affel
112585
Chain wheel
Ä112584
Steel sheet
3 pcs
Okuma LB15 (2030)
Reseting time: 25 min
Cycle time: 0,7 min
Okuma MA 50HB
(3210)
Reseting time: 30 min
Cycle time: 1,2 min
Okuma LB 15 (2030)
Reseting time: 70 min
Cycle time: 3,9 min
Ä112582
Steel sheet
Cutting (1010)
Reseting time: 1 min
Cycle time: 8 min
80020101
Steel bar

Product B – Production flows per component:


113716
Mutterbricka
Chromium plating
Distance 58 km
5 days
Okuma MC 400H (3120)
Reseting time: 40 min
Cycle time: 2 min
Okuma LVT 400-M
(2320)
Reseting time: 0 min
Cycle time: 4 min
Okuma LVT 400-M
(2320)
Reseting time: 32 min
Cycle time: 1 min
Okuma LVT 300-M
(2310)
Reseting time: 30 min
Cycle time: 10 min
Cutting (1010)
Reseting time: 1 min
Cycle time: 7 min
8020077
Steel bar
110698
Skydd bromsrör
Chromium plating
Distance 58 km
5 days
Ä110698
Steel sheet
74671
Axel vridhjul
Chromium plating
Distance 58 km
5 days
Manual machining
(4010)
Reseting time: 5 min
Cycle time: 2 min
Okuma MC 400H (3120)
Reseting time: 5 min
Cycle time: 1 min
8040008
Steel bar


113714
Vridhjulsgaffel UF
Painting (7010)
Reseting time: 0,1 min
Cycle time: 10 min
Okuma MA 50HB
(3210)
Reseting time: 40 min
Cycle time: 16,4 min
Manual weldning
(5010)
Reseting time: 20 min
Cycle time: 30 min
74694
Axel
Vridhjulsg
affel
112582
Plåt över
länkhjulsg
affel
Ä113717
Steel sheet
Ä74667
Steel sheet
74669
Cylinderf
äste 2 pcs
Okuma LB15 (2030)
Reseting time: 45 min
Cycle time: 0,8 min
Chevalier (3040)
Reseting time: 50 min
Cycle time: 5,25 min
Cutting (1010)
Reseting time: 2 min
Cycle time: 1 min
Okuma LB15 (2030)
Reseting time: 60 min
Cycle time: 3 min
Ä74666
Steel sheet
8010023
Square steel bar
Cutting (1010)
Reseting time: 1 min
Cycle time: 5 min
8020092
Steel bar

Appendix B

Product A - Bought components:

Article number	No comp./unit	Weight per comp.	Total weight per comp. and unit	Distance to supplier	Batch size
8140047	1	0,002 kg	0,002 kg	65 km	200 pcs
8140038	1	0,009 kg	0,009 kg	65 km	200 pcs
8140003	1	0,045 kg	0,045 kg	65 km	200 pcs
8140039	2	0,014 kg	0,028 kg	65 km	200 pcs
8140040	2	0,004 kg	0,008 kg	65 km	200 pcs
8130025	1	0,460 kg	0,460 kg	50 km	6 pcs
8130041	1	0,150 kg	0,150 kg	50 km	30 pcs
8090008	3	0,002 kg	0,006 kg	50 km	200 pcs
8140063	1	0,210 kg	0,210 kg	50 km	40 pcs
8140023	1	0,015 kg	0,015 kg	50 km	100 pcs
8130018	2	0,015 kg	0,030 kg	50 km	24 pcs
8130044	2	1,050 kg	2,100 kg	50 km	24 pcs
66103	1	0,015 kg	0,015 kg	58 km	200 pcs
114453	1	2,400 kg	2,400 kg	133 km	6 pcs
8120007	1	0,550 kg	0,550 kg	148 km	30 pcs
8130014	4	0,200 kg	0,800 kg	152 km	96 pcs
8140050	4	0,001 kg	0,004 kg	7 km	500 pcs
8150002	1	0,020 kg	0,020 kg	7 km	100 pcs
8140079	2	0,026 kg	0,052 kg	7 km	500 pcs
8140086	2	0,024 kg	0,048 kg	7 km	500 pcs
8140058	2	0,010 kg	0,020 kg	7 km	500 pcs
74639	2	11,750 kg	23,500 kg	187 km	12 pcs

Product B - Bought components:

Article number	No comp./unit	Weight per comp.	Total weight per comp. and unit	Distance to supplier	Batch size
8140090	4	0,009 kg	0,036 kg	65 km	1000 pcs
8140091	6	0,019 kg	0,114 kg	65 km	1000 pcs
8140075	6	0,001 kg	0,006 kg	65 km	200 pcs
8140092	6	0,015 kg	0,090 kg	65 km	200 pcs
8140065	2	0,001 kg	0,002 kg	65 km	200 pcs
8140066	2	0,002 kg	0,004 kg	65 km	200 pcs
8140089	3	0,003 kg	0,009 kg	65 km	500 pcs
5420	1	0,021 kg	0,021 kg	343 km	36 pcs
5540	2	0,015 kg	0,030 kg	343 km	60 pcs
8130044	2	1,050 kg	2,100 kg	50 km	24 pcs
8130018	2	0,015 kg	0,030 kg	50 km	24 pcs
8140023	1	0,015 kg	0,015 kg	50 km	100 pcs
8140063	1	0,210 kg	0,210 kg	50 km	40 pcs
8130040	4	0,500 kg	2,000 kg	50 km	100 pcs
8090029	2	0,007 kg	0,014 kg	50 km	100 pcs
14059	1	0,010 kg	0,010 kg	58 km	1000 pcs
66103	1	0,015 kg	0,015 kg	58 km	200 pcs
8140044	4	0,002 kg	0,008 kg	7 km	500 pcs
8140048	1	0,001 kg	0,001 kg	7 km	500 pcs
8140053	1	0,001 kg	0,001 kg	7 km	500 pcs
8140054	1	0,005 kg	0,005 kg	7 km	500 pcs
8140049	1	0,001 kg	0,001 kg	7 km	500 pcs
12371	1	0,001 kg	0,001 kg	7 km	500 pcs
8140058	2	0,010 kg	0,020 kg	7 km	500 pcs
8140050	2	0,002 kg	0,004 kg	7 km	500 pcs
8140059	1	0,015 kg	0,015 kg	7 km	500 pcs
8140050	1	0,001 kg	0,001 kg	7 km	500 pcs
12375	1	0,001 kg	0,001 kg	7 km	500 pcs
1631	2	2,730 kg	5,460 kg	244 km	12 pcs
113536	2	0,035 kg	0,070 kg	244 km	60 pcs
113537	2	0,021 kg	0,042 kg	244 km	60 pcs
110018	1	0,037 kg	0,037 kg	244 km	30 pcs
110019	1	0,030 kg	0,030 kg	244 km	30 pcs
110020	1	0,047 kg	0,047 kg	244 km	30 pcs
66106	1	0,090 kg	0,090 kg	244 km	24 pcs
66558	2	12,360 kg	24,720 kg	187 km	12 pcs
112130	1	0,050 kg	0,050 kg	329 km	42 pcs

Product A - produced components per unit:

Article number	No comp./unit	Weight per comp.	Total weight per comp. and unit	Distance to supplier	Batch size	Price [SEK]	Lenght [m]	Widht [m]	Height [m]	Diameter [m]
112591	**1**	**0,150 kg**	**0,150 kg**							
8010009	*1*	*1,400 kg*	*1,400 kg*	*68 km*	*6 m*	*16*	*0,080*	*0,040*	*0,060*	
112592	**1**	**0,335 kg**	**0,335 kg**							
8040010	*1*	*0,308 kg*	*0,308 kg*	*287 km*	*6 m*	*5*	*0,125*			*0,020*
8120010	*1*	*0,080 kg*	*0,080 kg*	*148 km*	*60 pcs*	*35*				
112590	**1**	**3,000 kg**	**3,000 kg**							
Ä112590	*1*	*3,210 kg*	*3,210 kg*	*101 km*	*30 pcs*	*43*				
74638	**1**	**1,290 kg**	**1,290 kg**							
8040008	*1*	*1,332 kg*	*1,332 kg*	*287 km*	*6 m*	*23*	*0,240*			*0,030*
112580	**1**	**18,000 kg**	**18,000 kg**							
8120009	*1*	*1,640 kg*	*1,640 kg*	*148 km*	*24 pcs*	*241*				
Ä112584	*3*	*2,430 kg*	*7,290 kg*	*34 km*	*54 pcs*	*129*				
8020101	*1*	*6,116 kg*	*6,116 kg*	*68 km*	*6 m*	*55*	*0,110*			*0,095*
Ä112582	*1*	*6,000 kg*	*6,000 kg*	*68 km*	*24 pcs*	*85*				
112586	**1**	**8,345 kg**	**8,345 kg**							
8010059	*1*	*0,083 kg*	*0,083 kg*	*287 km*	*6 m*	*1*	*0,035*	*0,012*	*0,025*	
Ä112587	*1*	*1,300 kg*	*1,300 kg*	*34 km*	*30 pcs*	*53*				
Ä74643	*1*	*12,870 kg*	*12,870 kg*	*177 km*	*48 pcs*	*277*				

Total product weight	**61,59 kg**
Weight raw material	**41,63 kg**
Scrap raw material	**10,51 kg**
Scrap rate raw material	**25%**
Price raw material	**963 kr**
Earned scrap money	**11,56 kr**

Product B - produced components per unit:

Article number	No comp./unit	Weight per comp.	Total weight per comp. and unit	Distance to supplier	Batch size	Price [SEK]	Lenght [m]	Widht [m]	Height [m]	Diameter [m]
74643	**1**	**6,920 kg**	**6,920 kg**							
Ä74643	*1*	*12,870 kg*	*12,870 kg*	*177 km*	*48 pcs*	*277*				
113714	**1**	**20,000 kg**	**20,000 kg**							
8020092	*1*	*5,330 kg*	*5,330 kg*	*177 km*	*6 m*	*55*	*0,135*			*0,080*
Ä74666	*1*	*7,595 kg*	*7,595 kg*	*68 km*	*30 pcs*	*271*				
Ä113717	*1*	*4,080 kg*	*4,080 kg*	*68 km*	*30 pcs*	*257*				
Ä74667	*1*	*4,035 kg*	*4,035 kg*	*68 km*	*30 pcs*	*221*				
8010023	*2*	*0,236 kg*	*0,472 kg*	*287 km*	*6 m*	*10*	*0,050*	*0,015*	*0,040*	
74671	**1**	**1,500 kg**	**1,500 kg**							
8040008	*1*	*1,554 kg*	*1,554 kg*	*287 km*	*6 m*	*27*	*0,280*			*0,030*
74672	**1**	**1,555 kg**	**1,555 kg**							
8040013	*1*	*2,995 kg*	*2,995 kg*	*287 km*	*12 m*	*48*	*0,240*			*0,450*
74674	**1**	**0,735 kg**	**0,735 kg**							
8020078	*1*	*2,224 kg*	*2,224 kg*	*68 km*	*6 m*	*14*	*0,040*			*0,095*
113715	**2**	**0,515 kg**	**1,030 kg**							
8020077	*2*	*1,234 kg*	*2,468 kg*	*68 km*	*6 m*	*14*	*0,020*			*0,100*
113716	**2**	**0,205 kg**	**0,410 kg**							
8020077	*2*	*0,926 kg*	*1,852 kg*	*68 km*	*6 m*	*10*	*0,015*			*0,100*
110698	**1**	**0,365 kg**	**0,365 kg**							
Ä110698	*1*	*0,365 kg*	*0,365 kg*	*66 km*	*60 pcs*	*28*				

Total product weight	**61,59 kg**
Weight raw material	**41,63 kg**
Scrap raw material	**10,51 kg**
Scrap rate raw material	**25%**
Price raw material	**963 kr**
Earned scrap money	**11,56 kr**

Appendix C

Average electrical power consumption for analyzed machines:

Machine	Idle	Busy
Okuma MA50	2,58 kW	4,30 kW
Okuma MC400H	2,63 kW	3,77 kW
Okuma LVT400	1,76 kW	7,36 kW
Okuma LB15	1,85 kW	3,76 kW
Okuma LVT300	1,97 kW	3,09 kW
Yang Eagle 1000	0,67 kW	1,78 kW
Haas	0,85 kW	2,87 kW
Chevalier	0,50 kW	1,46 kW

Appendix D

SLCA result for one piece of "Product A" with 100% hydro electricity:

LCI input/output	Before Production [kg]	During Production [kg]	Transportation [kg]	Total [kg]
CO2	49,12918076	0,277918185	0,000132994	49,40723194
SOx	0,048836223	0,000305046	1,3528E-08	0,049141282
NOx	0,203019086	0,001516922	4,96565E-07	0,204536505
CO	1,128876803	0,0017495	1,77437E-07	1,13062648
CH4	0,000504426	3,63949E-05	1,30209E-09	0,000540823
GWP	**49,14179143**	**0,278828058**	**0,000133027**	**49,42075251**
AP	**10,60927595**	**0,076230847**	**2,05695E-05**	**10,68552736**

Before production results:

LCI input/output	Raw material Accusition [kg]	Bought Components [kg]	Total [kg]
CO2	29,33177716	19,7974036	49,12918076
SOx	2,89E-02	0,019897289	0,048836223
NOx	1,21E-01	0,082318044	0,203019086
CO	0,675079839	0,453796964	1,128876803
CH4	2,99E-04	0,000205903	0,000504426
GWP	**29,33924025**	**19,80255118**	**49,14179143**
AP	**6,302678148**	**4,3065978**	**10,60927595**

During production results:

LCI input/output	Internal Manufacturing processes [kg]	External Manufacturing Processes [kg]	Total [kg]
CO2	0,256898371	0,021019814	0,277918185
SOx	0,000246923	5,81228E-05	0,000305046
NOx	0,001145375	0,000371547	0,001516922
CO	0,001631106	0,000118394	0,0017495
CH4	5,35515E-06	3,10398E-05	3,63949E-05
GWP	**0,25703225**	**0,021795808**	**0,278828058**
AP	**0,058402041**	**0,017828806**	**0,076230847**

Internal Manufacturing processes results:

LCI input/output	Auxiliary consumption (coolant, argon, paint etc.) [kg]	Electricity consumption [kg]	Total [kg]
CO2	0,027893133	0,229005238	0,256898371
SOx	0,000125977	0,000120946	0,000246923
NOx	0,000197923	0,000947452	0,001145375
CO	0,000313778	0,001317328	0,001631106
CH4	1,31329E-06	4,04186E-06	5,35515E-06
GWP	**0,027925965**	**0,229106285**	**0,25703225**
AP	**0,014323205**	**0,044078836**	**0,058402041**

External manufacturing process results:

LCI input/output	**Zinc Coating [kg]**
CO2	0,021019814
SOx	5,81228E-05
NOx	0,000371547
CO	0,000118394
CH4	3,10398E-05
GWP	**0,021795808**
AP	**0,017828806**

Transportation results:

LCI input/output	**Raw material transportation [kg]**	**Bought Component transportation [kg]**	**External Production transports [kg]**	**Distribution transports [kg]**	**Total [kg]**
CO2	2,4984E-05	2,72818E-05	7,9755E-06	7,2753E-05	0,000132994
SOx	2,54E-09	2,78E-09	8,11259E-10	7,40035E-09	1,3528E-08
NOx	9,33E-08	1,02E-07	2,97783E-08	2,7164E-07	4,96565E-07
CO	3,33E-08	3,63985E-08	1,06406E-08	9,70646E-08	1,77437E-07
CH4	2,45E-10	2,67106E-10	7,8085E-11	7,12296E-10	1,30209E-09
GWP	**2,49901E-05**	**2,72885E-05**	**7,97745E-06**	**7,27708E-05**	**0,000133027**
AP	**3,86414E-06**	**4,21954E-06**	**1,23353E-06**	**1,12523E-05**	**2,05695E-05**