THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Environmental Impact Assessment using Production Flow Simulation

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ABSTRACT

A higher-level perspective for production engineers and enables detailed assessment of dynamic manufacturing systems environmental impact at a system level. By using simulation, the simulation engineer enables to understand how minor adjustments affect the system. This thesis shows how to use simulation of manufacturing systems with an environmental sustainability focus. Thus, analyse the system from both an economical and environmental perspective at simultaneous.

Static assessments have been the main approach analysing systems environmental impact. Dynamic manufacturing systems cannot be modelled statically properly. Static assessment lacks the ability to predict how the system operates and react after adjustments of the system. However, dynamic simulations of systems are data intensive and require more resources and knowledge. This thesis elaborates on when to use simulation of manufacturing systems to assess environmental impact. In short, simulation of manufacturing system can be efficient when there is a need for both productivity assessment and environmental assessment.

This thesis used action research in two industrial cases to advance a methodology using simulation for environmental assessment of manufacturing systems. The initial methodology is developed from a literature review of previous studies and interviews with practitioners.

Current commercial software lacks out of the box support for the functionalities supporting the assessment proposed in this thesis. However, most existing software tools are possible to use due to the high adaptation potentials. This thesis proposes a set of new functionalities needed to support the proposed methodology in this thesis. A developed demonstration software presented in the thesis implements the functionalities. The result is a very simple demonstration tool to be used by production engineers with low experience of simulation.

Keywords: Environmental impact assessment, Life cycle assessment, Discrete Event Simulation

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> *"It is proven, three different theories says that plane crashes when above the North Pole" – Scientists at fika break*

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PUBLICATIONS

Publication I	Thiede, S., Seow, Y., Andersson, J., & Johansson, B. (2013). Environmental aspects in manufacturing system modelling and simulation—State of the art and research perspectives. CIRP Journal of Manufacturing Science and Technology, 6(1), 78-87.
	Andersson was responsible and performed the data collection together with the authors, He wrote the data collection chapter in the article.
Publication II	Andersson, J., Skoogh, A., & Johansson, B. (2012). Evaluation of methods used for life-cycle assessments in Discrete Event Simulation. Proceedings of the 2012 Winter Simulation Conference.
	Andersson initiated the paper, performed the study and wrote the paper with assistance from Skoogh and Johansson.
Publication III	Andersson, J., Skoogh, A., Berglund, J., & Johansson, B. (2012). Environmental Impact Assessment for Manufacturing: Data Requirements for a Simulation-Based Approach. Swedish Production Symposium.
	Andersson performed the study together with Berglund. Andersson wrote the paper with Skoogh and Berglund
Publication IV	Andersson, J. (2013). Life cycle assessment in production flow simulation for production engineers. 22nd International Conference on Production Research.
	Andersson initiated the paper, performed the study, and wrote the paper.

ADDITIONAL PUBLICATIONS

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Jain, S., Lindskog, E., Andersson, J., & Johansson, B. (2013). A hierarchical approach for evaluating energy trade-offs in supply chains. International Journal of Production Economics, 146(2), 411-422
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1 INTRODUCTION

The Kyoto protocol (Council Decision, 2002) legally forced a major part of the industrialised countries to lower their greenhouse gas emissions by 8 % until 2012. The protocol has been prolonged until 2020. Today, industry stands for 20 % of the world's greenhouse gases (IPCC, 2007). Energy intensive industries such as steel industry have not developed much and best practise has at most 10-30 % potential to decrease energy usage (UNIDO, 2011). However, manufacturing industry has potential to significantly reduce the environmental impact using less material and reducing scrap and waste by improving the operations (Gutowski, Dahmus, & Thiriez., 2006). Kiron, Kruschwitz, Haanæs, and Velken (2012) showed that more than 90 % of managers in manufacturing companies from a wide range of industries believe that pursuing ecological sustainability is and will be even more necessary in order to be competitive in the future.

The need for measures of sustainability and environmental impact of manufacturing processes is increasing (Haapala et al., 2011). Production engineers are indeed working with sustainability, increasing resource efficiency in the processes (Duflou et al., 2012). Production engineers perform improvement work on three levels: the single process level, the multi machine level, and the factory level. Different levels require different mitigation approaches. However, the driving force for improvements is often lower operation costs and rather than to improve overall sustainability. Economic benefits of manufacturing processes is sometimes, but not always, aligned with ecological improvement. When there exist multiple solutions that achieve the same effect, the production engineer can chose the solution with the lowest total environmental impact. However, that knowledge or facts must be available. Thus, the right tools and knowledge for production engineers increase chances to find the best improvement changes.

Many authors have investigated the link between environmental impact and financial performance. Horváthová (2010) described in a review evidence both for and against a relation between environmental performance and financial performance. It differs between sectors, companies, and markets. Salzmann, Ionescu-somers, and Steger (2005) highlight different theories saying that environmental impact could be positively influenced either by good financial performance or by the other way around. Either way, a survey by Kiron, Kruschwitz, Haanæs, and Velken (2012) states that 67% of the company managers participating in this survey think this aspect is important in order to be competitive today and that 22% think this will be important in the future.

Figure 1 shows the starting point of this research. The industry in the middle is a typical manufacturing site. The manufacturing site produces products. The manufacturing operation leads to indirect emissions, direct emissions, and costs. The company sells the produced products and makes a profit or loss. The goal for the company is to optimize its performance. Common performance indicators for companies defined by Slack and Lewis (2002) are quality, speed, cost, and dependability. Customers buy produced products directly or indirectly based on the performance indicators but also based on the company's image, affected by the environmental impact.

The main actor in is the production engineer who gets feedback from the market from his managers, sales, and marketing. Based on this response, the production engineer needs to act by modifying the manufacturing system. The engineer cooperates with product development and other departments. To analyse the current state and to investigate improvement, the engineer uses available tools to decide which actions to take.

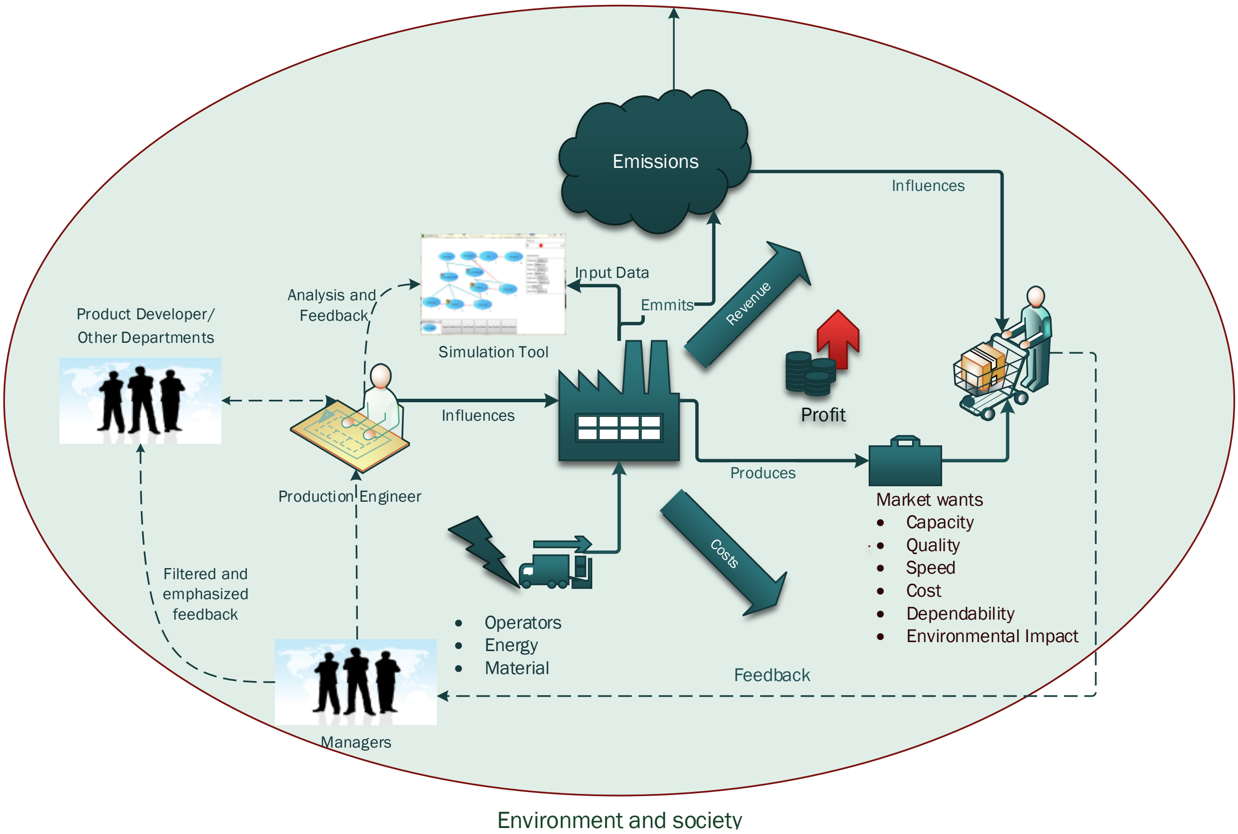

Figure 1 Schematic image of the research field

1.1 Environmental Sustainability of Manufacturing Systems

Life cycle assessment (LCA) is the main methodology to assess environmental impact. Companies use LCA mostly for process and product development as well as for information gathering for decisions (Verschoor & Reijnders, 1999). Most of product's life cycle cost and environmental impact are set during product design (Frei & Zuest, 1997). Products already designed still have potential to lower environmental impact during manufacturing. LCA is static in its nature and does therefore not suit detailed assessments of industrial systems other than the current state (Reap, Roman, Duncan, & Bras, 2008). There is a lack of commercial tools to assess manufacturing systems in detail. Methods and tools to assess and improve the environmental impact of manufacturing sites could potentially reduce impact or the total product lifecycle. However, by improving a single manufacturing site or process one must also consider the risk of sub-optimisation. Sub-optimisation can lead to a higher impact in other processes, suppliers, or product life stages. It requires a system approach that includes aspects when activities influence upstream and downstream actors (Tukker, 2000).

To make it possible to reduce the environmental impact of a manufacturing site, the first step is to understand and analyse the manufacturing system and the product life cycle. Discrete manufacturing industries in general (e.g. assembly plants and workshops, and not large continues process plants as steel, paper and oil process industries) do not emit that much emissions themselves, but use previously highly processed materials and energy. A production engineer needs help to perform detailed analyses in order to understand the complex relations between environmental impact and factory operation.

1.2 Using Simulation to Analyse Manufacturing Systems

A manufacturing system is a system that produces products and services; it contains elements such as humans, machines, and equipment. Manufacturing systems can be simple, but are often complex. Complex manufacturing systems consist of flows of information and products in manufacturing processes (Bellgran & Säfsten, 2009). These flows form a complex and dynamic system of connected and integrated processes. There is a need for simulation tools in order to fully understand and effectively improve the system. One such tool is Discrete Event Simulation (DES). DES is an extensive tool for analysing and evaluating manufacturing systems. There are many implementations of DES and a large number of applications. In the field of simulation of production flows, DES is mainly used for evaluating process improvements and justifying investment decisions. However, only few companies use DES on a regular basis (Eriksson, 2005). To enable a pervasive and wider use of simulation by companies on a daily basis, simulation tools should be made more user-friendly, more analytical and provide smarter and more extensive decision support. Extensions and improvements of the usability of simulation tools would greatly benefit simulation, and thus making it more worthwhile to use. Production simulation is established in industry. However, its full potential is rarely used. The skill to perform simulation studies is not widely spread and resources are limited (Jahangirian, Eldabi, Naseer, Stergioulas, & Young, 2010). Static Excel sheet calculations are trusted along with experience. However, an Excel analysis lacks the possibilities to a deeper analyse system dynamics that include the time aspect and cannot fully analyse future states.

It is possible to use simulation to overcome problems LCA has with modelling dynamic systems properly. Simulation has often been used to analyse manufacturing sited environmental impact. Two common approaches are to use either Banks methodology (Banks, Carson, Nelson, & Nicol, 2009) and add environmental impact, or to use LCA and using simulation of manufacturing systems in parts of the study. However, there is no generic methodology guiding a general practitioner in such cases. One main advantage of a simulation-based approach is increased accuracy in dynamic systems future states. This makes it possible to do multiple sequential virtual improvement iterations without implementing each improvement to see the results. An approach using a static Excel sheet cannot model future manufacturing systems as accurately as production simulation (Fishwick, 1997). Researchers have tested simulation of manufacturing systems to include sustainability measures including energy use, emission and resource use along with production simulation since Wohlgemuth and Page (2000). These studies and tests have shown high potential, especially by being able to mimic the system details and trustfully being able to model future states.

1.3 Gap

LCA lacks ability to in detail model dynamic manufacturing systems and future states of manufacturing systems properly (Reap, Roman, Duncan, & Bras, 2008). Due to that, researchers have used simulation for environmental impact assessment of manufacturing systems during the last decade. However, the approach still suffers many problems.

- Simulation is not commonly used and is often too complicated for non-experts and therefore hard to implement in everyday use (Jahangirian, Eldabi, Naseer, Stergioulas, & Young, 2010).
- The studies performed by previous practitioners use different methodologies, which reduces comparability and transparency.
- Tools used in previous simulation projects require own programing and tweaking.

1.4 Aim and Purpose

This research contributes to sustainable development and wants to support reduction of environmental impact from manufacturing. The purpose of this thesis is to facilitate and highlight use of environmental impact assessment in discrete manufacturing for production engineers. It aims to provide a structured approach for production engineers to conduct environmental impact analyses utilising production flow simulation.

This thesis synthesises project steps into a methodology that supports manufacturing system environmental impact assessment. It presents a tool to support the methodology and standardised analyses. The methodology will also include a vast bank of knowledge to support future analysts towards standardised analyses in order to enable comparable eco-labelling by using simulation.

1.5 Research Questions

RQ 1 In which situations, and why, should production engineers use production flow simulation to analyse environmental impact for manufacturing sites?

Several previous research studies have combined environmental assessments with simulation of manufacturing systems. Commercial tools are not yet available and the industry has not anticipated this approach. **RQ1** investigates the current industrial benefits. **RQ1** questions the use of the combined approach and clearly asks why this is the preferable approach.

The question requires to list prerequisites, benefits and drawbacks of performing such a study. The prerequisites define necessary system properties that are to be in place before starting a meaningful study. Benefits and drawbacks specify when to consider other approaches.

RQ 2 Which project steps can support simulation studies analysing detailed environmental impact of the manufacturing site and how are these steps interrelated?

Historically, methodologies of the approach vary from study to study. Developed methods focus on specifics as data collection (Solding, Petku, & Mardan, 2009). Different overall methodologies lead to incomparable results between studies. **RQ2** asks for a generic methodology for future studies.

Such project steps and their relation should contain previous experience from such studies. The guide to the stages helps the user to achieve a robust and valid model.

RQ 3 Which simulation software functionalities can help production engineers to perform a detailed environmental impact analysis of a manufacturing site?

Combining manufacturing simulation with environmental impact assessment is possible with current tools. However, even though usage of today's tool is possible, it does not mean that it is efficient or lead to valid models. To enable the use of the methodology and to enhance comparability of such studies, **RQ3** maps which important functions are needed for efficient work.

The answer to **RQ3** describes the advantages and disadvantages of the current tools and proposes functionality to support environmental impact assessment in these tools.

1.6 Delimitation

This thesis claims to make advancement towards a structured methodology and a tool functionalities. The methodology and tool functionalities provide comparable results and to support eco-labelling. However, the thesis does not claim to support all criteria for a commercial eco-labelling of companies or products. Moreover, this thesis has not validated the current version of the tool or the methodology presented. The proposed tool and methodology are a first version for further development, but a leap towards comparability and eco-labelling.

The term manufacturing includes production of various goods. Not only consumer goods, but also materials as steel, concrete, timber coal, oil. However, the operations and characteristics of energy intensive material producing industry and for example assembly operation differ largely. This thesis focuses on discrete manufacturing which includes industries such as assembly, and discrete material processing, i.e. production of consumer goods. All studies target discrete manufacturing. The thesis does not claim that the methodology and the tool are directly applicable in other industries. It is likely that other industries, such as continuous process industry, need to modify the results in order to find the tool useful.

1.7 REPORT STRUCTURE

The structure of this thesis is based on three research questions. Four publications and two case studies append the thesis to answer the questions. The cases and publications are grouped into research activities. The method chapter describes the activities and their connection to the research questions.

The three research questions structure the results chapter. Each section in the results chapter contains results that answer each research question. The following discussion chapter elaborate on the results and end with a general discussion. At the end, a conclusion chapter wraps-up the thesis by answering the research questions.

Figure 2 visualise the structure of the report. The boxes in Research Approach represent four research activities. The ellipses represent different publications and case studies in the research activities. In the result chapter, the circles represent practical outcome, a methodology for simulation projects, and a demonstration tool. The outcome together with other result, the squares, answers the research question that is further elaborated on in the discussion and conclusions.

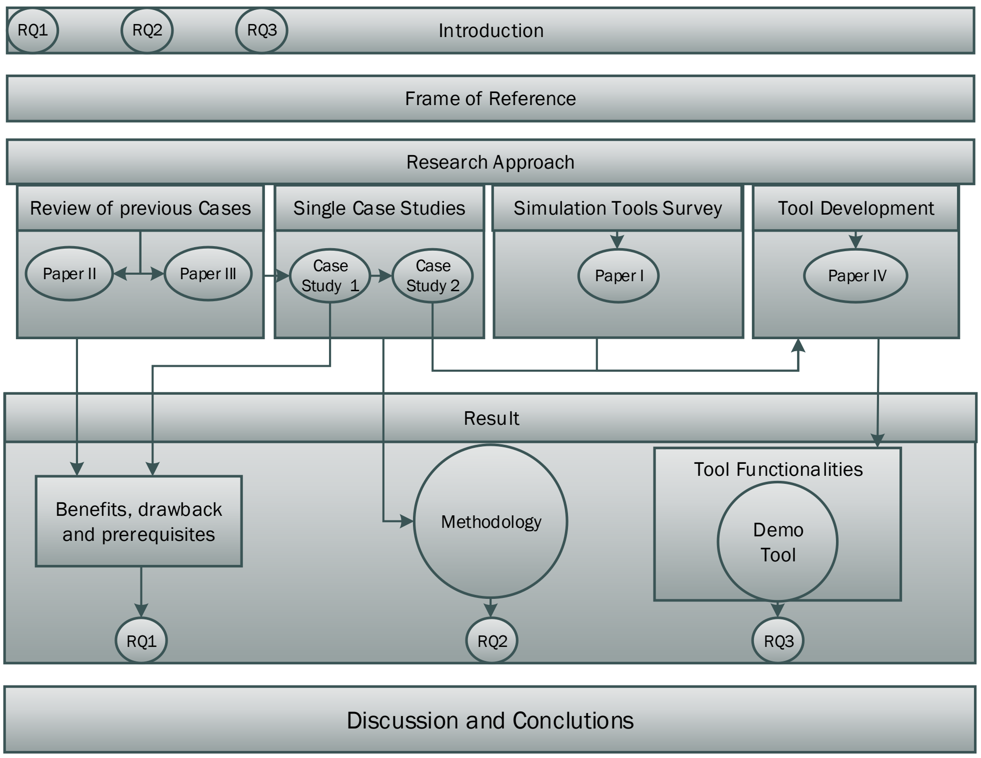

Figure 2 Report process

2 FRAME OF REFERENCES

This chapter presents theories and concepts used in this thesis. It includes definitions and explanations of concepts and expressions.

2.1 LIFE CYCLE ASSESSMENT

LCA is a central concept in this thesis. Not only the methodology and the tool functionalities built on the same concepts, but the final calculations and thinking as well. The differences are in in the detailed analysis of one production life cycle stage. LCA is the most recognised methodology used for environmental impact assessment of products. Commercial software for LCA exists and is frequently used. ISO standardised LCA in 2004, ISO 14040-44.

LCA is a mature product/service oriented methodology used to evaluate the environmental impact of a product. In short, performing an LCA is to make an inventory of all emissions and resources used during the studied products life. The analyst sums the emission and allocates them to a product or a service. The product's environmental impact is calculated by the analyst using the results of the inventory. Finally, The analyst reports the results and does something with the new knowledge (Baumann & Tillman, 2004). LCA allocates emissions from shared production sites and processes, which means to allocate all emission from a factory to all variants of products produced. The variants are often used in different ways and different products have different lifetimes. The product has often not entered all product life stages or is not even build when the LCA is conducted which means that there are many uncertainties. In worst case, the result could be, far from reality.

LCA counts all the emission from historical, current data or an assumed data (for life stages that have not yet been entered by the product or service). This makes experimentation and comparison of new manufacturing systems uncertain. Modifying parameters in LCA calculations gives direct results. However, in the real world the changes effect the system in many ways. Using a static calculation makes it impossible to take into account parameters as dynamic time and the effects this has on the system performance. For example, if the amount of deliveries is decreased with the same demand as the storage is increased. However, if one of the deliveries has a problem the receiver will get a higher impact, and eventually more actors in the system will have problems affecting the system in more than one way. To address such issues the system has to be modelled much more detailed and use other techniques (Reap, Roman, Duncan, & Bras, 2008).

LCA consists of four major phases: goal and scope definition, life cycle inventory, life cycle assessment, and interpretation (Baumann & Tillman, 2004). Figure 3 is commonly used to visualise the interaction of the different parts.

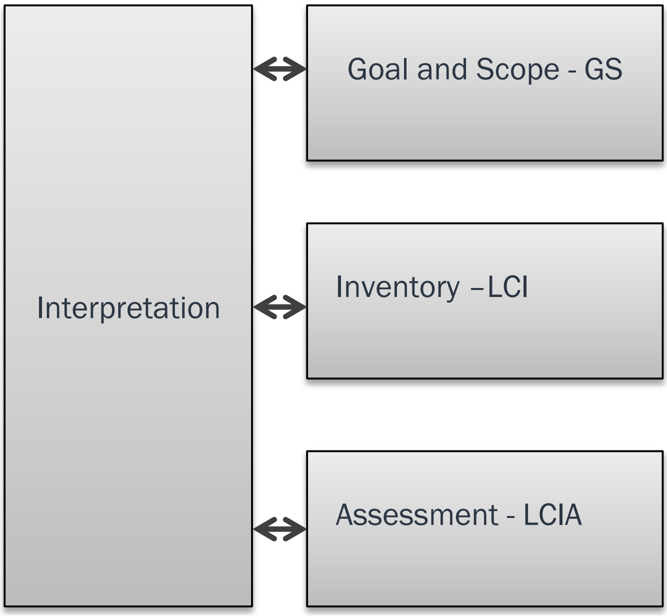

Figure 3 Life cycle assessment methodology (Baumann & Tillman, 2004)

However, even if all studies in some way or another contain the step it can differ in execution. Baumann and Tillman (2004) discuss different types of LCA studies.

- Qualitative LCA and LCI,
- Full quantitative LCA,
- Screening LCA,
- LCA-based rules of thumb
- Life Cycle Thinking

Quantitative studies are the ones most often referred to as LCA, but LCA has evolved and is now more about thinking in consequences for all life cycles and consider those in decision making (Rex & Baumann, 2004). The companies need decide which type of study to use. In this thesis, LCA will mostly be thought of as a quantitative study used to compare or to get the status of a manufacturing system allocated to a product.

Quantitative studies are divided into two main types of studies: accounting and consequential. Accounting LCA declares emissions and calculates the impact of a product or service. Consequential LCA compares products or services. To compare products or services that have different attributes and functions, a decided functional unit is used. The functional unit represents a needed value-adding function. E.g., a comparison between train and trucks should not be made in emission per 1 km transported but emission per ton goods transported 1 km. A comparison between using different material in a product must represent any performance difference for the product, e.g. expected lifetime (Baumann & Tillman, 2004).

Manufacturing systems producing a decided product can most often use a simple functional unit as the product. As long as the compared choices for the production system do not remarkably affect the produced products performance, a basic functional unit can be kept.

The inventory part of LCA retrieves emission data and needed resources for upstream processes and materials used for the functional unit. The emissions and resources are allocated and calculated to describe how much is used for one functional unit. This result in a new data sheet of all emissions and resourced emitted and used for one functional unit.

Some processes produce multiple products. In those cases, the emissions have to be divided between those products. For example, an incinerator both produces heat and electricity. The emissions are then divided per energy taken out for each output. For factory buildings where many varieties are produced, this can be very hard. ISO states that allocation should primarily be done by expanding the system to include the other products, secondly using some representative physical value, e.g. nr of products produced times their mass. If that is not possible one should use economical keys as turnover. However, according to later research (Feifel, Walk, & Wursthorn, 2010) it is claimed that allocation of physical factors often can be misleading, and economical factors often could be preferred. The analyst must judge each case seriously.

The resulting emissions can later be used to calculate the environmental impact. That is done using scientifically or subjective weighting keys. E.g., GWP is used to calculate global warming effects. GWP converts gases into CO_{2eqv} using scientific calculated keys.

2.2 Life Cycle Assessment with Discrete Event Simulation

Several previous studies tested to support environmental impact assessments with simulation of production flows. This section describes the work done in order to map current previous studies in relation to this study.

Wohlgemuth and Page (2000) were the first researchers to use a production flow simulation platform for environmental studies presented in a German language paper. This was before ISO had standardised LCA but after the main LCA development during the 1990s (Finnveden et al., 2009). Simulation approaches for environmental impact assessment and LCAs has further evolved during the last decade. Many researchers have performed studies and developed tools. Methodologies used in those studies are not reused and generalised. Here follows a list of studies and tools done by different researchers.

Wohlgemuth, Page, Mäusbacher, and Staudt-Fischbach (2004) developed a plug to a material flow management system to enable discrete event simulation. The Simulation plug modelled a production system and calculated the time needed in each process. The material flow management system used the output data and another plug-in software could calculate emissions and environmental impact.

Lind et al. (2009) developed add-on tools to an existing DES software and supporting tools for assessment. The tools (Simter) measure the impact per product on a product level. The tool claims to address all parts of sustainability: economic, environmental, and social. Social sustainability is assessed using a sub tool to assess the ergonomic impact on the operators at each station. The user assesses each station ergonomically and the product gets an impact when the machine is used. Economically the system is assessed of the capacity of the production system, and using a sub tool to assess the level of automation in the system.

Herrmann, Bergmann, Thiede, and Zein (2007) developed a framework for commercial simulation software. The framework should be used to assess energy usage in production processes. The framework uses a hierarchical approach where common services allocate depending on usage. The events in the DES model are the basis for the allocation.

Solding, Thollander, and Moore (2009) discovered and proposed four categories for energy representation of energy profiles for manufacturing processes. The simulation engineer categorise the process in one of the categories and thereafter knows how to collect data for the energy use for the process. The categories are:

1. A stochastically represented power load when processing, while idling and while off.
2. One stochastic representation for on and off.
3. A parameter that varies over time and/or with the situation.
4. A special logic, due to special or complex use of the resource, which does not fit into the first three categories.

The same article states that the first category is the most common Solding, Thollander, and Moore (2009). To emerge the data to fit a simulation model, the data should be fit to means or stochastic means for each state. Most cases the three state processing, idling, off is enough, however some processes need other states as well.

Seow and Rahimifard (2011) developed a framework to assess environmental impact of production processes. Seow and Rahimifard (2011) acknowledged the importance of indirect energy. Their framework proposes production zones from which indirect energy used is equally distributed down to the process using the zone. This adds up to the direct energy used by the process.

Reinhard, Emmenegger, Widok, and Wohlgemuth (2011) created a tool to assess environmental impact of larger systems including agriculture and food processing. They created a model based on a questionnaire aimed at people closest to the process. The questions in the questionnaire targeted materials and assets used in the processes. The tool used the material together with LCI data and calculated the actual emissions from these materials. The farmers do not know the emissions from their processes but the questionnaire asks the questions needed to calculate that.

Lee, Kang, and Noh (2013) developed a tool focused on calculating sustainability index using a structured information model and a commercial DES engine. The solution attempts to structure the information layers the tool modules needed and interactions of different assessment stages.

Zhou, Pan, Chen, and Yang (2013) proposed and tested to use an optimisation module to feed the simulation model with different parameters. A production system evaluated on economics, energy consumption, and emissions has many parameters where analyses need good optimisation techniques to be efficient.

To sum up the studies and tools, simulation tool functionalities is able to cover a large life cycle system, to allocate indirect and direct energy to processes and products, handle common services such as pressured air, handle hierarchical simulation, cover all aspects of sustainability, address input data problems, handle LCI data to calculate emission, and to have a structured calculation.

The major benefit with using simulation as a platform for LCA is that it can analyse stochastic behaviour including dynamic and changing production more accurately than static modelling. That means that you get a model that better represents the real production site. There are not too many benefits for current state analysis.

2.3 SUSTAINABILITY IN INDUSTRY

This research promotes sustainable production. It encourages companies to label product and provides them with the help to do so. This section describes why companies should enhance eco-labels and sustainable production. Environmental sustainability is important to the world. Companies that pollute or use resources in an unsustainable way do rarely affect the customers directly (Sterner, 2003). This section describes both ethical and competitive benefits with an environmental sustainable business strategy.

As stated in the introduction, company leaders believe sustainability must be on the management's agenda is important to stay competitive, but not to what extent. Costumers tend to choose environmental labelled products in favour of others in the same cost and quality segment (Manaktola & Jauhari, 2007). Rahbar and Wahid (2011) showed in a quantitative study that consumer are affected by trustfully eco-labels and branding in a positive way when they consume new products. However, all studies and discussion about green products and marketing consider the consumption of new products. As Peattie and Crane (2005) concludes, it is important to address non-purchase behaviour such as use, sharing, maintenance, disposal and take-back scenarios. Thus, labels and policies supporting environmentally friendly business models such as selling a function or service rather than a product (Rothenberg, 2007). Such a business model reduces the total needed products and support reuse, as well as the maintenance and quality, and consequently also the length of the produced products.

In the traditional view of the free market, the market itself helps companies evolve and forces them to improve competitiveness. This results in cost efficient companies producing more products at a lower cost. Lower product costs boost the market to consume more and the market evolves and grows stronger. In this traditional view, the environment and the social aspects are not included to the same extent. It results in increased consumption and production, leading to higher environmental impact. As long as no obvious environmental implications exist, the market does not consider environmental sustainability. In recent decades, there has been a stronger emphasis on sustainability in terms of environmental and social aspects. However, the drivers from the economic market are strong, and consumer requirements focus on costs than on social and environmental aspects. Policymaking for governmental and international agreement is needed to balance economic powers (Alm & Banzhaf, 2012; Sterner, 2003). Affective policies set new rules for competition, and are used by all actors in the system. However, policies attract cheaters. It is therefore important to have a strong follow-up institution that verifies that the policy rules are followed and correctly used. A large global market with limited global policies in place has low chances to regulate itself before the impacts affect the market. Market failure (Sterner, 2003) refers to how the free market system fails to support sustainable future, and fails to give the welfare that is postulated, even though many technical solutions for today and tomorrow's problem exist. Businesses should be perceptive to new policies to embrace new opportunities.

A market system is surrounded by externalities that take impact from side effects of production and consumption, e.g. landfilling that leads to emitted toxics, which pollutes the surrounding environment, or polluted water from agriculture affecting downstream societies. However, the actual affected people and societies are often not the customers of the service or product causing the impact, as illustrated in Figure 4. The major difference for environmental impact compared to economic costs is that the environmental impacts do not affect the receiver of the product. It is often hard to understand the implication of consuming a new mobile phone. In contrast, economically the receiver of the product pays a cost for a product, and is thus directly affected by the purchase, called a market failure (Sterner, 2003). The public goods, defined as services and resources used and owned in common, need a common owner who is responsible and account the ones responsible for the pollution. Such ownership must be governed by public organisations, government or institutions (Sterner, 2003). There are many positive examples of successful policy making, e.g. taxes to increase energy prices (Sandén & Azar, 2005).

Figure 4 The environmental impact affects people and environment not buying the product

Lower environmental impact in production is driven by the demand for low impact products from the market and from organisations, as well as by laws and regulations from states and communities. In order to be successful, it is important to monitor markets and provide incitements to use fewer resources and to decrease emissions. Without laws, regulation, organisations, green labels, media, etc., price rather than sustainable products will be emphasised.

Labuschagne and Brent (2005) present a model for sustainable development to foster in business. They categorised needed factors into four categories: pressure, push, pull, and support. Figure 5 explains these categories. The categories enable companies to localise and sort stakeholders for sustainability.

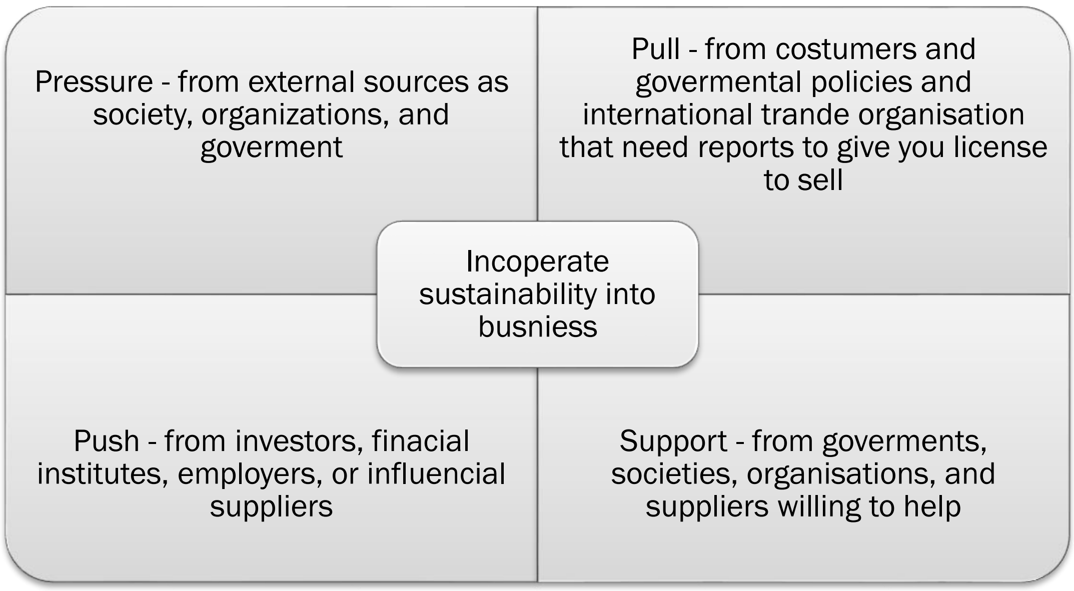

Figure 5 Labuschagne and Brent (2005) four categories to influence incorporation of sustainability in business

2.3.1 Marketing through Eco-labels

An eco-label is a label placed on a product or service declaring the environmental impact. For the customer, eco-labels partially or completely communicate the environmental impacts from defined parts of the life cycle of a product or service. Different eco-labels have been around for several decades. The eco-labels are frequently categorised into three different types. The requirements for each type of label have been defined by ISO through the ISO 14020-series (ISO, 2000), as well as by Environmental labels and declarations. The types differ in how many factors that are considered and what validation and verification that, is required, and by whom it is supposed to be performed. Below is a short summary of the types and their characteristics:

Type I (ISO, 1999b). Multi-factor labels that are issued by a either third party organisation, private non-profit or government. The label signifies good environmental performance relative to comparable products. There are plenty of examples from both Europe and the US; examples of type I labels are The Blue Angel and Nordic Swan (Charles & Anthea, 2000).

Type II (ISO, 1999a). Single factor labels are supplied by the manufacturing company itself. Examples of type II eco-labels could be the number of particles emitted by a car or the percentage of recycled material in a paper coffee mug.

Type III (ISO, 2006a). Multi-factor labels that quantify the emissions and impacts without any performance classification. Studies behind type III labels should be based on the ISO LCA standards, 14040 (ISO, 2006b) and 14044 (ISO, 2006c). An example of a type III label is the Swedish Environmental Product Declaration (EPD®) system.

Recent developments have shown that regulating bodies on an international level quick can have an impact on the operations of companies. In 2003, the European Union passed a directive to restrict the use of certain hazardous substances, called RoHS (European Parlament, 2003). The directive banned certain materials from being used in electrical products. It changed large parts of the electronics industry in a very short amount of time. What was regulated in Europe spread to an almost global level as manufacturers chose to follow the RoHS regulations on all of their markets. There are indications that there could be a similar development from the environmental product declaration. France has recently passed directive that will require Environmental Product Declaration (EPD) for all high volume consumer products (Hsiao, 2013). The system is currently under evaluation in a pilot project covering a subset of all intended products. The system in France will incorporate Type III labels, which could be an indication that future European level regulations will do the same.

2.4 Technology Readiness

The functionalities asked for in **RQ3** are implemented in a demonstration tool. In order to understand the developed tools maturity, this thesis uses Technology Readiness Level (TRL). This section describes the TRL level of the developed tool and previous projects.

TRL describes a technology's rout to market. It is defined by the United States Department of Defence (Assistant Secretary of Defense for Research and Engineering, 2011) as a metric grading of technology readiness for commercial application. The primary purpose of TRL is to provide a common view of technology readiness. TRL is used to support founding decisions and efforts needed to complete technologies. One benefit is to support risk assessment by using a specific technology. It uses a 1 to 9 metric scale where each level is defined.

One existing tool targeting the same problem is Simter (Lind et al., 2009) developed in a previous project. The readiness level of Simter on the TRL scale is 5. In order to advance the technology and reach higher levels with this project, the tool must focus on user-friendliness and be validated in an industrial project.

Critique of the TRL scale includes difficulties to assess software products. Smith (2005) proposed an alternative to the TRL scale. TRL uses two key contributor to readiness. The maturity of the functionality provided, and to what extent these functionalities have been validated. The technology is assessed using five categories:

1. How well the requirements for the product are satisfied.
2. How well the functionality has been demonstrated.
3. If the product fails, how critical this is.
4. If the product is available for the total needed time.
5. The technology's level of maturity.

Table 1 shows the maturity level of the current project. Reeliv and Simter are two earlier research projects, and EcoProIT refer to the latest project, which this thesis is based on.

Table 1 Technology Reediness Level for Reeliv, Simter and EcoProIT

Technology Reediness Level	DES LCA Implementation
TRL 1 – Basic Research	**2004** – First ideas emerged and basic research stated
TRL 2 – Applied Research	**2004** – Practical application found
TRL 3 – Proof of Concept	**2005** – Proof of concepts run at food companies, First methodology ideas tested
TRL4 – Lab Testing	**2006** – Simter is developed and tested **2012** – Methodology evaluated and revised
TRL 5 – Lab Testing of Integrated System	**2008** – Simter tested and evaluated **2012** – First prototype of EcoProIT Tool is developed, **2012** – Methodology documented and revised in a Wiki
TRL 6 – Prototype System Verified	**2013** – EcoProIT is tested and verified using an industrial case
TRL 7 – Integrated Pilot System Demonstrated	**2014 – 2015** EcoProIT tool and Methodology are applied and tested by production engineers in Swedish and US Industry
TRL 8 – System Test, Launch & Operation	**2016** – Final versions of tool and methodology launched in US and Sweden
TRL 9 – System Proven Successful in End-use Operation	**2020** – Methodology is state of art for DES – LCA studies, Production engineers all around use EcoProIT for simulation of production flows for LCA studies.

2.5 USABILITY

This thesis discusses the importance of high usability for professional tools not used every day. ISO 9126-1 (2001) defines usability in software as:

> *"The capability of the software to be understood, learned, used and liked by the user under specified conditions"*

The software itself but also auxiliary equipment as software manuals and compatibility with other systems used by the production engineer influence the usability factors. Software that is hard to learn and use can have decent usability if the handbook is good and if the software works well with the user's context. Likewise, an exceptionally easy software that is fully compatible with the context does not need a handbook.

Context includes the user's previous experiences of software and computers, the user's motivation, attitude and other systems used in the environment.

ISO 9126-1 (2001) factorises usability into understanding ability, learnability, operability, attractiveness, and usability compliance. A useable tool means that the software handles those aspects prominently.

Abran, Khelifi, Suryn, and Seffah (2003) proposed a model for usability based on ISO 13407 and ISO 9126 and a *literature review*. The proposed model attempts to harmonise the existing models into one, and includes the aspects effectiveness, efficiency, satisfaction, learnability, security.

3 RESEARCH APPROACH

This thesis in short ask to for when and how to use simulation for environmental impact assessment of manufacturing systems in a structured way. To utilise all previous research and knowledge, the thesis chooses an exploratory approach that searches for answers in previous work, but then test the ideas in own case studies. It starts with a *literature study* and a *survey*, and continues with *action research* in *Case Studies* to answer the questions. The research starts with a history phase containing two research activities, the Simulation Tools Survey, and a Review of previous cases, see Figure 6 and Table 2. The history phase maps current state of art in simulation-based approaches for environmental impact assessment. The research activities combine *literature reviews* with *interviews* and a *web survey*. The knowledge gained in the first phases applies as the base for the next action research phase for the methodology and the tool. The action research phase applies the knowledge, ideas, and initial methodologies in single case studies. The outcome from the single case studies is a further developed methodology and tool functionalities, which support the methodology. As a final activity, the researcher describes the functionalities and implements them into a demonstration tool. A wiki portal maintains the documentation and description of the tool and methodology.

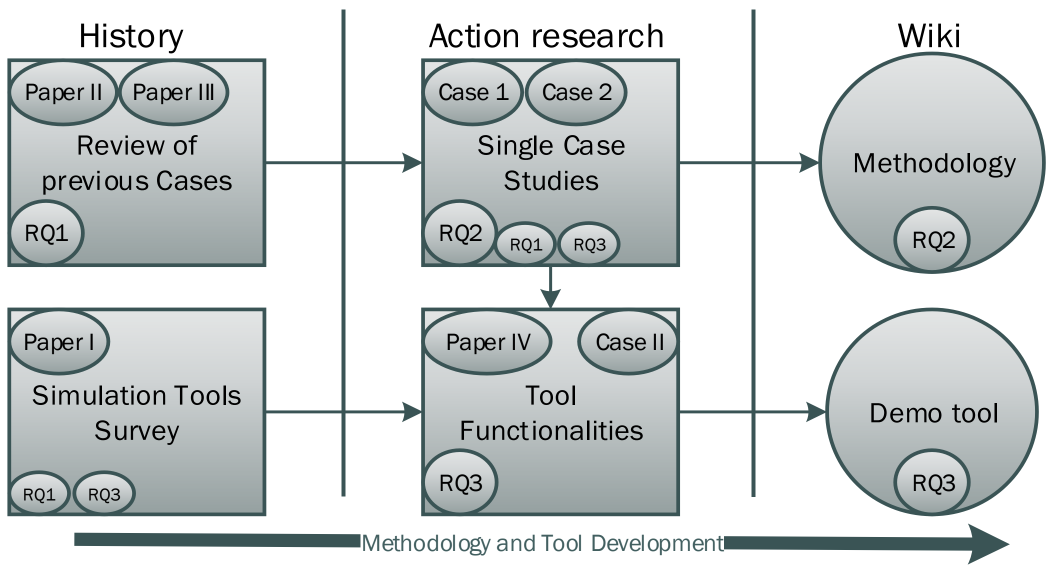

Figure 6 Overview of research design, big squares are research studies, big circles are practical outcome

The research approach for **RQ2** is action research. During the action research phase, the researcher is largely involved in the studied object and the researcher's experience influences the results. Thus, the researcher and the industrial cases bias the thesis result. The cases in this research use new practitioners for each case to decrease the risk that the results are too biased. Researchers use action research for exploratory research to test practical solutions and theories. The results that researchers use are less generalizable but give accurate results and experienced organisations. Action research is defined by Reason and Bradbury (2001) as:

> *"Action research is a participatory, democratic process concerned with developing practical knowing in the pursuit of worthwhile human purposes, grounded in a participatory worldview which we believe is emerging at this historical moment. It seeks to bring together action and reflection, theory and practice, in participation with others, in the pursuit of practical solutions to issues of pressing concern to people, and more generally the flourishing of individual persons and their communities." (Reason & Bradbury, 2001)*

The definition explains it as a process where all participants are highly involved in the research and that action research combines reflection in theory and in practice. Furthermore, Coughlan and Coghlan (2002) mean that action research is appropriate when the problem studied is a process and how to change this process, as well as and when the practitioner is also the researcher.

The methodology is acquired *inductively* from the experiences in the *Case Studies*. Induction is the approach when researchers generate a theory based on current data (Bryman & Bell, 2011). The team tests the methodology, improves it, and modifies it based on results, and experiences. The approach applies by giving the production engineer a methodology generated from previous studies and previous experience. The research team and production engineer evaluate and revise the methodology during the study. After the study, a new methodology is completed and published. This means that the methodology is biased by the specific study. However, as the project executes studies with different companies, the methodology improves and becomes transferable. This is an action approach where the methodology is developed throughout the project. Similarly, to the focus group approach, this approach makes it possible to see aspects that are not covered in the research. However, compared to the focus approach, an action research approach with case studies results in a usable methodology that has been tested in at least one case. Other alternatives, which could be used to do the same research, are:

- A focus group approach with experts in a workshop who design an initial solution together. This gives a rapid solution that concerns most aspects that the participants came across.
- A survey approach with interviews and discussions. This gives possibilities to reach a larger population. However, the target group for such a study would be scattered.

The research uses draft methodology versions to test the ideas in real cases. For **RQ3** the approach is based on testing software ideas by developing a demo tool and using it in real cases. The approach results in methodologies and tools, which work site specific and need further tests. However, the approach is fast and agile in response to problems and opportunities.

The results, which answer the research questions, come from four publications and three cases. The methods used in the publications and cases are summarised in Table 1. The four research activities are further explained in the following sections.

Table 2 Publication Actions

	RQ			*Research Activities*				*Data Collection*						*Data Analysis*				
	RQ1	**RQ2**	**RQ3**	Simulation Tools Survey	Review of previous Cases	Single Case Studies	Tool Functionalities	Literature Review	Archive Analysis	Questionnaires	Interviews	Wiki	Field Notes	Implementation - Result	Statistical analysis	Case Reviews	Triangular Notes	Tool Review
Publication I	X		X	X				X		X					X			
Publication II	X	X			X				X		X					X		
Publication III	X	X			X				X		X					X		
Publication IV			X				X							X				X
Case Study 1	X	X				X					X		X				X	
Case Study 2		X	X			X					X	X	X				X	

3.1 Simulation Tools Survey

The first activity, **Publication I**, was conducted in order to create a basic understanding of currently available simulation tools. The activity examined simulation software and their functionalities to model a production system to assess its environmental impact. There are many available commercial simulation tools and they work in similar ways. However, no simulation software so far supports environmental impact assessments. There are two approaches for this: either to learn and test how the tool works yourself, or to ask someone who knows about each simulation software. This study chooses the later approach in order to be able to reduce lead-time and used resources.

The first part of **Publication I** inventories three academic projects and describes their simulation approaches. The approaches set prerequisites of functionalities needed to use the simulation software. The functionalities set the base for a questionnaire sent to the companies.

3.1.1 Data Collection

An inventory based on experiences from four different simulation researchers, states the commercial simulation tools in the interest of this study. Relevant tools target manufacturing industry and have a serious commercial business. A *literature review* describes the current conditions in research and compares them to the current state of commercial tools.

The questionnaire in this survey uses a conceptual model of a production manufacturing line, including machines, support systems, and energy usage. All respondents receive the same conceptual model. Respondents answer questions regarding how this can be modelled using their simulation software. The questionnaire queries the differences in modelling approaches and features in the simulation software. It includes mainly closed questions that were possible to elaborate on in open text fields. Closed questions are easier and faster to analyse than open-ended questions, but lose in accuracy. However, by adding a commentary field after each question, the respondent can precise the answer Blair, Czaja, and Blair (2013).

A questionnaire is a set of questions asked to a sample of people. The answers are retrieved and summarised using quantitative and qualitative analysis approaches. Questionnaires are often used in surveys to collect answers from a larger sample. Designing questionnaires is an artwork that requires practice. Many books and articles describe the process. This research use Blair, Czaja, and Blair (2013) as main handbook.

3.1.2 Implementation

The questionnaire was distributed as a web questionnaire to all known and relevant simulation software companies targeting manufacturing industry. Web questionnaires do not limit the population though it is a lower cost per answer, therefore all commercial simulation software were included. The web survey enabled fast collection and analysis.

Kiernan, Kiernan, Oyler, and Gilles (2005) showed that web surveys are at least as effective as traditional mail services. The article measures response rate, question completion and evaluation bias. The paper evaluated the *web survey* slightly higher than *mail survey*. Greenlaw and Brown-Welty (2009) also made the same comparison concerning the evaluated cost of the study. They conclude that a mixed mode survey including both a web and a mail survey gives the best response rate, but that the cost for mail respondents is significantly higher. The cost for transcription of mail surveys is also significant. **Publication I** concluded that a *web survey* was enough, although direct contact with simulation software companies was established in most cases. Using a traditional mail questionnaire was not considered.

A meta-analysis by Shih and Xitao Fan (2008) of 39 studies showed, however, that a web survey gives significantly lower response rates, but there was a great variance between different studies. The results indicate that it is important to perform the survey carefully. Population selection and reminders proved to be significant factors to raise respondent rate. The study in **Publication I** contained at least two reminders which raised the response rate.

3.1.3 Data Analysis

The respondent’s answers are first analysed question by question. A table and a graph visualisation summarise the answers. Though the answers were all painting at the same answer, the population sample covered all known commercial simulation software, and as 9 out of 15 answered, no further data analysis was needed. Instead, the study presented in **Publication I** concentrates on the potential of functionalities in new versions of simulation software.

3.2 Review of Previous Cases

To fully answer **RQ1** this thesis reviewed previous cases presented in two publications (**Publication II** and **Publication III**). The review is also the base input to the action research to answer **RQ2**. The analysis generates theories and concepts from the collected data. **RQ1** needs a thorough archive case study analysis in order to study cases using a similar method and purpose as the one presented in this thesis, i.e. using discrete event simulation as the base for environmental impact assessment. The purpose of this research activity is to extract the knowledge gained from those cases. The population used in the review are studies at manufacturing companies closely linked to the research teams that were easy to contact.

3.2.1 Data Collection

Previous case reviews use historical archive analysis as a base of knowledge. Archive analysis is a method where data from previous documented studies are used for further studies.

Archive analyses in general are unbiased to the extent that the analyst does not guide the practitioners preforming the case (Flynn, Sakakibara, Schroeder, & Flynn, 1990). In this study, semi-structured *interviews* complement the archive study. The *interviews* help to find unreported experiences as the main problems executing the study. The experiences noted in *Field notes* but not in the report, are impossible to retrieve and depend on the interview. The semi-structured *interviews* implemented through text messages where open-ended to enable the practitioners to describe rather than to filter their experiences.

3.2.2 Data Analysis

The researcher reviews the reports, and pays special attention to a set of studied research questions. **Publication II** reviews methods used, emission calculation, verification, validation, waste streams, used impact categories, as well as quality and waste management. **Publication III** focuses on data management, output management, and representation. Besides listing facts, the study summarises experiences from the practitioners. After the review of the reports, interview data with most of the practitioners filled in the existing gaps.

3.3 Single Case Studies

The review of case results and ideas gathered from surveys and previous studies forms the initial methodology. Single case studies iteratively test and revise the methodology to answer **RQ2**. This part is the backbone of this thesis and use Action Research as research design.

The single cases followed a sequential and iterative plan. The case was firstly carefully planned both in terms of which methodology that was to be used, but also by discussing important focus area. Focus areas are used not to lose focus in a long-term project. The research areas are then evaluated and the experienced gained is transferred to the next case with other focus areas. Appended **Case Study 1** focuses on prerequisites to perform such a study. Appended **Case Study 2** focuses on the start-up and verifies the conclusions from **Case Study 1**. Both case studies cover all parts of the methodology, but to various extents.

3.3.1 Execution and Methodology development

The practitioners using the methodology are simulation experts. The practitioners perform the study, but the researchers are also involved. The researcher mainly guides and discusses problems with the simulation practitioners, but also performs some practical work.

After each step of the project, the practitioners and researchers discuss the gained experiences and summarise them in a report. The team performs subjective valuation of the experiences, but summarise all of them. The team updates the methodology with possible solution or improvements. The new methodology is then tested in the next case iteration. Changes that compete with other parts of the methodology or are specific for the case are not implemented in the next iteration.

The final methodology combines all gathered experiences collected and documented in the *single case studies*, *literature*, and discussions. The methodology used in each specific case can have limited adjustments to their projects, due to time limits or specific companies. The practitioners of the single studies have had a major influence on the specific methodology used in their study. The final design, however, is a solution combining all studies.

3.4 Tool Development

This thesis develops a demonstrator tool to preview the functionalities and ideas for **RQ3** emerging within the project. From early results and experiences, the researcher develops a tool to test modelling concepts and support for the analyst. A user test assessed the potential of the tool to help production engineers.

3.4.1 Wiki

During the tool development, the concepts and the tool were documented in a Wiki. A Wiki is web based information media optimised for easy updates. Wikis are used as information banks where users are able to update the content without much effort. It includes full backups and history and enables revisions of changes (Wheeler, Yeomans, & Wheeler, 2008). This makes it possible to build up a common information platform in order to gather with practitioners to collect and share their experiences. The wiki becomes a handbook for the methodology and a manual for the tool.

A wiki is a website with version control that can be edited, changed, or deleted by registered webpage users or anyone with access to the page. Information on the website is interconnected and combined in a flexible but simplified webpage language that is close to that of a normal document. The concept behind wikis is that it is easy to correct and change, rather than hard to misuse. The fact that it is easy to change makes it possible for many people to work on the same page, and they do not need any programming skills (Wheeler, Yeomans, & Wheeler, 2008).

The most known wiki is Wikipedia which is an encyclopaedia developed by its users. Wikipedia Foundation has developed MediaWiki, which is the base for, among many others, Wikipedia. MediaWiki is an open source project supported by a large community. A large unknown number of pages use MediaWiki as their base. Until December 2013, all text written on MediaWiki sites had to be written with a certain syntax. However, third party add-ons, such as VisualEditor expected to be included in the official release of MediaWiki, including features to enable word processor functionality, also called “what you see is what you get” (WYSIWYG). The semantics of wikis is a barrier, which is solved by using WYSIYG editors (Parker & Chao, 2007). Wikis are efficient for collaborative learning but have to be easy to use (Chu, Siu, Liang, Capio, & Wu, 2013). User-friendly WYSIYG editors could overcome such problem. In wikis in general, people tend to add information while they seldom delete any. This problem leads to outdated data complemented by new, correct data. Therefore, such pages need super users managing the page.

Case Study 2 uses a Wiki to enable fast development and the sharing of a handbook for the tool and methodology. The Wiki is closed for external edits to ensure correct contents. It is, however, obviously open for readers.

3.4.2 Pilot Software Development

The researcher developed the tool using waterfall methodology. Waterfall gives a rapid and agile development flow. The methodology often gives unstructured software harder to maintain than creating software made for testing (Collins & Lucena, 2010). The software is used to test concepts and not to target a release. This makes the benefits more important than the drawbacks. To support iterative work during pilot testing, the testers used a Wiki to follow up on all issues. A small user group consisting of students also used the tool and documented software issues in a Wiki. The students tested the tool iteratively using the same conceptual model and results as the concurrent **Case Study 2.**

4 RESULTS

This chapter summarises the results from the appended publication and cases. The end of this thesis withholds the referenced publications and cases. Each section contains the results to support one research question.

4.1 BENEFITS, DRAWBACKS AND PREREQUISITES FOR SIMULATION WITH LCA

This section presents results used to answer **RQ1**. The section discusses problems with LCA that is performed by simulation. It covers specific situations when not to use simulation for LCA studies. That is benefits, drawbacks, and prerequisites using simulations of production flows in LCA studies.

Many variables influence manufacturing systems, directly or indirectly. Several mechanisms in the manufacturing system act together with external markets and depend on each other. The total system is hard to analyse, as analytical approaches are not very accurate for other assessments than for the current state. **Publication I** describes a complex production system with a many entities, however still only a single manufacturing system. The system contains measures of consumptions of energy and materials for each entity. This current state can easily be assessed by allocating the consumptions to the products produced during the time the measurement was performed. This corresponds to a detailed assessment of the system. However, any change to the system, such as changing a machine or reallocating buffers, changes the dynamics of the system. Such changes to the dynamics cannot accurately be represented using a static model, but must be investigated in a simulation model. Simulation aids assessments of the future state of complex manufacturing systems.

Before any project starts, the commissioner must believe that the project provides more benefits than it costs. LCA is a resource and time expensive methodology. **Publication III** presents drawbacks of the approach including an extensive need of data, which requires rigid data management and sufficient time. In **Case Study 1** it was obvious that time spent on data, collection and management take a significant amount of time, 49 %.

Publication III and **Case Study 1** investigate problems with heavy data management. Each specific case should investigate available data before the decision to use simulation or before deciding how to design the model. If the required data is, too expensive it is possible to change the type of analysis and focus on some other less data intensive method. Figure 7 visualises the benefits and drawbacks.

Case Study 1 and **Case Study 2** reported a long implementation time due to the more complex modelling and calculation. As this project is the first of the kind for the practitioners, who are used to conventional simulation modelling of manufacturing systems, the implementation phase probably sanctions from that.

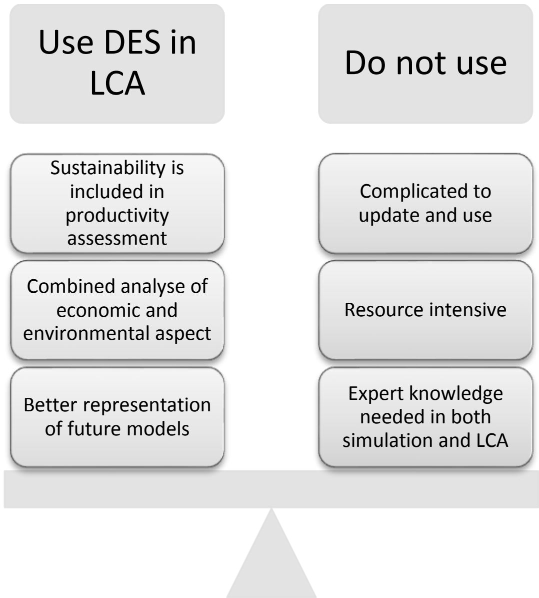

Figure 7 Most important arguments

Case Study 1 evaluates the prerequisites when to perform such study. Arguments in favour of using a simulation model for environmental impact assessment are:

- The company needs an evaluation of environmental impact on a detailed level of the production system.
- The company needs a simulation model of their production system.
- A pre-LCA study already exists with much existing data.
- A simulation model of the company's production system already exists.

A simulation model for environmental impact is not a preferable method if the prerequisites PR1 and PR2 and PR3.1 or PR3.2 are not fulfilled.

PR1. The focus of the analysis is a complex manufacturing system.

PR2. There is available or collectible data to model the system in detail.

PR3.1. There is a need for detailed production flow analyses.

PR3.2. Or, there is an existing simulation model that can be used for the purpose.

4.2 Methodology

Publication II and **III** attempts to structure the knowledge and experience from previous methodologies used in the cases. They include situations to avoid and best practices from the cases. The main results are however that there is a need to standardise and formalise methods and a methodology with best practices and experiences. The final methodology is included in this thesis and documented on the Wiki (Andersson, 2013) and presented in next section.

The following section lists and answers **RQ2**.

- Data management is expensive, it is thus important to use supportive data management methods.
- The project should perform a pre-data collection, in order to understand the availability of data before designing the model.
- Important data to collect in a study of manufacturing processes are,
    - Use of raw material
    - Waste and spillage
    - Quality rates
    - Direct energy
    - Overhead or indirect energy
- Use separate calculations from the simulation model to enable faster verification and validation.
- Use sensitivity analyses to understand important process steps and prioritise those.
- As in LCA, an external reviewer must be involved in order to use the result externally.
- Vague problem formulation results in unnecessarily extensive and expensive models not answering the correct question.
- Non-standardised verification and validation procedures result in unreliable results inappropriate for comparisons and benchmarking.

The study resulted in a methodology later tested in the studies presented in 4.2 and 4.3. The research group in **Case Study 1** designed the initial methodology based on the results of the study.

The procedures in the archive case study and the two executed cases weighted together as a methodology. A proposal was first generated from the archive case study, which was used and evolved in the two cases. The used methodologies in the studied archived cases were used as input to the first proposal. The methodology is based on discussions with the research team.

The methodology is divided in three parts that are connected. Start-up phase, modelling and verification, validation and analyse. Dettmann et al. (2013) present the start-up phase while this thesis describes all phases.

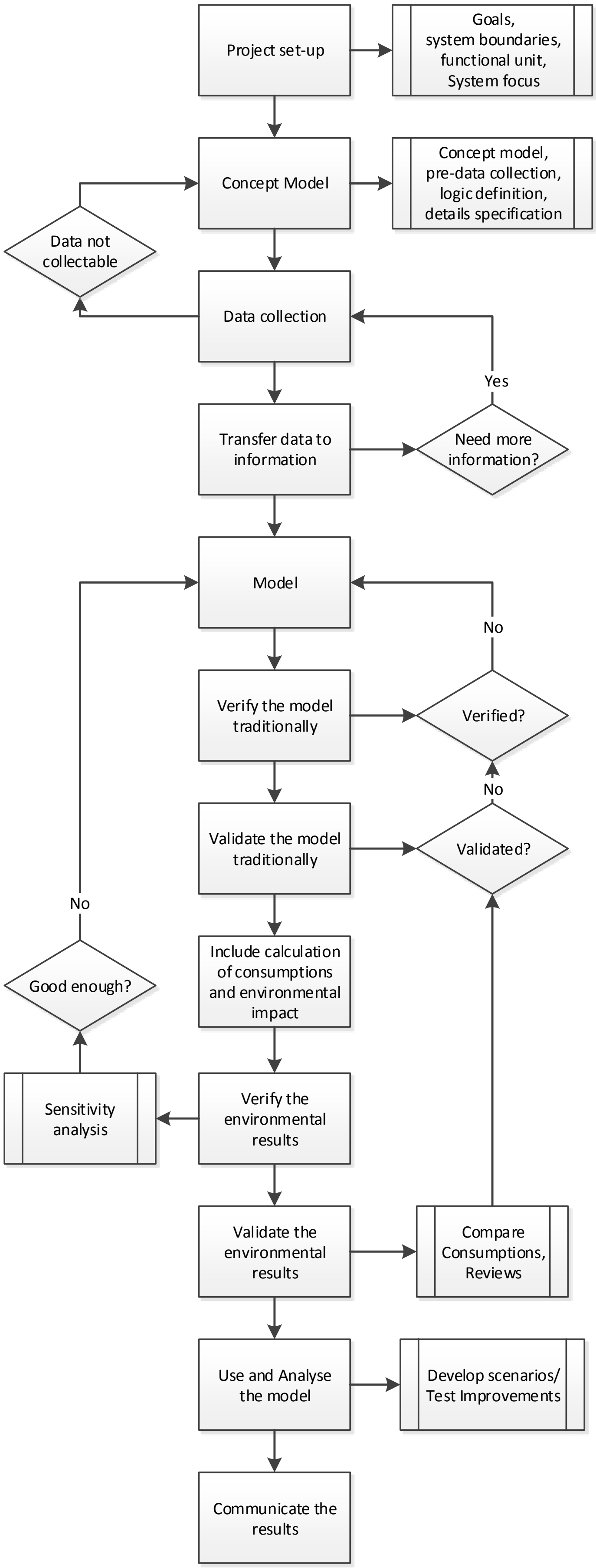

Figure 8 Graphical representation of the methodology

4.2.1 Project Set-up

Important choices are made early on in the project. These choices define what is the most important and help to prioritise later on in the project stages. It helps the conceptual modelling phase to define which part to model in a detailed way. It guides data collection to define what is good enough; it helps during the modelling phase to understand the need for output and the details of modelling. The project goal must be set together with the commissioner of the project. Include cost restriction for the project here.

The next step for the team is to set the functional unit to measure. Normally this should be one product or service produced, but could also be defined according to the actual value the product or service is adding, e.g. an available product function per year. Such a functional unit is affected by the product lifespan. Thus, a change to the process that changes the product lifespan has a major impact on the result.

Before modelling and collecting data, it is important to contemplate some relevant questions. For example:

- What/which is the unit of analysis?
- How can the data be collected?
    - Are there any logged data in databases?
    - Are measurements or estimations needed?
- How many data samples do we need to get a reliable value?
- What kind of measuring instruments is needed and how accurate must they be to get a reliable result?

The results differ depending on how the measurement is performed and what the user wants to analyse.

Set your project goals and define the level of detail for the project.

- Define functional units (one product, batch of product, factory etc.)
- Define system boundaries according to the goals for the environmental analysis.
- Define limitations for the model according to the goals and system boundaries.
- Identify available data that can be used for the conceptual modelling.

4.2.2 Concept Model

Next important step is to design a conceptual model in order to grasp the situation and discuss the problem with important stakeholders. Start with a high level of system description using text, diagrams, and numbers. Use and update the model during the project.

In the start-up step, the conceptual model contains brief data but one should try to include at least the basic information including: the main resources used, where resources are located, the product path in the production system, brief lead times, and energy and material consumptions for each resource and building.

The energy and material consumption should be defined conceptually in detail. It is also necessary to define how they are consumed by stating if the consumption depends on hours used or if it is the same consumption every time.

Sometimes the energy load profile for a process differs a lot during different stages. For example, there could be a small internal transportation inside the process. If such processes are important for detailed analysis, they should be divided in into more states than normal processes. For example, one low power state for the transport and one high power state during processing. As **Case Study 2** concludes this enables the model to handle improvements of the separate stages without lot of re calculations of average power states, e.g. speed up the transport.

- Use the conceptual model throughout the project as a tool for communication and visualisation while communicating with people.
- Verify the conceptual model with operators/engineers/management, i.e. discuss all assumptions made with people that have knowledge of the real system.
- Identify how the resources should be measured, is there different stages in the machines operation that could be divided into several steps.
- Identify outputs from the simulation model needed to calculate consumed energy materials and support. Use some or all of the listed outputs.
    - Measured time a product has been using a resource or location.
    - Number of times a resource or location has been used.
    - Measured time a resource has been, down, idle, off, maintained.

4.2.3 Data Collection

Data gathering is an important and time-consuming task in a simulation study. There are existing sources of data in a typical case, such as databases, documents, and existing models. However, those may not be enough to create a validated model. The team must then perform expensive and time-consuming measurements and estimations.

Data are categorised into three categories: available, collectible, and non-collectible (Robinson, 2004). Available data exist in databases or documents, such data need to be carefully cleaned and processed to contain the data needed for the application. Consider to change the conceptual model if the data represent another flow. If the process is important for the analysis, consider to collect new data if possible.

Data that are collectible require most effort and planning. In an existing system, the data need to be carefully monitored or measured without disrupting and disturbing the current operation. Collectible data, that is short cyclic data such as cycle times, common disturbances and simple human decisions, are easily collected by straightforward *time studies*, *interviews*, and *observations*. However, long cyclic data such as complex human behaviour, machine failures and complex repairs need either longer time to collect or careful *interviews*.

In cases were data are neither available nor collectible the data need to be estimations. Estimations should, if possible, be done in a team or using experts. People often tend to underestimate tasks. Ask for how much time the task takes to carry out, when everything works perfectly, and how long it could take if everything fails. Compare the estimation to other similar processes or materials. Convert that information to a triangular uniform or similar distribution and use that for your model.

Consumption

Beside conventional data for simulation studies, an environmental impact assessment needs data about consumed materials. Typical consumptions in manufacturing industry include consumed materials, consumed energy, and subassemblies. To get a trustworthy assessment it is as important to collect qualitative data for consumptions as well as for system flow aspects.

Consumptions are provided to the model as static values per use of resource or time spent using a resource. It is as important for a valid assessment that the models cycle times are correctly measured as it is to measure and calculate correct consumption rates.

To model consumptions based on time as for example energy use a mean consumption in each cycle-time for each state (idle, busy, down, or more). The states to use for a model are very dependent on the process. Some process must be modelled using more than three states and some only process and off.

As concluded in Case Study 2 the major difference between a traditional simulation model and a model used to assess consumptions is that consumptions can vary during process sub cycles. Figure 9 show an example of energy profile of one process that is repeating the same task (three times). The process can only have one product simultaneously during the cycle. The graph is marked idle when no products use the process. The analyst has two choices, either consider the total cycle as the state processing, or consider it as two or three different parts. In a traditional simulation model, the cycle time would be the total cycle. In this case, it depends. First choice is to calculate time dependent consumption, time in state multiplied by the consumption rate. If it is possible to separately influence the time during the low power states but not the high it should be modelled as more than one state, otherwise model it as a full cycle. A model with more states needs more data collection and modelling. However, such model is much more flexible model.

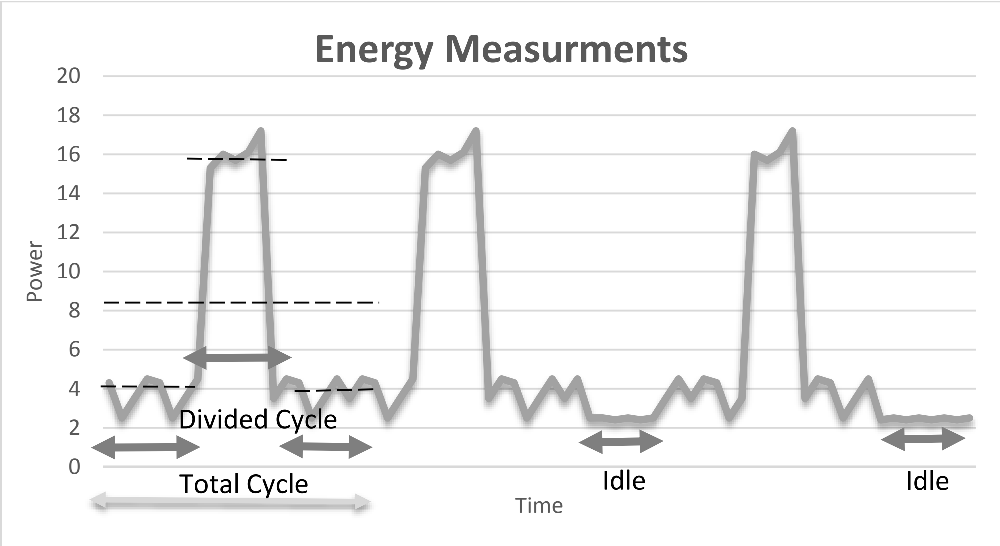

Figure 9 Energy profile for repeating cycles of processing, three cycles

As investigated in **Case Study 2**, it is also important to use appropriate measuring equipment. For example, if the cycle time is short it is vital to use a measuring instrument that has a high sample frequency in order to get a result that is as detailed as possible. If the cycle is long, for example one hour, the sample frequency can be lower allowing cheaper equipment. A good data collection measure the cycle multiple times to ensure that the means are valid measure.

Consumption data for higher-level consumption as for example facilities is found in overall bills or databases. The most common consumption for higher levels is heating and light. Companies mostly use facilities for other things than produced by the modelled part. The consumption than has to be allocated to the modelled part. As in LCA, use physical data for allocation. Gather facility consumptions on at least a year. Calculate the models use used space in the facility and compare it to other parts used space; do not consider free space in a facility. If 20 % of the used space in the facility is used for this modelled part, allocate 20 % of the consumption. If modelled part of the facility is used for more products than modelled in our model allocate the consumptions to the products produced in the model. If 30 % of the production time is used for the products modelled, allocate 30 % of the consumption.

4.2.4 Transform Data to Information

Next step is to convert all gathered data to information to be used in a simulation model. A simulation model use distributions to represent the data. There are many commercial simulation software to fit data to functions and distributions. Convert the gathered data to distribution and information for the conceptual model. The simulation tools have a specific set of distributions, e.g. normal distribution, Weibull distribution. Choose the best-fitted distribution that is supported by the simulation tool.

Sometimes you have too little data or data that is not of good quality. If the information enough is not enough, gather more data. The intention is that the methodology should capture this kind of problem should in the conceptual modelling phase. However, some problems are hard to capture in an early phase.

Use means for consumption data in most cases but consider other distribution if the process have specific behaviour and the process is a major interest of the analyse.

4.2.5 Model

Findings in **Publication I** show that all discrete event simulation software included in the survey is possible to use. Furthermore, the publication shows small or no advantages to use any of them, hence, software should be used based on other criteria such as licence costs, required experience, support for current operation, documentation and support (Nikoukaran, Hlupic, & Paul, 1998).

This step is the actual implementation phase. It is not described in detail though most implementation work depends on the actual software package. The main idea is to use and implement a model according to the conceptual model. The simulation engineer should use a high level modelling approach with no more information than needed. Start by using a couple of nodes for different manufacturing parts and increase the model information in later iterations.

To enable later calculation of consumables and environmental impact one has to use an extensive data output and store the timings for individual products claim and release events for resources in the model. Let the model export if not the commercial package have a simple spreadsheet functionality. The model should export to any convenient spreadsheet or database structure where it is easy to do simple mathematical operations as multiplication, division, subtraction, and addition. It is not required to export the data if it can be post-processed in the simulation software internally.

To summarise and clarify the implementation steps.

- Create a simple simulation model of the manufacturing sections
- Export times when products start and stop using a facility, machine or other resource and if the product got wasted because of quality problems
- Export times for other states as broken down, maintenance.
- Increase detail of the sections that is important for the analyse

4.2.6 Verify and Validate the Model Traditionally

This step does not differ from other simulation methodologies. Sargent (2010) describes for example many useful methods to use for verification and validation. Use any valid verification methods to ensure that the model works as intended and compare it to the conceptual model. Validate that the results and the flow in the model is operating according to reality. Based on verification in **Case Study 1** and **2**, recommended validation techniques are to:

- Compare historical output data with the output from the model. Then compare aspects such as capacity, lead-time, resource utilisation, storage levels, etc. Does the model perform according to the real system on historical input and output data?
- Does the model behave according to reality during extreme conditions, such as increase in orders, major breakdowns etc.?
- Can someone familiar to the system tell the difference between output data from the system and output from the model?

4.2.7 Include Calculation of Consumptions and Environmental Impact

When the engineer has built a validated simulation model that exports event times to a spreadsheet, it is time to calculate consumptions and environmental impact. The calculation sheet bases everything on collected consumption rates and the output from the simulation model. The sheet only does simple mathematical operation to multiply times divide by produced product and add up consumption and impact. The equations should be as transparent as possible to boost verification and validation.

Use the definitions in the conceptual model to define the equations. Table 3 shows examples of consumptions for common resources. There are mainly two types of consumptions: direct or indirect. Direct consumption directly corresponds to the use of the resource. Either the consumption is calculated by the total time the resource has been used or by a static value added each time the resource is used.

A resource or facilities indirect consumption uses the consumable even though no product is using it. The product shares the indirect consumption using some defined allocation key. The real resource defines the allocation depending on what drives consumption or the resource existence. A facility exists because products and processes need space; therefore, the allocation key should be based on time and used space. In general, use the time in combination and when needed some physical attributes of the product to allocate the consumptions to the products.

Table 3 Examples of allocation rules for resource consumption

Resource state	Consumable	Value	Allocation
Machining	Electricity	Per operation	Each time used
Machining	Material	Per operation	Each time used
Idling Machine	Electricity	Time operating	Per time used
Set-up operation	Electricity	Time operating	Per time used
Oven	Gas	Time operating	Per time used
Building	Heat	Time operating	Per time and area

In general, it is not interested to allocate the consumption to a specific product in the simulation model. Rather, it is interested to get the consumption per variant or product type produced in a facility. Hence, to calculate the energy consumption from the facility:

Multiply the consumption per time of the facility with the simulation time, multiply by average used space of a specific product type and divide by average total used space for all produced products. Described in Equation 1, where the allocation key is equal to the fraction.

$$Electrical\ cosumption\ for\ Facility\ A * Simulation\ time * \frac{Total\ Number\ of\ Product\ Type\ A * Average\ Time\ in\ Facility\ A * Used\ Space\ for\ one\ Product\ A}{\sum_{All\ products} Total\ Number\ of\ Product\ N * Average\ Time\ in\ Facility\ A * Space\ for\ one\ Product\ N} \quad (1)$$

After the verification and validation of the consumption equations, explained in the next step, the results of consumptions is a good base for analysis. As concluded in **Publication II**, it is often better to use consumptions than emissions to analyse the factory. However, if there is a need for further analysis of the environmental impact of the consumptions the sheet is expanded.

Use emission data from LCI databases for the consumables used.

Multiply the consumption with the emissions in the LCI sheet.

Use any valid index or characterisation method to weigh emissions and their impact against each other. Global warming potential (GWP), acid potential (AP), and eutrophication potential (EP) are useful characterisations, e.g. defined in IPCC (2007). There are also multiple index methods combining multiple environmental impacts into one index. Use such indexes with care, though they are subjective and differ from each other.

GWP contains the sum of all emitted gases equivalent to CO_2 in terms of greenhouse effect. Though all gases have a different lifespan, the equivalent factor depends on the time horizon. GWP100 defines constants for a 100-year span. To calculate GWP100 for an imaginary material, one has to multiply each emission with the characterisation weight and then sum up all the terms. Table 4 exemplifies this. Hence, by only analysing results from Table 4, mitigation proposals should cover the reduction of methane and nitrous oxide. IPCC (2007) includes a full list of the gases included in GWP100.Gases not included are not seen as major greenhouse gases.

Table 4 Example calculating GWP100

Emission type	Emitted	Weight	Result
CO_2	0,6 kg	1	0,6
Methane	0,11 kg	25	2,75
Nitrous oxide	0,01 kg	298	2,98
HFC-23	0,00002	14800	0,296
		Sum	6,626 $CO_{2\ eqv}$

The results from **Case Study 1** and 2 show that for manufacturing industry with few hazardous production processes waste is a main contributor to the analysis. In the first case at Emballator, internal waste accounted for 49% of the total GWP. However, it is not the process itself that emits the emission. The wasted materials emissions origins primly from material extraction and material processing. The emissions are accounted for the node or process that wastes that material because of quality problems. This has to be calculated separately by removing emissions from material extraction to those processes at the end. Each process with quality problems multiplies the number and wasted products with the accumulated emission for that product type until that process.

4.2.8 Verify and Validate the Environmental Calculations

Start with an extra manual review of the equations to find any glitches. Start with the consumptions, continue with the emissions, and stop with the categorisation and indexes.

Exclude the simulation model and use only the sheet to perform a sensitivity analysis. A basic sensitivity analysis varies according to the input parameters, which would come from the simulation model, and records which parameter that influences the most. Make sure the model parts affecting those parameters are qualitatively modelled. Vary the consumption rates in the sheet and record those that stand for 80% of the impact. Make sure the consumption information of these consumables is qualitative. Make sure that the LCI data for the consumables are as good as possible. A pedigree matrix can assist with LCI analysis.

Validation of the result is difficult. Try to compare at different levels wherever there are measurements from the real system to compare with. Compare the consumptions from the current state model run by comparing it to the usage in the real system. Then compare this to analyses made on similar products and explain any differences.

Finally, Let a certified LCA reviewer examine the results if they are intended to be used comparatively or for external communication.

4.2.9 Use and Analyse the Model

Manufacturing simulation models are especially suitable to analyse and compare new scenarios or changes in the system. Different types of analysis performed in **Publication II**, **Case Study 1,** and **Case Study 2**:

- Assessment of manufacturing system, assess environmental impact and analyse in detail the current system and its properties
- Scenario comparison, compare different strategies, machine types or storage levels
- Optimise a manufacturing parameters, vary one or a few parameters to find the optimal solution in terms of environmental impact, production capacity, and cost

4.2.10 Communicate the Results

There are two type of analyses, which are sometimes combined: accounting and change oriented. An accounting report only provides all current state key indicators for the system. Such a report includes production performance properties related to both economic and environmental impact. One has to make sure to provide all consumption rates, emission and indexes, and not only provided indexes. However, it is important to emphasise important results.

If using a change-oriented approach, it is required to carry out an analysis of the improvement potentials. One has to make sure to provide both environmental assessment and productivity potentials.

4.3 Tool Functionalities

Publication I describes the need and benefits of integrating energy and resource assessment into simulation tools. The focus of the study is energy. The publication also considers full environmental assessment. Moreover, it presents a survey that shows the very limited support in current simulation software. However, all of the studied simulation software is so flexible that experienced simulation engineers with knowledge of environmental assessments are able to adapt it to modelling energy and resource consumptions.

Publication I concludes that an important feature lacking in current simulation software tools is allocation of indirect impact form sources as technical building equipment, heating, cooling, compressed air or other energy sources. In conventional LCA, such sources are allocated by rough estimations. Allocation using results from simulation runs have the possibility to be much more accurate, when time and individual productions are possible to track. Therefore, future state modelling in production processes has the potential to significantly increase the reliability compared to conventional LCA.

Publication I propose to build a database with common processes that can be used by simulation engineers developing simulation models. Figure 10 describes a vision for the demonstration software developed in this research. Closely linked companies continuously share updated analyses of the shared products bought from each other. It also shows how these companies use and upload their products to a common database and use 3rd part databases.

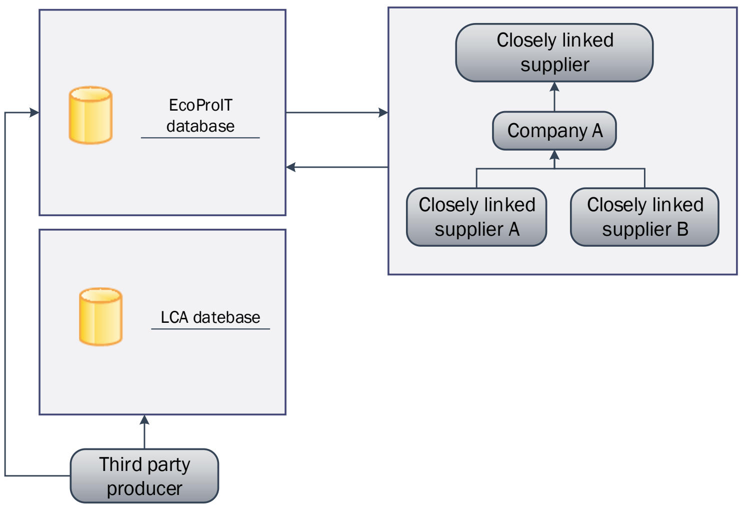

Figure 10 Visualisation of how future databases could share information with companies.

All work done with simulation cases and literature studies emerge as input to this development. The demonstration software tests concepts and ideas from these studies. This chapter summarises these concepts and presents the tool. **Publication IV** presents all the details.

Table 5 Summery of functionalities discussed in Publication IV

Functionalities	**Why**
Life cycle perspective	Reduce risk for sub optimization, get the full product environmental impact
Hierarchical Modelling	Enable allocation of shared resources in a uniform way, enable increased details as project runs
Simple and guiding	Enable the experts of a production system to do the assessments, require lower knowledge for simulation and LCA
Support standards for simulation models	Enable to import other models, and to import data in a standardised structure
LCI database included	Include a collection of common materials, energy sources, and their emission, to reduce input data time.
Connection between supplier	Enable to share result between companies in a supply network

4.3.1 Life Cycle Perspective

Simulation models of manufacturing processes combined with environmental impact assessment give the production engineer the opportunity to improve the system with lesser environmental impact. However, the analyst is the target for sub-optimisation focus in the local manufacturing system. Gained improvements in a simulated system can be even greater outside this system. E.g. an outsourced process can reduce the environmental impact locally while the product still needs the process. It is therefore important to keep the product as the functional unit and to include the total product lifecycle in the analysis, however not as detailed as in the local manufacturing system. The production engineer should aim to reduce emissions from the total system instead of from local processes.

The manufacturing system is the focus because that is what the production engineer can influence. However, it is important that the study considers and/or includes all other important produced product life stages. Those stages can be declared vague, but enough to compare total in-house manufacturing, and to avoid sub-optimization of the environmental impact of a product.

4.3.2 Hierarchical Modelling

Modellers use hierarchical modelling in order to focus on the right things as models become larger and more complex (Al-Ahmari & Ridgway, 1999). Starting analysing at a brief company level will result in an overview of the problem, and by digging into a production part or into a production cell one gets the details.

When adding a life cycle perspective from suppliers to use and scrap, the system becomes very large and complex. It becomes expensive to model everything with that much detail. One should model large nodes that are not the focus, e.g. suppliers, user phase, and end of life as basic as possible. Model nodes that are the focus, such as the production system, should be detailed. Furthermore, the engineer uses different levels of details regarding the production system that is the focus. It is in general important to find a good level of detail. A too brief model does not answer the questions asked. A too detailed model is too costly and requires unnecessary resources and time (Zhou, Pan, Chen, Yang, & Li, 2012). Models with wide system boundaries, such as LCA, need a low level of detail. However, some nodes in focus can be more detailed.

Conventional simulation models typically only need one level of detail. However, simulation models calculating environmental impact need to allocate consumptions from auxiliary inventory as buildings, conveyor belt, and ovens. By using a hierarchical modelling, resources coupled to other resources use the lower resources use of products to calculate their own assessment. In Figure 11 Facility A is modelled in detail down to the single machines. Facility B is only briefly modelled and does not include any dynamics. The time for Line 1 includes the time the product has been using Machine 1 and Machine 2, plus any extra time. The time the product spends in Facility A includes the time for Line 1 to 3. It is noteworthy that not all products need to use all resources - this is specified for each product.

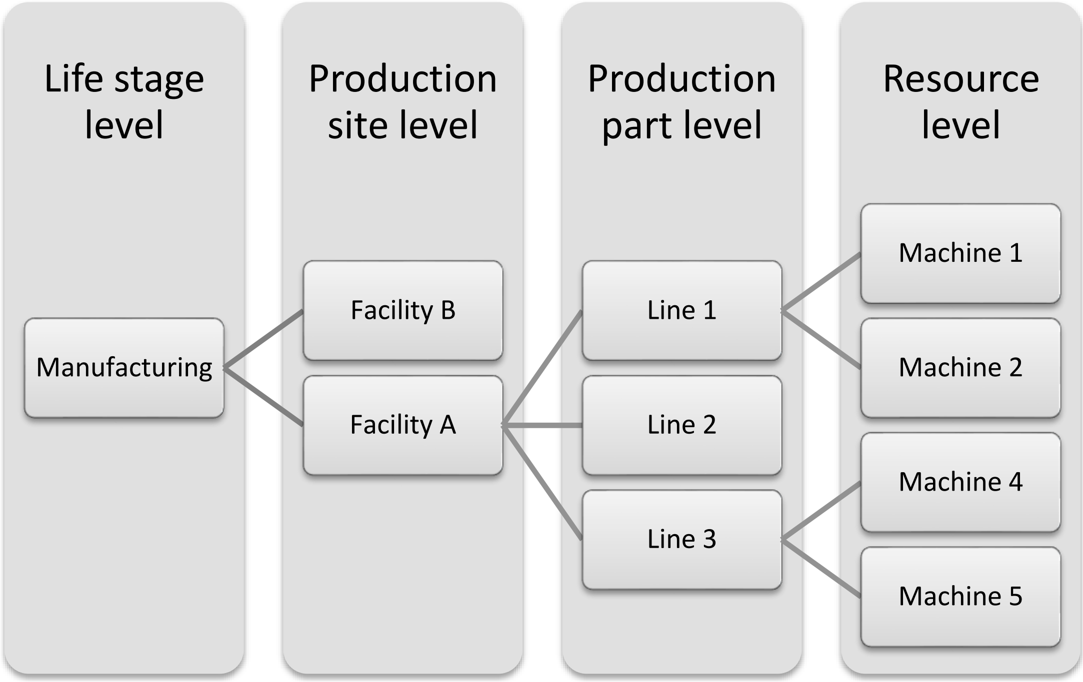

Figure 11 Hierarchical diagram of modelling approach

4.3.3 Simple and Guiding

The intended users of the developed demonstration software are assumed novices in simulation and life-cycle assessment. Users of the demonstration software should be experts in the manufacturing processes that are to be modelled. Thus, the demonstration software needs to guide the engineer into making the right decisions. This is implemented by using simplified modelling to instead of exact and complicated software. Advantages of simple models are that they run faster, are more flexible, require less data, enables faster development, and gives results easier to understand (Robinson, 2007). However, the lack of details limits the analysis capability.

The developed demonstration tool requires little information to start running. However, as new and extended information later complement the model increase the details and accuracy.

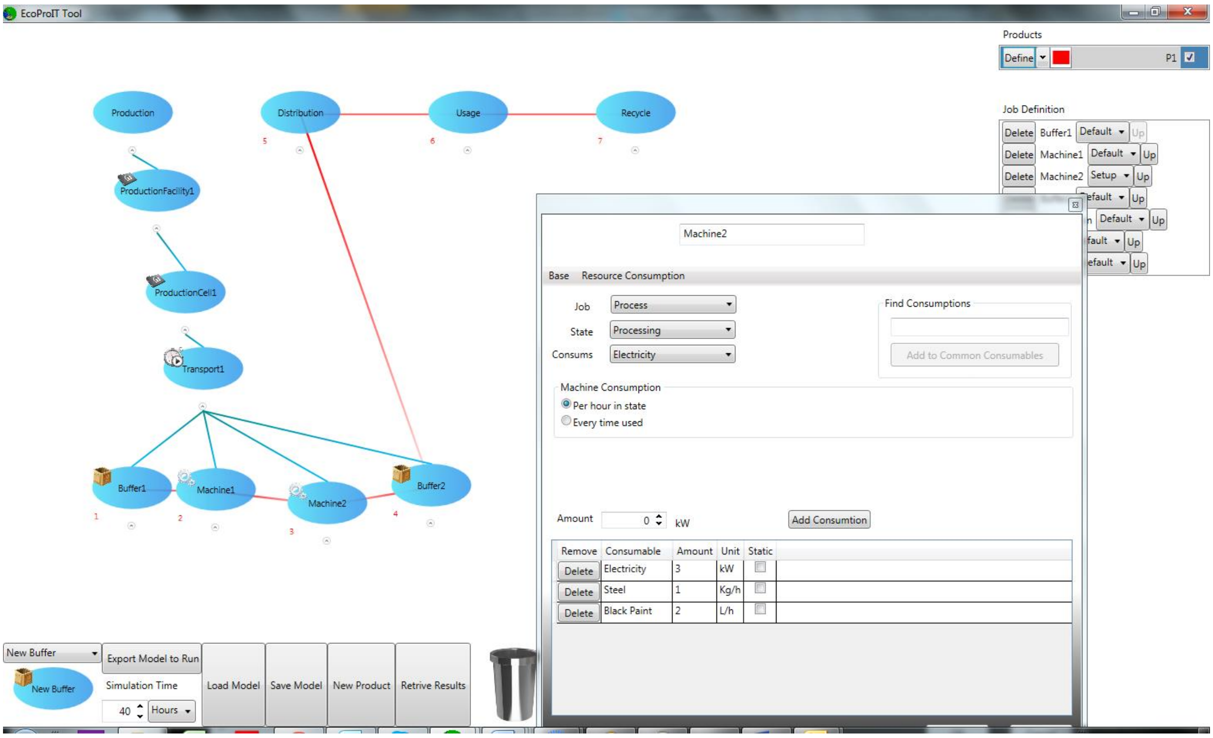

Figure 12 Screen shot of the demonstration tool showing the interface to declare consumptions

4.3.4 Model Structure

Figure 13 shows the concepts of the design of the model structure. A product that has already accumulated consumed material and energy enters the production system and uses resources. The resources are hierarchically connected to facilities and other resources.

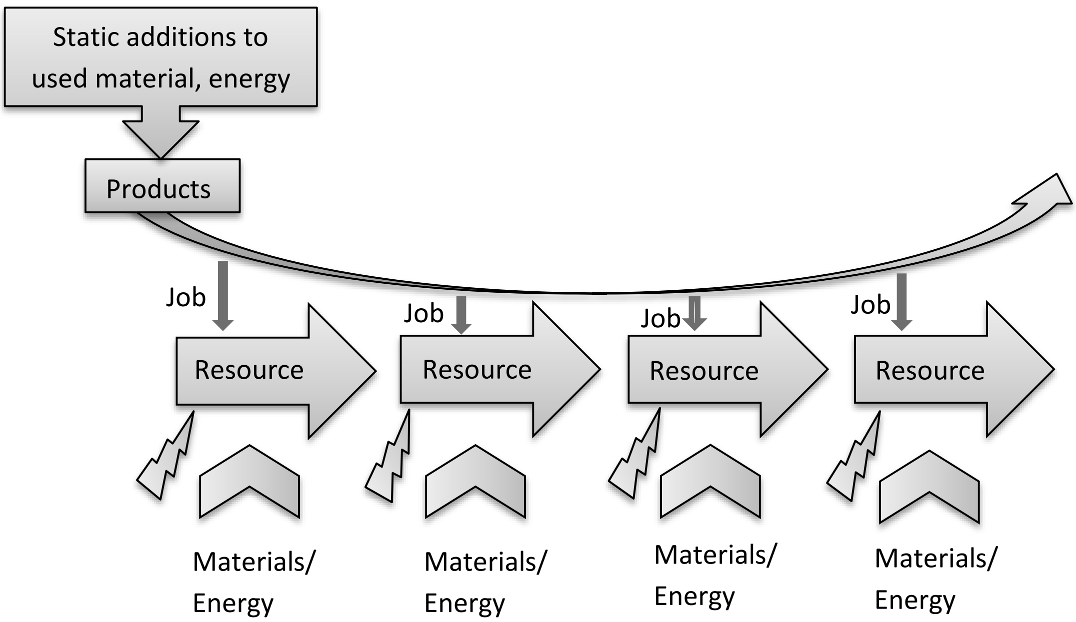

Figure 13 The two parts of the model interact with jobs performed by the resource on the product

Two parts define the logic of the models, the resources, and the products. Each resource can perform several jobs. The jobs of the resource generate a code for each individual product type that is defined to use it. The products declare the route in the production system. The demonstration software generates a code for each product to a discrete event engine. The codes for all the products execute in parallel and it stores the time each product used a certain resource, including the start time. The demonstration software imports the time data for each individual product, calculates how much resource was used by the system, and allocates this based on the time of the different products. Figure 14 describes the data model for the demonstration tool.

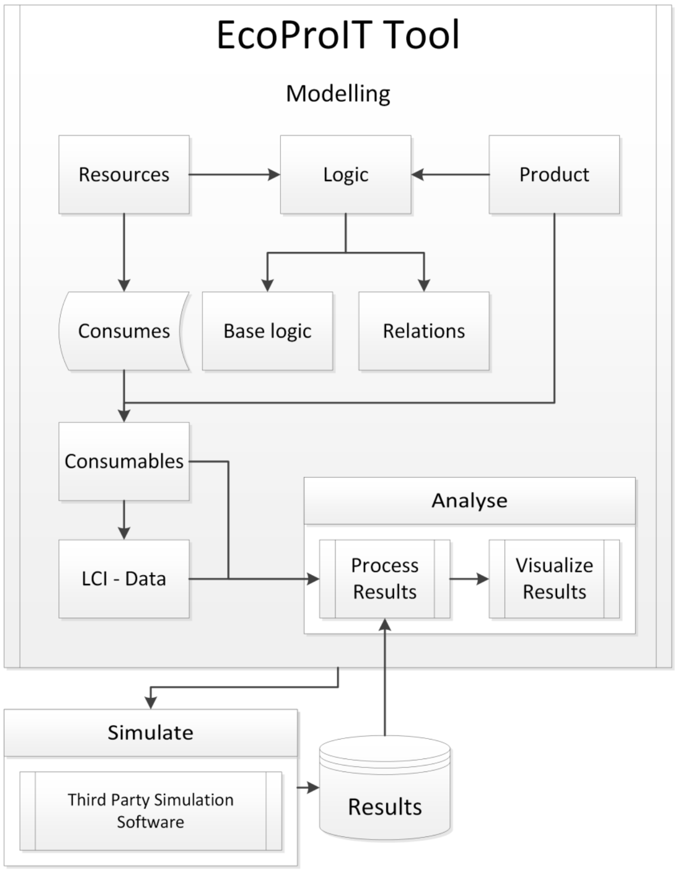

Figure 14 Schematic diagram of the demonstration tool's data structure

5 DISCUSSION

This thesis has so far presented results to answer **RQ1**, **RQ2**, and **RQ3**. This chapter will discuss any remaining issues in regards to the questions and elaborate on its implications.

The production engineer is mostly not in direct contact with the end customers. The intention of companies to be resource efficient, to lower energy use or minimise environmental impact comes from managers and through economic incentives or market potentials. It is important that companies communicate the response from the market regarding sustainability aspects in order for the production engineers to understand. The production engineer, in the system map in Figure 15, relies on feedback from the managers and on collaboration with product developers to be able to lower the environmental impact of the company. The production engineers use tools to analyse and test new systems. One such tool is simulation of production flows. For companies that previously have emphasised and tested their manufacturing systems in a simulation tool, it is a small step to include consumptions and emission in the same analysis. However, doing this in a structured way to support comparability and a trustworthy analysis requires a generic methodology and supportive tools. This thesis has presented one such methodology with supporting tool functionalities.

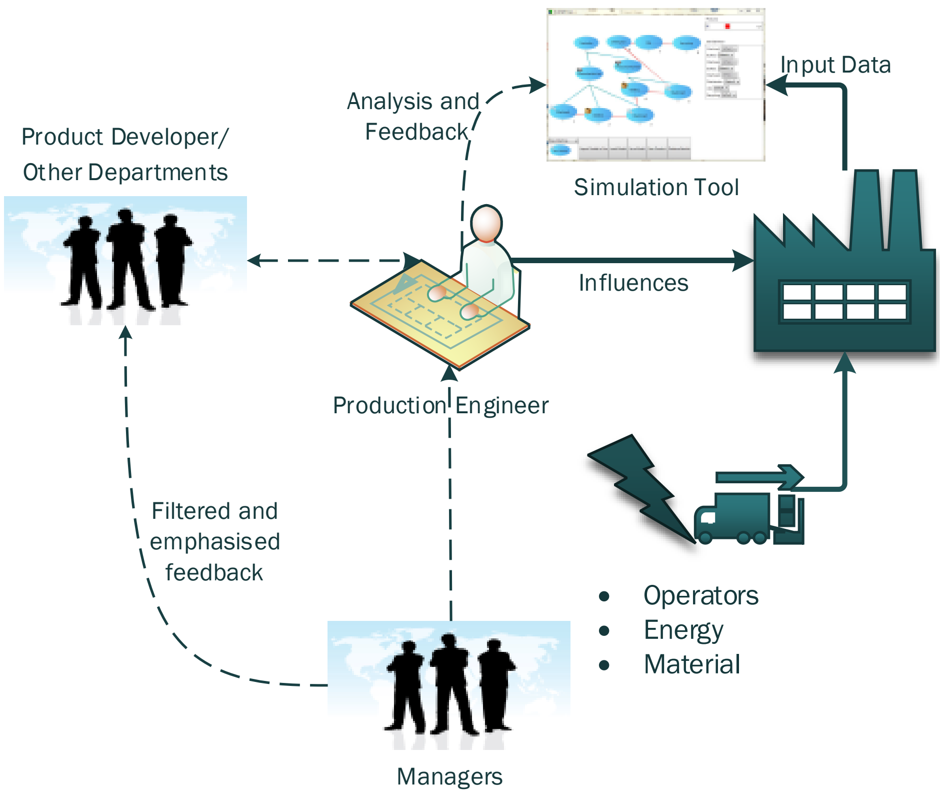

Figure 15 Actors closest to the production engineer

5.1 Benefits, Drawbacks and Prerequisites

This thesis proposes a set of prerequisites and checkpoints assessing if simulation is suitable together with LCA. **Publication II** and **Case Study 1** PR1 study this question. The main result is that the focus of the study should be a complex manufacturing system. PR1 could probably be generalised to other complex dynamic systems such as supply networks or to other industries. However, that is not in the scope of this thesis. The prerequisites are set to limit unnecessary work, and the production engineer should evaluate them before starting or as early as possible in the project.

Based on the literature study in **Publication I**, the most important advantages of using simulation in LCA projects for manufacturing systems are mainly better future state representations, as well as detailed assessments of manufacturing systems. There are no quantitative results of exactly how much better or when it is better to use simulation in LCA. Future industrial cases could compare possibilities and advantages with a Static LCA approach and a dynamic simulation – LCA approach.

The cases in **Publication III** and **Case Study 1** and 2 reported the same drawbacks. Simulation together with LCA is resource expensive due to a vast data collection phase. **Case Study 1** and Andersson, Skoogh, and Johansson (2011) concludes that projects that both need detailed assessment of environmental impact and a simulation analysis of a manufacturing system do not require longer time for data collection than to do the analyses separately. However, **Case Study 2** considers that the data that need to be collected in some cases are significantly different and more useful for a simulation model that excludes environmental data. Projects that execute all preparing steps, adapt data collection, and adapt modelling to the current processes, probably have a low risk of being too expensive. However, projects with a low concern of potentially costly risks of modelling in unsuitable ways may have to carry out expensive remodelling and additional data collection.

5.2 Methodology

Two publications, **Publication II** and **Publication III** review previous cases. The result leads to an initial methodology. The developed methodology is tested and further developed in two cases. The research used an action research approach where the researcher is actively involved in the case developing the methodology. The approach results in a useful methodology rather quickly. Future studies should further improve and generalise the methodology by expanding the guides and use it more frequently and in more cases. Fundamental structural changes ti the methodology steps are unlikely though the steps are defined generic - instead it is likely that the contents of the steps change.

In this iterative research process, a Wiki is a good tool for new versions and updates of the methodology. In future industrial operation, companies can use the portal to share experiences with each other. Wikis are efficient for collaborative learning but have to be easy to use (Chu, Siu, Liang, Capio, & Wu, 2013). Using user-friendly "what you see is what you get" editors, a cross company Wiki for simulation experts could overcome such problem.

The results from *Case Studies* do not contradict previous knowledge and cases. The results complements, summarise, and expand the knowledge. The current methodology focuses on discrete manufacturing. Similar case studies in other areas performed in a similar way can extend this methodology. DES is the only simulation paradigm used until now. Other areas might require other simulation paradigms. Jain et al. (2013) tested using system dynamic (SD) together with DES to model the brief parts of the product life cycle. The test case turned out successful. The benefits using SD for the product life stages not in focus, is that it is less computing expensive. In the case study, the studied production was modelled with DES and the rest modelled with SD. This multi modelling strategy is probably useful in many cases. However, more comparative studies are needed. Other simulation paradigms as system dynamics agent based modelling could also be useful. Future case studies need the same type of input data and calculations that are needed for SD and DES. Thus, the main part of the methodology would be the same.

Case Study 1 and **Case Study 2** indicate waste in forms of quality problems and removed material as a major contribution to environmental impact. The cases did not include energy intensive processes. However, the upstream processes to extract and process the raw material is very energy intensive. Therefore, low energy manufacturing processes as assembly or other low energy processes should focus on quality and using less material to lower total environmental impact.

Both cases tested techniques to visualisation the results. The cases used a flexible result data format. From that format, it is possible to present the data allocated to a product, for a production process or the total production system. This flexible data visualisation enables multiple ways to display the results in the report. However, more research is needed to identify the best ways in different situations.

Case Study 1 had problems with large computer memory in the model. Two approaches to solve this problem exist. One can either use a simulation tool with larger memory space capability (i.e. 64 bit), or change the modelling approach. The model can be changed either by using a secondary memory or by reducing the needed memory. In a situation such as described in this case, where products were stored in middle storage during a significant time, could the products be stored on a hard drive meanwhile. The implementation is often straightforward and considerably reduces the needed memory. However, the implantation slows down the model significantly. Initial unpublished tests show significant impact on the simulation run time. Another approach is to reduce the information stored for each product or to group some information for a total batch, product group, manufacturing resource or any other group.

5.3 TOOL FUNCTIONALITIES

The purpose for presenting simulation software functionalities in this thesis is to facilitate special circumstances in the methodology and simulation used for LCA.

Special issues that do not exist in conventional simulation modelling allocation of consumables used consumed by common resources and the time perspectives of product life cycles.

To solve the time perspective, the approach uses static numbers for life stages with low focus, e.g. material extraction, usage, and end of life. This means that the tool models the life stages in focus dynamically, whereas the other aspects are modelled as static numbers with no time delay. This requires an adaptive modelling structure.

A generated model should use the same allocation as with normal resources to allocate consumptions from common resources. The output from the model is time when a product enters and leaves a resource or facility. The allocation should then be done using an allocation keys with time and possibly combined with a physical usage of the resource, i.e. space usage for facilities. The products in the model could use many resources at the same time, e.g. using a machine and an operator that is placed in a factory.

The software should be very simple. A simple concept is easy to adapt for new and non-experienced modellers. However, it could possible lacks the support to simulate complex systems, as the case for the developed demonstrator. Using the demonstrator, the production engineer needs to simplify the models of the production system considerably. The flexibility of the modelling has to be improved, but was not further examined.

The Wiki used as a handbook is an effective platform for development. It enables multiple actors to work on the same handbook. In the future, the portal will be used for further development of the handbook. The Wiki contains two types of users, readers, and editors. Editors add material and readers consume material. As readers become experienced in the community, readers will also become editors.

The previous project Simter (Lind et al., 2008), had the possibility to analyse ergonomic aspects and were thus able to validate the production in both ecological, social and economic aspects. However, the social analysis was time-consuming and had many other conceptual problems. Social aspects are not the priority in this thesis, however, these possibilities have been analysed (Andersson, Skoogh, & Johansson, 2011). It should be possible to add information manually concerning ergonomic aspects in the same way as the Simter project did. However, this is a very extensive approach. It could also affect the simplicity that is very important to the system.

5.4 Research Approach

The work has two main phases. In the first passive phase, knowledge was extracted from literature and previous studies. The knowledge was based from a wide set of cases but it was hard to understand wherever the result made sense in a real case. The outcome was the first benefits and drawbacks of using simulation for LCA studies and a basic methodology. The second phase was conducted iteratively in an active role. The active role in the studies helped to faster collect and filter the practical knowledge. The active action research gives fast results that are applicable on the settings where it is performed.

New experiences are easier to test and implement directly. The methodology got deeper and with more examples. The benefit with the first approach is that the result become more generalised. However, the benefits with the action research are the deep knowledge. The benefit of the approach is also the drawback. The results are biased by the researchers' previous experiences. That means that only one team and one case influence the next iteration. A better way would be to have multiple teams doing the same case and draw experiences and from all of the teams. Action research could still be used by having close collaboration between the teams and the researchers.

There are alternative research approaches that could be used to answer the questions in this thesis. **RQ1** focuses on background information and the current state of art. The question requires data based on practitioners' thought. However, the practitioners and cases in this study originate only in academia. Another approach is to include industrial simulation and LCA practitioners in *panel discussions* or *interviews*. This was not considered possible due to the lack of actual commercial cases. Furthermore, the research group have close relationship with the practitioners in the used cases, which ease communication with them when needed.

The last methodology was never tested and fully used. It describes **Case Study 2**'s work procedure, with a few additions and generalisations.

5.5 WRAPPING UP

The main purpose of this thesis is to facilitate and to highlight how to use environmental impact assessment in discrete manufacturing for production engineers. This thesis potentially can influence the industry to use existing modelling resources for a new purpose. Production engineers using simulation often get a good system perspective that other production engineers lack. The overall perspective is of major importance to sustainable manufacturing. However, LCA does also provide a life cycle perspective for products. Production engineers using LCA potentially understand how decisions in manufacturing can help to decrease environmental impact of the total life cycle.

The main outcome from this thesis is a methodology to perform environmental assessment using production flow simulation. The knowledge for the methodology has been developed using two specific *Case Studies* and by reviewing previous cases. RQ2's needed steps to perform such study are answered by this methodology. RQ1 is answered using the same research and the answer is some prerequisites to fulfil to benefit from a simulation for LCA approach. **RQ3**'s functionalities to support the methodology were developed during the same time as the methodology. The functionalities was tested and implemented in a demonstration tool. The demonstration tool bases its engine on .NET, is programmed in WPF and C#, it is available to download on the web portal (Andersson, 2013).

This thesis helps companies and production engineers to analyse their environmental impacts. However, influencing a company to reduce environmental impact is another issue. Strong market or governmental policies must target the concept of market failure for environmental impact; there are minor evidence that that a free market is able to handle this. However, there can be a healthy competitive market if there are regulating policies and structures handling costs of environmental impact, e.g. carbon taxes or heavy fines.

It is complicated to arrange a global overall cost structure. Thus, one has to start with a limited geographical area with a strong economy. Then, one can expand the system once it is working, and protect the regulated internal market by using e.g. strong market tolls. External companies that want to sell products need to adapt to the regulations or pay heavy fees. It is necessity to make a large effort to audit the market and to charge fees to companies that do not follow the rules. Such a system could to some extent protect the public property.

The thesis provides an explanation of important functionalities for simulation tools. The functionalities has been implemented in simple demonstration tool designed for manufacturing companies. The tools assess manufacturing companies on a more levels than productivity and economy. The results could potentially be used in marketing and for ethical purposes. Ecological and social responsibility is important to build a strong brand.

Well-customised simulation tool for detailed environmental assessment of manufacturing systems support production engineer to do assessments. Easy assessments support the engineer to continuously analyse and improve environmental sustainability in the manufacturing. By following the methodology presented in this thesis, engineers reduce potential problems with the project and promote comparable results. A future validated methodology enables comparable results and type III eco-labels for the company.

6 CONCLUSIONS

The purpose of the thesis is to facilitate and highlight the environmental assessment in manufacturing industry for production engineers. It provides them with methods and tools for detailed assessment of the environmental impact of the engineer's part of manufacturing. The thesis uses three research questions.

RQ 1 In which situations, and why, should production engineers use production flow simulation to analyse the environmental impact of manufacturing sites?

This thesis has reviewed literature, analysed previous cases and used one Case study to define rules of when it is beneficial to use simulation of production flows and LCA in combination. Simulation is preferable to use for LCA when the studied subject is a production system with multiple variants, or variance in processes, or complex planning that is hard to analyse. Furthermore, simulation is favourable when evaluating changes that affect the dynamics of the production system. Production engineers should use simulation when changes and improvements affect the dynamics in the systems in such ways that it is not possible to analyse it using statically.

However, the prerequisites for using simulation for LCA are important to note. The focus of the analysis is a complex manufacturing system. Needed data and information should be collectible or accessible. There is a need for detailed manufacturing flow assessment or there is an existing simulation model that can be used for the purpose. If the prerequisites are not fulfilled, there are probably other, better methods to use.

Using simulation for LCA deepens the system knowledge in a team. An in-house project potentially gives knowledge or solutions to different problems than the one studied. When performing environmental impact studies, simulation simultaneously provides productivity results for changes. Combining a simulation model combined with an environmental analysis gives an additional aspect to consider during the analysis. However, the approach will always require more resources and it requires collectible or available data for continuous updated models.

RQ 2 Which project steps can support simulation studies by analysing detailed environmental impact of a manufacturing site and how are these steps interrelated?

Two publications have examined the methodology of eight previous cases. Based on them, a methodology with 13 project steps has been developed. The methodology has been further tested and improved in two other cases. This thesis presented the methodology aimed for simulation engineers to support modelling and simulation work. The methodology needs to be validated in additional industrial cases. Since the development of methodology use the same type of manufacturing industries as reference, the transferability of the methodology to other industries is not verified.

RQ 3 Which simulation software functionalities can help production engineers to perform a detailed environmental impact analysis of a manufacturing site?

Publication I concludes that current simulation software on the market lack user support for environmental assessment. However, any simulation software can be used, though they are all very configurable. **Publication IV** presents functionalities that supporting environmental assessment in simulation software. The functionalities include supporting production engineers when using it and features to supporting the methodology presented in this thesis. The functionalities include simplification for modelling and guides for engineer to enable a production engineer, rather than simulation experts, to perform the assessments. It uses a hierarchical modelling approach to enable different abstractions of modelling. It handles life cycle product perspective and allocates all emissions by one product.

A demonstrator tool is developed to test the functionalities. The tool is complimented by a handbook that guides the engineer through all project stages, including data acquisition, modelling, and analysis. However, this thesis recommends implementing the presented functionalities into existing commercial software, or continuing to develop of the demonstration tool.

7 Future Work

Future work to enable industry to benefit from the results includes.

- Methodology Validation
- Tool Development

The current version of the methodology is beneficial to most projects of this type. However, it still requires further validation and addition to be value adding and help prioritise activities. This thesis recommends using the methodology in additional cases and updating the procedure at the Wiki. This portal shares ideas with other practitioners and could potentially be an effective portal for continuous improvement of the methodology.

The developed demonstration tool needs further development. The main thing needed is more advanced ways to model production systems. This must be implemented without compromising the simplicity of the software. Furthermore, the demonstration tool needs a standardised database import with better ability to add own consumables. The demonstration tool needs a larger database, meaning that the impact categories could be extended. The goal so far has been to produce a demonstration tool with the purpose of showing how this could be made. The next step is to take the tool and accompanied methodology from TRL 6 to industry to higher TRL levels. Alternatively, collaborate with major simulation software developers to adapt their tool to the functionalities.

This thesis provides a base for future development of standards to assess manufacturing systems. Standards are important for companies in order to be efficient and to get the largest possible value from the assessments. If they can use a national or international standard for their assessment needs, this would be positive for the companies. A standard provides a better base for comparability and usage of results for marketing purposes.

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CASE STUDY 1

The first study was done with a market-leading manufacturer of packaging cans. They provide can packages used for food, paint and in technical chemistry industries. They also make bottles, bottle caps for cans and containers. The studied manufacturing unit produces cans ranging from 0,33l to 25l with a majority of the customers in the paint industry. The brand has a market strategy focused on an environmental image.

As a mean towards an even more sustainable company and brand, they wish to label their products with environmental metrics. This would enhance their environmental profile among their customers as well as creating an advantage over their competitors (Gallego-Álvarez, Prado-Lorenzo, Rodríguez-Domínguez, & García-Sánchez, 2010). Emballator anticipates similar restrictions and regulations as those already in place in the car industry, not only in their own field, but also in their customers' fields. Two practitioners therefore studied one of their main flow of products. The results from the case provide values that can be used to label a product with environmental emission using simulation.

Purpose and Study Focus

The main purpose of the first study is to test the first version of the methodology in total but roughly. However, it also focused also test and develop methods of how to calculate the emissions from the simulation output. As an extra task, the case studied and synthesised prerequisites for when to use simulation for environmental impact assessments.

Method

The practitioners received an initial methodology developed and extracted from the archive case analysis. They performed a case study at Emballator using the methodology and extra supervision. Experiences and notes from the execution were taken throughout the case at regular meetings.

The study used a literature study and experiences from the case to examine when it is appropriate to use simulation for an environmental impact assessment study. The prerequisites were discussed throughout the case with the research team.

The project and its results is in detailed documented in (Törnberg & Larsson, 2013).

Outcome and Experiences

The first result from the case regards whenever the methodology is applicable or not. The discussions resulted in several prerequisites that had be fulfilled in order to use simulation to perform environmental impact assessment.

PR1. Is the focus of the analysis a complex manufacturing system?

PR2. Are there enough available or collectible data to model the system?

PR3.1. Is there a need for detailed production flow analyses?

PR3.2. Is there an existing simulation model that can be used for the purpose?

Simulation of production flows is data intensive and often 1/3 of the time is spent on data management activities (Skoogh & Johansson, 2007). LCA studies are data intensive, too. In this case study, the total time spent on data management was 49 %.

During the implementation phase, there were problems associated with the simulation model. The company had many products a middle and finished storage. The developed simulation model kept all information of the use of manufacturing processes and resources by each product. This lead to a high amount of used internal memory during the simulation. Thus, the memory space used for the simulation was increased with a tweak by 50 %, but there were still some limitations to the simulation needed. A simulation tool using a 64-bit memory space was needed to expand the memory space even more. This high amount of data also slowed the simulation model. For similar cases with large and long storages, the product and list data structure in the simulation is important for simulation speed.

The case used a developed a calculation method for environmental emissions. The sheet use standardised output form the simulation model. The simulation model provides times for how long the product used resources. The sheet use information to calculate the used materials and energy (consumables) in the model. The used amount of consumables is then used calculate the emissions to produce them. The sheet adds up the consumables and emissions for one product, for each machine, and other resources. This why to calculate the emission in multiple steps are in this thesis called levelled calculations. Using levelled calculation, the practitioner had a larger potential to verify the calculations on each step. The result calculation sheet is transparent and can be injected with real result at each level. It took a large amount of time to develop this calculation sheet, however once it is done it is easier to expand and change it.

In highly processed material - such as metal - most environmental impact has already been emitted before it reaches the manufacturing site that produces the final product. This means that the emissions from the internal processes are very low compared to the emissions during the material production. Material that is wasted during manufacturing, such as clip spillage and quality problems, directly affects the material usage. Emissions for producing that extra material are usually allocated to the material. However, from a responsible point of view, it is the problem of the manufacturer and the purchaser that buy, use, and waste materials. In this study, the emissions were allocated to the manufacturing process. In the study, 49 % of the origin came from waste and quality problem, while 51 % came from other steps of manufacturing, including facilities and processes.

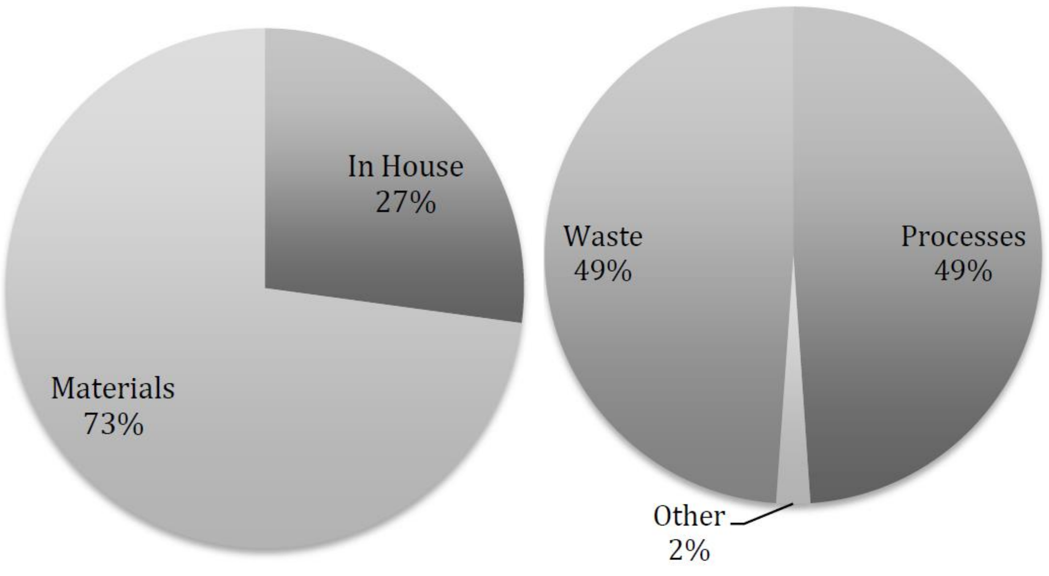

Figure 16 First figure visualises emissions from material compared to processes and wasted materials Second figure shows the relation between those.

Additional Result

As expected, the material was the largest contributor to the environmental impact. Consequently, material scrap was the largest contributor to environmental impact among the controllable sources of the manufacturing system. The second largest contributor was the ovens for heat treatment. The company received information regarding the environmental impact of the product and their production system. By being aware of the large contributors, the system perspective changes and is able to guide them while purchasing material and improving processes.

Case Study 2

The second case is for an automobile subcontractor. The company produces few products but supplies them to many car manufacturers. The processes are stable and heavily atomised. The amount of manual handling of products is comparable to the previous case at Emballator, and mainly consists of adjusting, loading, unloading, set-up, and storage operation.

The studied production line produces break discs. There are eight variants of break discs manufactured at the line. Compared to the case at Emballator fewer variants simplify data collection, modelling, and validation.

Research Purpose and Study Focus

This case has two purposes: to continue the methodology development and to test and verify a developed tool.

The improved methodology of **Case Study 1** was tested and further improved and generalised. The study focuses on the start-up phase of the methodology, including all steps until implementation.

Collected data and results from this case were used during the development phase and for early verification. The purpose is to develop a working tool able to analyse this type of serial and atomised manufacturing. The tool, a handbook for the tool, and the methodology developed during Case Study 1 and Case Study 2 used a Wiki (Andersson, 2013) to synchronise the work and to document the results.

Method

Two simulation experts advised by the researcher assessed the environmental impact and productivity potential of the company using the methodology from **Case Study 1**. The simulation experts participated every two weeks in meetings with the researcher. The meetings included discussions on recent progress and problems. Everyone discussed how to improve the methodology and how future projects can avoid the same problems. The discussion ended by summing up changes and additions to the methodology. The case study was in detailed documented and presented in Andersson and Dettmann (2013).

The changes and methodology discussions form the Wikimedia webpage. The researcher added changes to the specific sections affected by these changes.

Parallel to this, the researcher implemented the tool presented in this thesis. Important implications and practice in the implementation and data collection phase of the Case study became the input to the user interface and structure. The tool was verified by using the same input data collected by the simulation experts and compared the results from the tool with their study, which implies that their implementation was correct.

Four students documented the functions of the tool on the Wikimedia page. The researchers review and discuss the contents and consider the implications from the running case (Hedström Kuosmonen, Isaksson, Jansson, & Karlqvist, 2013).

Outcome and Experiences

This Case study contains three main outcomes:

- The study described a start-up methodology for simulation of production flows for LCA cases (Dettmann et al., 2013)
- A improved methodology, presented in this thesis
- A Wiki containing the methodology and tool handbook(Andersson, 2013; Hedström Kuosmonen, Isaksson, Jansson, & Karlqvist, 2013)

It is not always a straightforward process to add consumption data to a simulation model. The states used for the dynamic representation could potentially have a bad mapping of the consumption of the process. The energy consumption needs the process modelled in higher resolution in order to make a correct representation. Imagine a turning machine with a separate feeding system; such process electrical load profile could be something like Figure 17. The machine can be modelled as a delay where the feeding system and the machine time is the total delay. The simulation model calculates the energy consumption by multiplying the average energy consumption times the delay. However, if another variant have a different machining time this will drastically give a different energy consumption. The engineer must collect energy consumption for each variant. Additionally, the modeller cannot compare different feeding systems without recalculating the energy consumption per variant. Thus, a simulation in LCA approach needs to model manufacturing processes in different states as loading, setup, processing, broken down and idle. All studied processes of the assessment must be modelled in detail and according to the process type.

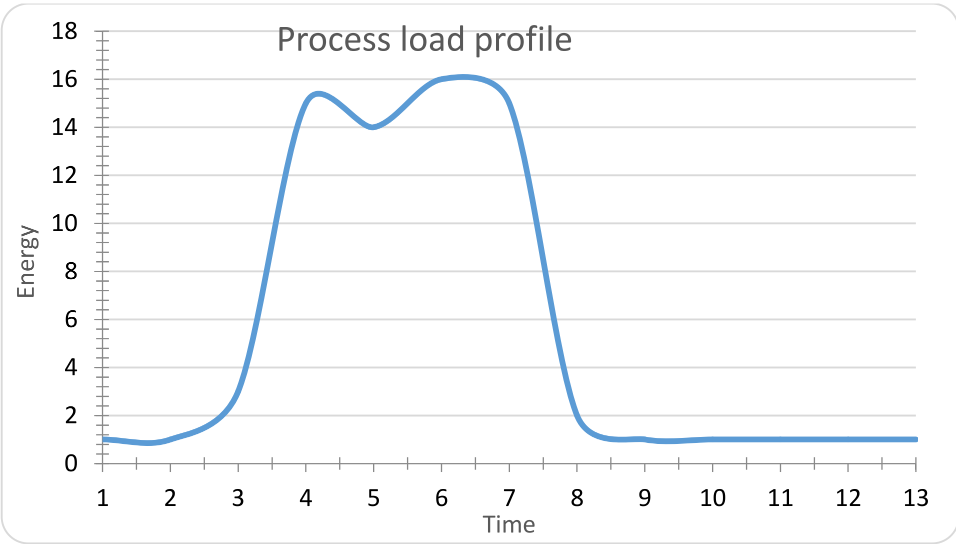

Figure 17 Fictive load profile with loading and unloading states, loading time 1-3, unloading 8-13

Company Outcome

During the case, the practitioners were able to provide a detailed analysis of the current system. To lower the environmental impact or raising current capacity the practitioners proposed and ranked solutions. In the same analysis, the different alternatives were judged from both an economic and environmental perspective.