Evaluating environmental impacts of production process by simulation based life cycle assessment

Yu Liu[1], Anna Syberfeldt[1], Matias Urenda Moris[1], Mats Jägstam[2], Jenny Everbring[3], Henrik Kloo[3]

[1]University of Skövde, Department of Engineering Science, Skövde, Sweden

[2]Jönköping University, School of Engineering, Jönköping, Sweden

[3]Volvo Group, Advanced Technology & Research, Gothenburg, Sweden

yu.liu@his.se

Abstract

Historically, the manufacturing industry is one of the main contributors to the environmental issues. With conservation of the environment becoming more and more critical for survival, it is of importance for the manufacturing industry to take responsibility for minimizing their productions' environmental impacts. Life cycle assessment has been widely used in the product's development phase within the manufacturing industry. However, the environmental impacts that come from various dynamic manufacturing processes are only estimated with large uncertainty. Some studies have suggested that the combination of life cycle assessment and production flow simulation is an appropriate approach to address the environmental impacts from the manufacturing processes. Nevertheless, these studies are often limiting their concerns to the limited life cycle phases or certain environmental impacts. This study proposes a framework regarding how to develop a method for evaluating and identifying improvements that help reduce the life-cycle environmental impacts of complex production processes. In addition, this work employs a simplified case study to demonstrate the proposed framework.

Keywords: Life cycle assessment, discrete-event simulation, simulation based optimization.

1. Introduction

From the first United Nations Environmental Programme set up in 1972 to the recent United Nations Climate Change Conferences in 2015 [1], environmental issues have been recognized as one of the main limiting factors in future development of humanity [2]. As one of the main contributors to the environmental problems, the manufacturing industry needs to take responsibility and minimize their environmental impacts. On the other hand, innovated products with substantially improved environmental performance are more and more attractive in the market. Moreover, legislations are pushing forward to reduce the negative environmental consequences of production of goods [3]. Thus, properly addressing the environmental impacts of production processes provide not only challenges but also opportunities for the manufacturing industry.

Life cycle assessment (LCA), a method for evaluating the potential environmental impact of a product throughout its life cycle [4], has been widely utilized in the product's development phase within the manufacturing industry. However, LCA of the production system and/or production processes has often given uncertain results and moreover it has not serve as a suitable tool for identifying improvement areas. A main reason is the methods inability to correctly monitor the dynamic characteristic of production processes [5]. Some studies suggest the combination of LCA and discrete-event simulation (DES) as a better approach to address the dynamical nature of manufacturing processes. Nevertheless, these studies have often been limited to the assessment of manufacturing processes' electricity consumption and CO_2 emission, while other considerable environmental impacts, such as volatile organic compounds (VOC), waste material scrap, waste water etc. are often ignored [6, 7].

This study proposes a framework regarding how to develop a process LCA method, which uses a DES based LCA approach to evaluate the environmental impacts of complex production processes. This combination also allows to reduce the overall environmental impact from production processes by using simulation based optimization of the whole system.

1.1. Aim

The aim of the proposed framework is to evaluate and identify improvements that help reducing the life-cycle environmental impacts of complex production systems within automotive industry. The outcome of the work is to increase the awareness of sustainability in automotive industry and help to evaluate and improve the environmental performance of production activities.

1.2. Objectives

The overall aim is broken down into following sub-objectives.

- Identify important parameters to be considered when developing the process LCA method, including both input and output data.
  The input data includes the extractable data from the production flow simulation model and required additional information for calculating lifecycle environmental impacts. The expected output data includes a set of key performance indicators (KPI) for evaluating the life cycle environmental impact.
- Develop a process LCA method based on identified parameters, for evaluating the life-cycle environmental impact of production systems.
- Implement and validate the developed process LCA method in real-world cases: energy-intensive and chemical-intensive production processes. Based on the results from the case studies, prioritize and adjust the

important parameters that can improve the reliability of the method.

- Identify improvements to help reduce the environmental impact of production systems by optimization, based on practical constrains of the input data and the developed process LCA method. The optimization is achieved by the ranging the input data with consideration of all the practical constrains to achieve the lowest possible
- Evaluate the applicability of the life cycle environmental impact optimization in the automotive production processes. Provide suggestions from the optimization results to improve the environmental performances of the production activities.

1.3. Delimitation

As the project is performed in close cooperation with Volvo Group, the scope of the project is limited to the automotive industry and its related production processes. The developed process LCA method might therefore need to be modified if applied in other problem domains.

2. Theoretical framework

2.1. Life cycle assessment

LCA is a method for gathering and evaluating potential environmental impacts of a product throughout its life cycle [4]. The life cycle includes the extraction of resources, processing of materials, product manufacturing, use, maintenance as well as end-of-life. The result of LCA can be used for decision making, product development, communication, etc. [8].

To illustrate the framework of the LCA method, the structure of the LCA methodological is shown in Figure 1. It contains four different steps including definition of goal and scope, life cycle inventory analysis, life cycle impact assessment as well as their interpretation.

In the first step, definition of goal and scope, the aim, the scope and the limitations of the LCA study are defined. How to model the system is also specified in this step, e.g. defining system boundaries and what types of impacts to be evaluated, which will set requirements on the data collection. In the second step, life cycle inventory analysis, data related to in- and out-flows of materials as well as energy for the different activities are first collected, followed by calculating the elementary flows (resources, emissions and wastes) of the

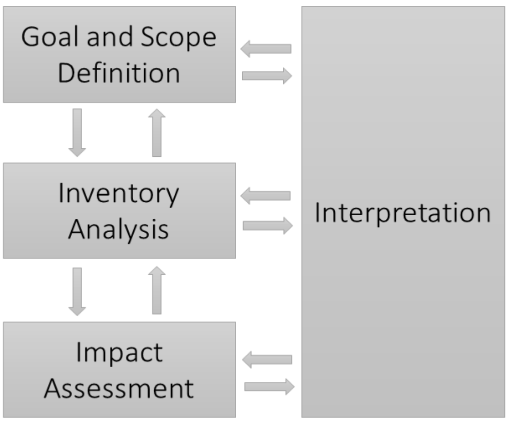


Fig. 1: *The structure of LCA methodology.*

defined system's functional unit. Life cycle impact assessment is performed as the third step, in which the elementary flows are assigned to pre-selected impact categories (classification), such as global warming, acidification etc. Indicator results are then calculated for each category (characterization). Interpretation is a parallel action that interacts with all other three steps to evaluate and summarize the assessed environmental impact and determine the level of confidence in the final results and communicate them in a fair, accurate, and systematic manner. The outcome of the interpretation phase is a set of conclusions and recommendations for the study [4, 9].

LCA is widely used in the product development phase, however, its static nature [5] limits its application in assessing environmental performance of dynamic industrial manufacturing processes, which shares an important part of environmental impact and need to be accurately assessed with help from DES.

2.2. Discrete-event simulation based life cycle assessment

DES models a dynamic system's operations as a discrete sequence of events in time. Each event occurs at a particular instant in time and marks a change of state in the system [10]. This provide a static view of a dynamic process and allows LCA studies to be performed on a dynamic process.

The first incorporation of environmental consideration into DES was introduced in 2000 by Wohlgemuth and Page [11]. In this study, a material flow simulation (a similar method as LCA) is performed using DES and both economic and ecological factors of a production process are evaluated. Later, some other studies [7, 12-14] used a similar approach but they mainly focused on evaluating the energy efficiency of systems. A broader application of DES based LCA studies requires further exploration and as [15] suggests the method should only be applied to processes which the company has a full control of. In addition, a recent study [5] also proposed a set of functionalities, such as modelling simplification and engineer guidance, for DES software to support LCA studies.

2.3. Simulation-based optimization

Simulation-based optimization is the process of finding the best inputs for a system, in which the output performance from a simulated system model is evaluated [16]. It is an interactive process, similar to numerical approximation, in which an optimization algorithm repeatedly uses a simulation model to evaluate a set of outputs based on a set of inputs and form a solution. In each iteration the optimization algorithm uses the solutions generated in previous iteration(s) to predict better inputs to be used in the current iteration. The iteration continues until some boundary conditions are reached [17]. The sets of inputs for the first iteration are usually randomly generated. For hard problems the performance can be sensitive to the initial sets of inputs. For this reason, having some background knowledge of the problem can be beneficial to initialize sets of inputs.

The simulation model can often be seen as a black-box function evaluator between input parameters and output values [18]. Thus, the system model and the optimization algorithm are often completely separated, which allows the optimization algorithm to be applied in various different system models [19]. This, however, limits the used of the optimization algorithm to problem-specific information [18]. Evolutionary algorithms developed from biological theories of genetics and reproduction are often used in optimization of black-box models [20].

3. Research methodology

3.1. Research strategy

This project uses design and creation as the main research strategy. Other strategies, such as case study and experiment, will also be used as supplementary strategies to address some parts of the research questions but is not of main focus in the research strategy. The research strategy is designed based on the information systems (IS) research framework [21] and also shown in Figure 2.

Research environment is the first aspect to be addressed. From the research environment, the driving force of the research topic, defined as the business needs, are analysed from three different perspectives: people, organizations and technologies. Results of the analyses will help framing the research activities to address the needs and assure research relevance to appropriate context [21]. In this project, the business needs are clearly addressed as it is initiated in cooperation between the automotive industry and the academy. In addition, from the technology aspect, the well-established LCA and DES have rarely been combined to assess the production processes although both technologies can benefit from each other to provide more insights of production activities. Thus, business needs are clearly represented in the framework.

In terms of the IS research activities, the design and creation strategy is often applied when developing new IT products, also called artefacts. There are four types of IT artefacts: constructs, models, methods and instantiations [22]. In case of this project, a method that used for process LCA studies will be developed as main part of project outcome.

Four of the research activities suggested in [21] need to be involved in this research framework: develop, build, justify, and evaluate. Among these, build and develop are considered as design science and focused on improving performance of the developed artefact, whereas justify and evaluate are characterized as natural science and targeting at extracting general knowledge [22].

The research strategy is strongly connected to the distinction between research outputs and research activities, where interaction between design science and natural science will be involved [21]. Design science produces and apply knowledge of tasks or situations to create effective method for process LCA studies. Natural science produces general theoretical knowledge of process LCA and supports design science technique solutions. Several case studies will eventually be utilized to verify, evaluate and improve the developed process LCA method and reduce the environmental impact.

As a research project, this work will not only provide technical answers to certain questions, but also demonstrate academic qualities related to analysis, explanation, argument, justification and critical evaluation [23]. These activities will lead to new, general theoretical knowledge as well as insights in a new application domain. So far, the process LCA studies have not been performed in the automotive industry to optimize the environmental performance of different production processes. Thus, this project will not only help the industry by demonstrating the advantage of quantifying and optimizing the life cycle environmental impacts but also contribute to improve the theoretical level of understanding.

3.2. Data collection and analysis

Large amounts of various data are required in the project and data collection and analysis techniques are therefore of importance in the project. The following subchapters discuss how the data will be collected and analysed.

Data collection

Two main data collection methods will be used in the project: documents and interviews.

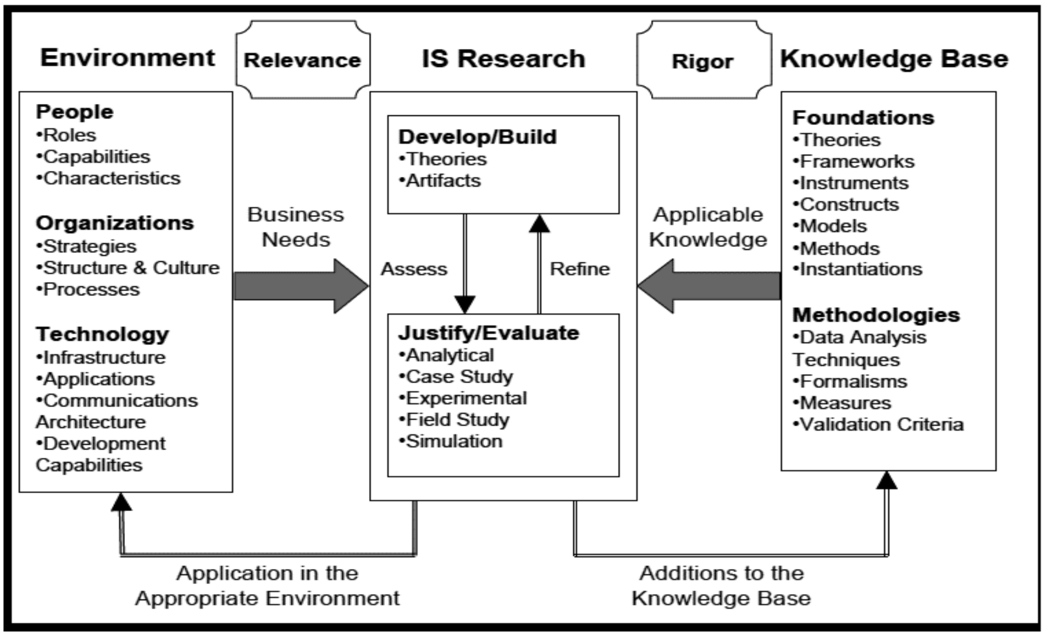


Fig. 2: *Information system research framework.*

Two types of documents are involved: found documents and researcher-generated documents. The found documents exist prior to the research, such as production schedules, internal documents in an organization and academic literature etc. The researcher-generated documents refer to data that only exist for the purpose of the research, such as models and diagrams that have been designed and obtained during the research activities [22].

Documents will be the main data source in the project. In terms of found documents, policy related documents will be used to identify the needs of the input and output parameters. Production-related data will be obtained from production logs and simulation models. The life-cycle environmental impact will be calculated from data that is collected from academic literature and LCA databases. In terms of researcher-generated documents, many models and diagrams are produced during the whole study and these are important to demonstrate and evaluate the design processes.

As a supplementary method to the documents this project will use interviews. An interview is a conversation between people that aims at acquire specific information from others. There are three types of interviews: structured interviews, semi-structured interviews and unstructured interviews [22]. This project will mainly use semi-structured interviews, which allow the interviewee to express their ideas within a specified area. Semi-structured interviews can be used to gain knowledge about the production activities to be studied.

Data analysis

Both quantitative and qualitative data analysis will be used in the project. In the validation step, the experiments and case studies will generate large amounts of data, which is more suitable for quantitative analysis. The analysis can determine whether the developed method can correctly pinpoint environmental hot-spots based on comparisons of other evaluation methods. The analysis can also indicate how much improvement that is possible to achieve. In addition, the use of various tables, charts and graphs to visualize the results facilitate recognizing patterns in the results.

A qualitative analysis is more applicable in the optimization of production processes, in which choice of different production processes or use of different materials need to be decided to reduce the environmental impact.

4. Case study

To demonstrate the application of the proposed method, a case study considering a painting process including both chemical intensive (paint) and energy intensive (oven) aspects of a production process is presented in this chapter. The identified input and output data for the case are shown in Table 1. The input data includes both the extractable data from the simulation model and the required information, collected from a LCA database, for calculating life cycle environmental impacts. The output data including both production flow simulation results (lead time and throughput) as well as the life cycle environmental KPIs.

Two production steps, painting and drying, are considered in this painting process:

In the painting step, the environmental impacts of energy and paint usages are considered. In addition, there is also impact from the cleaning of painting machines, which is required when changing colours and this is also included in the assessment. For the drying step, the impact that come from the use of energy for heating the oven is considered.

For all the steps, the assessments are addressing not only the on-site impact from the factory, but the impacts that are generated by the energy and material suppliers are also included.

In the basic scenario, the factory uses solvent based paint and the painted products are dried in the oven fuelled by liquefied petroleum gas (LPG), due to demand of high drying temperature. Therefore, this scenario is selected as the reference for comparing to other alternatives. Solvent based paint contains large amount of VOC, which is one of the main environmental impact. To reduce such impact, an alternative is to use water based paint, which can substantially reduce VOC emission. By changing to water based paint, demands on drying temperature is reduced. This provide an opportunity of using district heating instead of LPG, which may further reduce the impacts from energy usage as district heating is often biomass fuelled. Therefore, two alternatives, water based paint + LPG and water based paint + district heating, are compare with the most commonly used solvent based paint + LPG in the painting process.

Figures 3 shows a comparison of the two alternatives and the basic scenario, which is normalized to 1, with respect to the two environmental impacts as well as the lead time. The results of the supplier, factory as well the total result also compared. All the calculations are based on the same amount of throughput.

For VOC emission, both alternatives reduce the impact in both supplier and factory, in which water based paint + district heating has the lowest emission. For CO_2 emission, both alternatives reduce the total CO_2 emission, however, for the water based paint + district heating solution, the CO_2 emission increases at the suppliers. The impact has been shifted due to

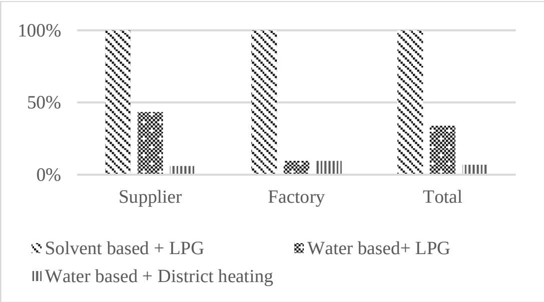
Table 1: *The identified input and output data for the case study of a painting process.*

Data group	**Data name**	**Data source**
Input data		
From simulation model	Processing time	Simulation model (normalized)
Additional information for calculating life-cycle environmental impacts	Energy and material consumption	Production logs (normalized), literature data
	Life cycle inventory data for producing energy and material	LCA database
	Emissions from the processes	Production logs (normalized), literature data
Output data		
Production flow simulation results	Lead time, throughput	Calculated
Life cycle environmental KPIs	CO_2, VOC	Calculated

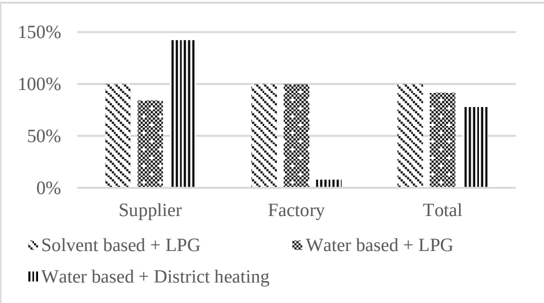
the emission of LPG is allocated to the factory whereas emission of the district heating is allocated to the supplier.

For the total lead time, both alternatives can provide shorter lead times, but the water based paint + LPG has the shortest lead time. However, the best performance in environmental impacts is achieved with the water based paint together with district heating.

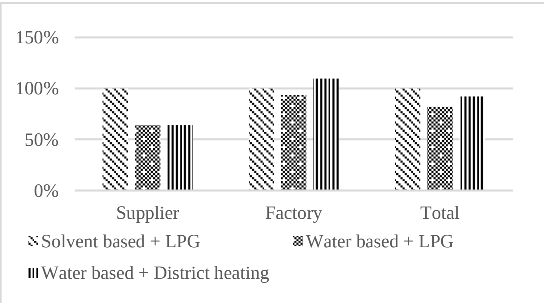
With this case study, we demonstrate different alternatives that could help to reduce the environmental impacts meanwhile taken into consideration other important aspects for a production process, such as lead time, throughput and cost. Insights like these can support decision making and aid industrial actors in make the right choices.



VOC emission.



CO_2 emission.



Lead time.

Fig. 3: *Comparison of three different scenarios in painting process with respect to environmental impacts as well as lead time.*

5. Conclusions and discussions

This paper suggests a framework for the development of a method that make it possible to obtain the lowest possible environmental impact KPIs of production processes as well as evaluation other aspects that is important for decision making within industry. The proposed method is based on production flow simulation and life cycle assessment methodology and combines the strengths of both these.

The proposed framework is demonstrated through a case study which considers a painting process that includes both chemical intensive and energy intensive steps. In the case study, extractable data from a production flow simulation model is first identified and additional information is acquired for calculating environmental impacts as well as setting up KPIs for evaluating the life cycle environmental impacts of the process. By considering and comparing different possible scenarios the optimized environmental impact KPIs are provided together with consideration of other important aspects of production process, such as lead time.

6. Future work

Future studies will focus on developing a software based toolbox that provides a process LCA method to bridge between the acquired input data and the output KPIs. In addition, applicability analysis of the life cycle environmental impact optimization will also be further performed in two key full scaled automotive production processes, chemical intensive and energy intensive. Based on optimization and applicability analysis suggestions will be provided to the industry to improve their environmental performances of these key production processes. From the results, important insights from two process LCA case studies of energy intensive and chemical intensive production processes within the automotive industry will also be generated and abstracted for academic purposes.

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