Review of simulation-based life cycle assessment in manufacturing industry

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ABSTRACT
The manufacturing industry has a duty to minimize its environmental impact, and an increasing body of legislation mandates environmental impact evaluations from a life cycle perspective to prevent burden shift. The manufacturing industry is increasing its use of computer-based simulations to optimize production processes. In recent years, several published studies have combined simulations with life cycle assessments (LCAs) to evaluate and minimize the environmental impact of production activities. Still, current knowledge of simulations conducted for LCAs is rather disjointed. This paper accordingly reviews the literature covering simulation-based LCAs of production processes. The results of the review and cross-comparison of papers are structured in terms of seven elements in line with the ISO standard definition of LCA and report the strengths and limitations of the reviewed studies.

1. Introduction

Environmental issues concern everyone’s daily lives and were identified at the 2015 United Nations climate change conference as among the major factors limiting future human development (United Nations, 2016). Like many other industries, the manufacturing industry has been obliged to reduce its environmental impact, for example, by regulations related to carbon dioxide emissions. Nowadays, legislation is also pushing from the life-cycle perspective, which implies that the environmental burdens of a product need to be considered throughout its entire life cycle rather than the burden only from the usage of the product (European Commission, 2011). This however put more pressure on the manufacturing industry. Besides the legal compliance aspect, many companies have realized that there are positive branding and marketing opportunities related to having an environmental strategy. From a life cycle perspective on the production process, environmental impact reduction provides not only challenges but also opportunities for the manufacturing industry.

Life cycle assessment (LCA) is a common way to assess the environmental impacts of a product throughout its life cycle (ISO, 2006a). It is widely accepted as part of the product development phase, but if applied in the production process, it often results in uncertainties and may therefore not serve as an appropriate tool for identifying ‘hotspots’. One main factor...
hindering the application of LCA in the production phase of the product life cycle is the dynamic nature of production processes (Andersson, 2014). Several studies have suggested using a combination of simulation and LCA to evaluate the environmental impacts of production processes while addressing their dynamic nature. However, as the current literature is scattered, to obtain a more comprehensive understanding of the proposed methodology and its applicability, this paper presents the results of an extensive literature review covering 27 selected scientific papers on this matter. The intention is to provide independent and applicable information and suggestions for both academics and industry.

2. Methodology

This paper reports a structured review (Tranfield, Denyer, & Smart, 2003) of simulation-based studies of LCA as applied in the manufacturing industry. The review is intended to provide an overview of existing studies and perform an independent technical review of both the relevant academic research as well as industrial applications.

The time frame is 2006–2018, as the mainstream LCA standards (ISO, 2006a, 2006b) were published in 2006, and these standards were used as the basis for determining the reviewing criteria elaborated on below.

The online scholarly databases ScienceDirect, Scopus, and Web of Science were used for the literature search. Table 1 shows the search strings used to identify the relevant studies. These words were combined with the Boolean expression ‘AND’ to capture all possible relevant combinations in the search fields of the topic, title, abstract, and keywords in the selected databases, in order to identify the relevant studies. To ensure full coverage, additional relevant articles were identified through the manual screening of cross-references.

Within the searched literatures, only studies focusing on comprehensive environment assessment are considered here; for example, studies focusing on electricity modeling without considering life cycle aspects are excluded.

The detailed selection process, shown in Figure 1, identified a total of 27 articles for review. These papers were organized in a table, and a common way of classifying them was sought in accordance with the ISO standards (ISO, 2006a, 2006b) for LCA. The selected papers were reviewed in terms of the following seven elements: goal formulation, scope definition, level of modeling detail, verification and validation, data collection, life cycle inventory and impact, and means of communication. More detailed review and discussion based on these elements are presented in the ‘Results’ section.

3. Results

The selected articles can be divided into three groups according to their methodology, as shown in Table 2. Methodology development and case evaluation is the most

| Table 1. Search strings. | Simulation | Manufacturing |
|--------------------------|------------|--------------|
| Life cycle assessment    | Simulation | Manufacture* |
| LCA                      | Discrete   |              |
| Life cycle assessment    | Event      |              |
| Life cycle analysis      | Agent      |              |
|                          | System     |              |
|                          | dynamics   |              |
common approach. These studies concentrate on quantitative evaluation, often first proposing a methodology and then demonstrating the methodology via a case study. The second largest group is conceptual work, in which the studies propose ideas at an abstract level without detailed practical case application. The articles in the literature review group summarize previous work. All the reviewed articles and their applied methodologies are listed in the Appendix.

### 3.1. Goal formulation

In accordance with the ISO standards (ISO, 2006a, 2006b), goal formulation is examined based on three criteria: intended application, reasons for conducting the study, and intended audience. Most of the studies report the intended application, and the major applications are: learning about the life cycle, supporting product development, and supporting manufacturing strategy. In terms of the reasons for conducting the study, two general questions are often addressed in the studies: ‘What process contributes the

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Table 2. Study methodologies.

| Methodology                                      | Percentage |
|-------------------------------------------------|------------|
| Literature review                                | 11%        |
| Conceptual work                                 | 33%        |
| Methodology development and case evaluation     | 56%        |

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Figure 1. Steps in the literature search.
most to the environmental impact?’ and ‘What manufacturing configuration has the least environmental impact?’

Concerning the intended audience, 81% of the studies define their audience as ‘stakeholders/decision makers’ or do not specify it. Some exceptions were evident in the review, with, for example, production engineers (Andersson, 2013; Paju et al., 2010), engineering managers (Orji & Wei, 2016), and production planners (Schönemann, Schmidt, Herrmann, & Thiede, 2016) being defined as the intended audience. In addition, the actor’s perspective could be included in the goal definition (Löfgren & Tillman, 2011), as actors can directly influence the environmental consequences of their production processes.

3.2. Scope definition

We examined the scope definition using two criteria: functional unit and life cycle phases (ISO, 2006a). The traditional schema of life cycle phases in the ISO standard (2006a) include raw material acquisition, manufacturing, use, and end-of-life (i.e. waste treatment, recycling, and final disposal), and is considered as a cradle-to-grave approach. Most of the reviewed studies follow the traditional schema however, two studies use other classification methods: Heinemann et al. (2014) divide the factory system’s entire life cycle into the building setup, machine usage, technical building shell usage, and building disposal phases, whereas Orji and Wei (2016) define six phases of a product, comprising the development, manufacturing, operation, maintenance, decoupling, and waste collection stages.

As shown in Table 3, all the reviewed studies cover the manufacturing phase, since our review focuses on the LCA of manufacturing processes. In addition, 64% of the studies also cover the raw material acquisition phase, including the production of the direct raw material for the product. The use and end-of-life phases are often disregarded because manufacturing companies have limited influence on them and because of the difficulty of collecting relevant data (Andersson, 2013).

The functional unit is the basis for evaluating and comparing LCA results (ISO, 2006a). Of the reviewed studies, 21% explicitly define the functional unit and 25% do not specify any functional unit. In the other 54% of studies, the functional unit could only be extracted from the context. In the various functional unit definitions, ‘product’ or ‘production processes’ are the most commonly used terms. In terms of the product, the evaluations are based on a certain number of products, whereas for the production process, assessment is based on production activity in a certain time period.

| Life cycle phases       | Percentage |
|-------------------------|------------|
| Raw material acquisition| 64%        |
| Manufacturing           | 100%       |
| Use                     | 18%        |
| End of life             | 23%        |
| All                     | 18%        |
3.3. Level of modeling detail

The level of modeling detail determines the accuracy of the simulated manufacturing processes, directly influencing the accuracy of the obtained LCA results. The level of modeling detail is surveyed based on three sub-categories: production variants, supporting systems, and machine working states.

Regarding product variants, only 21% of studies consider the contributions of different product variants; others either consider just one type of product or the products are so similar that their differences can be neglected. However, the energy consumption and auxiliary material usage in producing different variants may vary significantly, directly influencing the environmental impact.

During production, the machines always work with various supporting systems, ranging from basic pumps to advanced auxiliary systems. As all these supporting systems consume energy and therefore have emissions, they must be specified for the detailed calculation of LCA impacts. Of the reviewed studies, 54% do not consider any contributions from supporting systems, while others consider various support systems, such as auxiliary materials (Bengtsson, Michaloski, Proctor, Shao, & Venkatesh, 2010; Paju et al., 2010), air compressors (Heinemann et al., 2014; Löfgren & Tillman, 2011; A. Sproedt, Plehn, Schönsleben, & Herrmann, 2015), and shielding gas and welding rods (Andersson, Skoogh, & Johansson, 2011).

In most production processes, machines are not always in a busy state, so consideration of different machine states may have significant impacts on LCA results. About one third of studies do not consider the machine states, another third consider only busy and idle states, and the rest consider three or more machine states.

3.4. Verification and validation

Model verification and validation are critical steps to ensure the reliability of both simulation and LCA models, and over 80% of the reviewed studies do not explicitly report these steps. Verification is often defined as ensuring that ‘the model is correct and matches any agreed-upon specifications and assumptions’, whereas validation is often defined as ensuring that ‘the model represents the real system to a sufficient level of accuracy’ (Carson, 2002). Of the reviewed studies, two (Andersson, 2013; Kim, Shin, Shao, & Brodsky, 2015) acknowledge the importance of verification in simulation-based LCA, but do not provide any practical guidance. One study notes that the simulation-based LCA model can be verified by reviewing the critical processes in real manufacturing activity (Lindskog et al., 2011). Another study conducts verification on the enterprise, shop floor, and operation levels (Zhang, Amodio-Calvo, & Haapala, 2013).

According to an ISO standard (2006b), LCA results should be validated by external reviewers. However, possibly for practical reasons, none of the studies fulfils this requirement. Nevertheless, 29% of the reviewed studies perform internal validation reviews, and their approaches to doing so are analysed as follows.

In the case of simulation-based LCA validation, as most of the environmental impact calculations are based on data extracted from a production simulation model, it is important to validate the process simulation model before validating the LCA results.
Four studies validate their production model (i.e. the production part) against historical production data (Lindskog et al., 2011; Löfgren & Tillman, 2011; A. Sproedt et al., 2015; Zhang et al., 2013) and one study uses a mathematical approach to validation (Kim et al., 2015). When it comes to LCA model validation, two main approaches are applied: validating against the results of traditional LCA (Andersson, et al., 2011; Lindskog et al., 2011) or against historical production data (Löfgren & Tillman, 2011; A. Sproedt et al., 2015; Zhang et al., 2013). In all, two models must be validated in simulation-based LCA studies. The validation of manufacturing process models against historical data seems to be common, although the LCA model validation must be enhanced based on the results of external review.

3.5. Data collection

Two types of data are needed for simulation-based LCA studies: production-related data (e.g. processing time and availability) used in describing the production process, and environmental data (e.g. electricity consumption, material usage, and waste) used in environmental impact calculation. Table 4 presents the data sources used in the reviewed studies. For production-related data, most studies use a mixed data collection approach in which measured data are used whenever available, and some studies even use real-time monitoring for data collection (Bengtsson et al., 2010; Mani, Johansson, Lyons, Sriram, & Ameta, 2013). For data that are difficult to obtain from field measurements, historical data are often used. The preferred approach is to use estimated data based on previous knowledge or obtained from simulation results, including dummy production data used in methodology demonstration. However, 17% of the reviewed studies do not specify their data sources. For the LCA-related data, as for the manufacturing data, measured data are preferred, and 42% of studies use such data. The second most popular approach is to use the results of production simulation models. In this approach, the material or energy consumption figures obtained from a production simulation model are scaled according to the predefined functional unit and applied in LCA studies (Andersson, et al., 2011; Smolek, Leobner, Heinzl, Gourlis, & Ponweiser, 2016). Over half the reviewed studies use a combined approach, as it is often difficult to collect all the desired data using any single approach.

3.6. Life cycle inventory and impact assessment

According to an ISO standard (ISO, 2006a), ‘LCA considers all attributes or aspects of natural environment, human health and resources’, so LCA results can be presented in numerous ways. For example, life cycle inventory (LCI) results specify detailed

| Data collection approach        | Manufacturing | LCA |
|--------------------------------|--------------|-----|
| Measured data                  | 33%          | 42% |
| Historical data                | 33%          | 29% |
| Estimated data                 | 58%          | 17% |
| From simulation model*         | -            | 33% |
| Literature data                | 8%           | 8%  |
| Data source not mentioned      | 17%          | 21% |

Note: The data collection approach is evaluated separately, i.e. several approaches can be applied in one study.
substance flows of resources and emissions, whereas life cycle impact assessment (LCIA) results convert the LCI results into a common unit specified in the defined impact categories, such as climate change, ozone depletion, and resource depletion. Our review of LCI and LCIA studies is based on whether the studies report their results in terms of energy, waste, climate change, or any other additional impact categories, and the results are shown in Table 5.

Energy consumption is the most common indicator considered when assessing manufacturing processes. As electricity is the major power source for machines, electricity consumption is addressed in all studies. Other forms of energy, such as oil, gas, or other thermal energy, are also addressed in one quarter of the studies.

Regarding waste, 54% of studies take this factor into consideration. Of these studies, five (Harun & Cheng, 2011; Löfgren & Tillman, 2011; Muroyama, Mani, Lyons, & Johansson, 2011; A. Sproedt et al., 2015; Zhang et al., 2013) consider waste as losses of direct material (e.g. scraps and paints), and the rest consider the importance of waste but without specifying the exact type.

Concerning the impact assessment, 71% of the studies report the impact in terms of climate change, though most of them only calculate the kilograms of CO$_2$ equivalent based on electricity consumption. A few exceptions can be found, namely, three studies (Bengtsson et al., 2010; Heilala, Paju, Montonen, Hentula, & Heikkilä, 2010; Kim et al., 2015) that consider NOx when performing impact assessment in terms of climate change. However, other on-site emissions are often ignored. Only one study (Harun & Cheng, 2011) reports the volatile organic compounds emitted by the painting process.

Regarding other impact categories besides climate change/GHGs, 17% of the reviewed studies consider them but in an implicit way. These are often conceptual studies addressing only the impact categories that can be considered without quantitative evaluation. Nevertheless, one study (Brondi & Carpanzano, 2011) presents comprehensive LCIA results specified in 11 impact categories. Moreover, six studies link the inventory and impact assessment with economic valuation, the monetary indicators they have addressed including eco-efficiency (Alexander Sproedt, Plehn, & Hertz, 2013; A. Sproedt et al., 2015), environmental activity based cost (Andersson, et al., 2011) and energy/material related cost (Bengtsson et al., 2010; Heilala et al., 2010; Paju et al., 2010).

### 3.7. Means of communication

As one of the most critical aspects of LCA studies, means of communication concerns how results are presented and communicated. The means of communication used in the reviewed papers are summarized in Table 6.
Graphic presentation is the most common communication approach as it is the most intuitive, and it is often used in presenting results at the LCIA level. Of the different types of graphic representation, the bar chart is the most preferred in the reviewed studies. Results can be shown in the stacked bar format to represent the environmental contributions of different life cycle phases, materials used, machine states, etc., to help identify the significant items, as shown in Figure 2, a typical bar chart. Tables are the most effective way to present extensive detailed data, and they are used in one quarter of the reviewed studies, mostly to present LCI-level data. Only one study uses text to communicate the results, an approach that limits the efficiency of the data presentation. In addition, 29% of the studies do not present any quantitative results, as they are mostly conceptual in nature and present their methodologies without any quantitative analysis.

4. Discussion and conclusions

This study reviews papers in the area of simulation-based LCA in manufacturing that have been published since 2006. The aim of the review is to evaluate and discuss the characteristics of the methods used as well as the obtained results. The reviewed papers are classified and evaluated considering seven elements in accordance with the LCA standards. The obtained results are discussed and conclusions are drawn as follows.

The goal is often defined in the first step of an LCA study, though due to the lack of a systemic understanding, often only vague and broad questions are formulated. This often causes unnecessary complexity in the system modeling. To improve on this, an iterative goal definition process could be applied, and the goal can be refined as the system is better understood and/or the critical issues are identified. Moreover, the

Table 6. Review results concerning means of communication.

| Means of communication | Type   | Percentage |
|------------------------|--------|------------|
| Bar chart              | Graphic| 33%        |
| Pie chart              | Graphic| 4%         |
| Dot chart              | Graphic| 4%         |
| Line chart             | Graphic| 4%         |
| Table                  | Table  | 25%        |
| Text                   | Text   | 4%         |
| No quantitative results| -      | 29%        |

Figure 2. Example of a bar chart presentation.
intended audience—an important consideration in goal definition—is generally neglected or only vaguely defined as decision makers in general. Alignment between the intended audience and the actors directly involved in manufacturing processes can substantially reduce the total environmental impacts in an efficient manner.

The scope definition specifies the life cycle phases to be studied as well as the functional unit to be benchmarked. In the life cycle phase definition, studies often only consider the manufacturing phase or the manufacturing plus material production phases. These ’cradle-to-gate’ approaches are feasible providing that the environmental impacts generated by the downstream phase are not influenced by any changes occurring in the upstream phases; otherwise, all life cycle phases need to be considered. The functional unit serving as the basis of evaluation should be explicitly defined. However, only 21% of the reviewed studies clearly define the functional unit to be evaluated, and most of the studies (54%) define it only vaguely in terms of the context. In most studies, two types of functional unit are defined, i.e. the product or the production process. However, as the function of the production process is to produce products, it is more reasonable to use a product rather than a production process as the functional unit.

Complex production processes are often simplified in system modeling, so the level of modeling detail is important in determining the resolution and accuracy of the results. In our opinion, a good system model should cover the following three aspects: machine states, product variants, and supporting systems. In this review, 70% of the studies consider at least two machine states when evaluating energy consumption. However, 83% of the studies do not consider the product variants and half of the studies focus on the machine or production line without considering the supporting system.

Material and energy consumption may differ between product variants, and the production line supporting systems also contribute to the environmental impacts. These impacts therefore need to be allocated to the defined functional units. The use of different allocation methods may significantly alter the results, so it is important to choose the appropriate allocation method to represent the aim of the LCA study. We suggest that the allocation method be based on physical properties, such as weight, space, and volume, as well as on economic factors (ISO, 2006b).

Verification and validation are often disregarded in simulation-based LCA studies, as they are often complicated processes and difficult to implement in practice. To avoid the inherent errors often appearing in studies, separately validating the process simulation model and the LCA calculations seems an effective approach.

Data collection is the most time-consuming step in simulation-based LCA studies due to the large quantity and availability of the required detailed data. In the simulation model studies, a mixed data collection approach is generally applied, and measured data have priority over statistical or estimated data. In LCA calculations, measured data are also preferred, and scaled data based on the functional units from production simulation models are also utilized.

In LCI analysis, energy use is well captured in the form of electricity consumption, so other types of energy are often disregarded. Waste is considered by half of the studies, often in the form of the losses of direct materials. For impact assessment, 71% of the studies report the impact in terms of climate change; however, most of these studies make calculations based solely on the electricity consumption, and the on-site impacts
are often disregarded. Nevertheless, as LCA should consider all attributes or aspects of environmental impacts, more impact categories should be evaluated.

Means of communication are important in LCA studies as they concern how the results are presented and communicated. Graphical representation is the most intuitive communication method and is commonly used in presenting results at the LCIA level. Tables are the most effective way to present extensive detailed data, and are mostly used to present data at the LCI level. However, one third of the studies do not present any quantitative results due to their conceptual work and focus on methodological elaboration.

Simulation-based LCA studies still constitute a fairly new research area combining the subjects of production simulation and LCA models. Numerous studies have claimed to use this approach, though some of these studies clearly lack certain required elements of standard LCA studies, causing difficulties in the cross-comparison of different study results. This implies that standard guidelines for working procedures are needed to ensure the quality and value of future LCA studies in the context of manufacturing systems. Our aim is to look further into developing such guidelines, and in doing so we believe that the following two points are worth to be addressed. Firstly, the choice of simulation approach is worth to evaluate. This is more preferred in applications where the interrelations among different elements are complex. Especially, the balance between the benefits gained from a simulation approach and the data management effort required in the system modelling need to be considered. Secondly, it is of interest to consider to include conventional techniques (e.g. optimization) and indicators (e.g. throughput, lead time etc.) that often used in the traditional production simulations into simulation-based LCA studies. A manufacturing system has its own characteristics, and it would be valuable to take these techniques and indicators into consideration when developing the future LCA guidelines for providing standard benchmarks and to increase its applicability.

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**Appendix**

Articles included in the systematic review:

| Articles                                                                 | Type                          |
|-------------------------------------------------------------------------|-------------------------------|
| (Johansson, Mani, Skoogh, & Leong, 2009)                                | Methodology and evaluation    |
| (Bengtsson et al., 2010)                                                | Conceptual work               |
| (Heilala et al., 2010)                                                  | Conceptual work               |
| (Paju et al., 2010)                                                    | Conceptual work               |
| (Shao, Kibira, Lyons, & Asme, 2010)                                     | Conceptual work               |
| (Andersson, et al., 2011)                                               | Methodology and evaluation    |
| (Brondi & Carpanzano, 2011)                                             | Conceptual work               |
| (Harun & Cheng, 2011)                                                   | Methodology and evaluation    |
| (Lindskog et al., 2011)                                                 | Methodology and evaluation    |
| (Löfgren & Tillman, 2011)                                               | Methodology and evaluation    |
| (Muroyama et al., 2011)                                                 | Methodology and evaluation    |
| (Andersson, Johansson, Berglund, & Skoogh, 2012)                        | Conceptual work               |
| (Widok, Schiemann, Jahr, & Wohlgemuth, 2012)                            | Conceptual work               |
| (Andersson, 2013)                                                       | Methodology and evaluation    |
| (Mani et al., 2013)                                                     | Conceptual work               |
| (Alexander Sproedt et al., 2013)                                        | Methodology and evaluation    |
| (Thiede, Seow, Andersson, & Johansson, 2013)                            | Literature review             |
| (Zhang et al., 2013)                                                   | Conceptual work               |
| (Heinemann et al., 2014)                                                | Methodology and evaluation    |
| (Kim et al., 2015)                                                     | Methodology and evaluation    |
| (A. Sproedt et al., 2015)                                               | Methodology and evaluation    |
| (Orji & Wei, 2016)                                                     | Methodology and evaluation    |
| (Schönenmann et al., 2016)                                              | Methodology and evaluation    |
| (Smolek et al., 2016)                                                   | Methodology and evaluation    |
| (Cerdas, Thiede, Jurachek, Turetskyy, & Hermann, 2017)                  | Methodology and evaluation    |
| (Ramanujan, Bernstein, Chandrasegaran, & Ramani, 2017)                   | Literature review             |
| (Gbededo, Liyanage, & Garza-Reyes, 2018)                                | Literature review             |