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Shop-floor Life Cycle Assessment

Felipe Cerdas[a],*, Sebastian Thiede[a], Max Juraschek[a], Artem Turetskyy[a], Christoph Herrmann[a]

[a]*Chair of Sustainable Manufacturing & Life Cycle Engineering, Institute of Machine Tools and Production Technology (IWF), Technische Universität Braunschweig, Langer Kamp 19b, 38106 Braunschweig, Germany*

* Corresponding author. Tel.: +49-531-391-7177; fax: +49-391-5842. *E-mail address:* juan.cerdas-marin@tu-braunschweig.de

Abstract

Although manufacturing companies increasingly acknowledge the environmental impacts of their activities disregarding where in the supply chain these occur, a factory perspective is still predominant within the environmental management practices of organizations. The adoption of a life cycle perspective in the Manufacturing industry is essential to develop consistent strategies that leads to decrease environmental impacts of product systems. In this paper we present a methodology to implement technically a continuous LCA at the manufacturing shop-floor. The concept is further illustrated with a research scale production line.

*Keywords:*shop-floor LCA, MTConnect, LCA, DES Simulation, Sustainable Manufacturing

1. Introduction

Manufacturing is imperative for ensuring global well-being. It can be defined as the transformation of resources into goods to fulfill human needs and is one of the most important sectors generating wealth and employment [1].

Manufacturing, however, is currently also linked to a large portion of environmental stress. Industrial activity demands high amounts of renewable and non-renewable resources [2] and produces great quantities of emissions that lead to damages in ecosystems, human health and earth's support systems. Industry-related emissions have almost doubled since 1970 to 15,4 $GtCO_2$-eq in 2010, which represented more than 30% of the global GHG emissions [3].

While any product influences the environment throughout its life cycle, the impacts can differ in quantity and nature at every stage [4]. Improvement measures that are localized at one specific stage of the life cycle poses, therefore, the risk of shifting environmental problems between the different life cycle stages and the different areas of protection.

The Life Cycle Assessment (LCA) methodology has been largely applied for the evaluation and description of environmental impacts of product systems. It provides a solid scientific base to identify environmental hotspots throughout the life cycle of products and potential shifting of impacts. However, factors such as system complexity, subjectivity in the data collection process and in the interpretation of results, availability and quality of data, have not only held up manufacturers from acknowledging the responsibility of their product systems, but have also prevented them from developing strategies to decrease consistently their degree of environmental impact.

State of the art manufacturing software, in particular systems related to shop-floor information management, offer in this regard a broad range of possibilities to enable the integration of manufacturing data into the environmental life cycle data inventory of a product system. In this paper we describe a methodology developed for the integration of the LCA methodology at the shop-floor. The methodology presents a two folded benefit. On the one side it makes life cycle environmental information visible at the shop-floor and therefore broadens the understanding of the consequences of manufacturing beyond the factory. On the other side, it contributes towards the automation of primary data collection reducing time intensity, subjectivity and uncertainties.

In the paper we summarize the main barriers and opportunities to integrate LCA at the manufacturing shop-floor. We identify current technological systems (hardware and software) that can support our methodology. Finally, we

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introduce a conceptual framework and demonstrate its applicability with a prototypic case study.

2. Theoretical background and state of the research

2.1. Life Cycle Environmental Impacts of Manufacturing

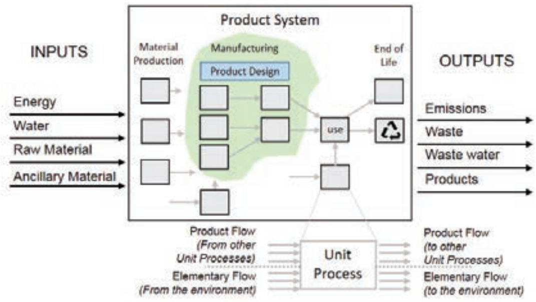


Fig. 1. Manufacturing in the context of a product system

Manufacturing can be considered as a subsystem of a product system (see Fig. 1). Traditionally, it starts with product design and ends by delivering finished goods to the market [1].

The impact of manufacturing cannot be thought of as being limited to the factory gates. Manufacturing decides the type, amount and origin of the resources to be transformed into products and defines important parameters that affect the performance of the product during the use phase, its lifetime and its fate at the end-of-life phase.

A product system is defined in the ISO 14040:2006 [5] as a group of unit processes performing one or more specific functions. Each of these unit processes transform energy and material into a product (or a service) releasing emissions and producing waste on the way (see Fig. 1). The goal of a product system is to deliver a function that serves a human activity, e.g. driving a certain amount of kilometers, containing a beverage, etc. While the impact of manufacturing (understood as manufacturing and design) on a factory perspective (i.e. considered as an isolated group of unit processes) might represent a small, sometimes insignificant, fraction of the total environmental impact caused by the product system, it is at the heart of a system and its actions (e.g. introduction of new materials, production technologies or business models) could contribute to dramatic shifts of impacts occurring outside the factory gates. This interdependency of manufacturing with most other elements in the product system has lead manufacturers to acknowledge responsibility of the impact caused by the product system supported.

2.2. Life Cycle Assessment

LCA is a methodology defined and standardized by the ISO 14040 and ISO 14044 for the estimation and analysis of the environmental impacts caused by product systems. The methodology consists generally speaking on: i. the development of large data inventories of resources used and emissions produced throughout a product's life cycle and ii. an estimation of the type and degree of environmental impact caused by this compiled inventory.

As argued by Hauschild [6], there are two reasons to follow an LCA for the analysis of environmental impacts of productive activities. On the one side, the LCA framework offers a solid methodology to interlink the activities in the material extraction, manufacturing, use and end-of-life stage. This contributes to understand the impact of the product system with a higher resolution and to identify potential shifting of problems between stages, sectors or types of impact. On the other side, the framework provides a sound scientific base to quantitatively evaluate the impact generated by productive activities in an exhaustive set of impact categories (e.g. ozone depletion, human toxicity, acidification, eutrophication, land use to mention a few) which are mutually exclusive. This allows representing the environmental impact of a product system beyond a carbon footprint.

2.3. Motivation and barriers for implementing LCA in manufacturing

In most organizations where LCA is currently being applied, it is seen as a fundamental activity as it is the best available methodology to reliably and transparently do research towards environmental sustainability, it can be used for both internal and external communication and it can support decision making [7]. There is a general consensus in different professional sectors that the LCA is the right methodology to evaluate environmental impacts of product systems in an holistic and exhaustive manner [6]–[8].

Table 1: Barriers to implement LCA in manufacturing

#	Barriers	Source
1	LCA doesn't allow to identify quickly hotspots and trade-offs.	[9]–[11]
2	LCA is complex and requires intensive support from environmental experts.	[9], [12]
3	Defining the system boundaries of the product system is difficult and often subjective.	[9], [12]–[14]
4	LCA is time consuming, costly and does not support reduced time to market.	[7], [9], [12], [13]
5	LCA is inflexible and difficult to update and maintain.	[9], [12]
6	LCA provides "only" one static snapshot in time of the complex interactions of a product system.	[9]
7	The data used entails high uncertainty and is often not representative of the industrial reality.	[7], [12], [14], [15]
8	The inventory entails high uncertainty as many assumptions are subjective or difficult to justify.	[7], [14], [15]
9	Relevant environmental impacts are difficult to consider.	[14], [15]
10	The shop-floor has not been fully integrated within the information systems of factories.	[7], [12], [13], [15]
11	It is difficult to share LCA-related information between workstations and facilities.	[12]
12	Specific "expert" knowledge regarding processes, materials and markets is often required.	[12]
13	Results doesn't relate directly environmental consequences with the root cause.	[7], [10]

Moreover, there is currently a successful exchange of detailed supply chain information in business-to-business secured communications channels [7] that could profit from high resolution primary data from the production shop-floor.

Nevertheless, several authors have identified some of the most common critics and obstacles that have to overcome to soundly implement the methodology in manufacturing (see Table 1).

A more active integration of the LCA methodology at a production shop-floor level can contribute to effectively widespread the benefits of the methodology in the manufacturing sector. The reasons why it is important to implement LCA in manufacturing at the shop-floor level can be described as follow: (1) to support sharing environmental information internally and between the different stakeholders in the supply chain. An in-house life cycle information flow generated at the shop-floor level can support product and process development and make Environmental Management Systems (EMS) more robust; (2) to support sustainability management: the question of sustainability will become a guiding principle in many organizations. In order to comply with product and process regulations and to quantify environmental performance, sustainability managers are required therefore to align their work outputs to highly demanding and dynamic manufacturing environment; and (3) to foster a life cycle thinking culture within the organization: spreading life cycle thinking in an organization represents a challenge that goes beyond the development of methods and tools. The endorsement and adoption of a life cycle thinking culture in manufacturing is to a great extent also a matter of organizational and social change as reviewed in [16]. By making LCA available and understandable at the shop-floor, the staff themselves are proactively included in sustainability issues so that it becomes part of the working culture and continuous improvement processes.

2.4. State of the research: implementing LCA at the manufacturing shop-floor

Research efforts towards the implementation of the LCA methodology in manufacturing has ramped up in the last years. Different approaches have been taken to address the challenges. Therefore, the sake of this paper, we reviewed previous research in two different fields: i. dynamic building of life cycle inventories in manufacturing through data monitoring and simulation, ii. methodological frameworks for the implementation of LCA in manufacturing.

Although there is much research regarding the assessment of material and energy flows in manufacturing activities, approaches towards consolidating LCI out of production processes is scarce. Research done by Posselt [17] provides a methodological approach to monitor energy flows in manufacturing under a continuous process. The concept presented allows to achieve objective levels of energy transparency in factories that enables consolidating data inventories which are easily allocable to specific reference flows. A similar approach is presented by Zampous and colleagues [18] who show a concept of an energy aware manufacturing system combined with analytical functions that integrates handling of energy data with operations information in real time. Research from Herrmann and colleagues [19], [20], Thiede and colleagues [21] and Sproedt and colleagues [22] present as well diverse simulation based approaches for planning of manufacturing systems based on discrete models to estimate energy consumption.

Approaches for the monitoring of material flows in manufacturing systems were presented by Gould and colleagues [23] who provided a framework to model and track material flows from different transformation processes within the context of a product system. Further simulation approaches from Schönemann and colleagues [24] and Thiede and colleagues [25] provide approaches for the implementation of multiscale simulation procedures in manufacturing that enable identifying the interaction of product and process parameters in complex production systems and allow the estimation of potential inputs and outputs of energy and resources consumption for a given set of scenarios.

Specific approaches to couple discrete event simulation DES with life cycle assessment are scarce. Andersson [26] presents in this regard a simplified software tool that develop life cycle inventories that are further fed in a model able to calculate environmental impacts. Research developed by the National Institute of Standards and Technology (NIST) [27] presents a methodology to combine MTConnect production data and DES to execute LCA continuously. The concept provided has been tested with shop-floor data from Boeing machine tools. Finally in this listing, the sustainability cockpit presented by Li and colleagues [28] offers a tool supported methodology based on DES that connects with the company's resources planning to evaluate sustainability dynamically. Although, the approach presented in the Sustainability Cockpit is restricted to the factory gates, i.e. ignoring effects in the downstream phases, the approach is useful in providing a platform to evaluate what-if scenarios in terms of material and energy consumption in factories. Concepts to integrate LCA within manufacturing has been also a recurring topic in the literature. Cha and colleagues [12] presented a conceptual framework to develop an Ubiquitous Computing Technology based LCA. A similar approach is presented by Eun et al. and Moon et al. [13].

3. Shop-floor Life Cycle Assessment: conceptual development

The conceptual framework of the methodology presented in this paper is shown in Fig. 2. The concept of a shop-floor LCA (SF-LCA) intends to combine real time production information, i.e. resources consumption, generated scrap and assets flows with discrete event simulation modelling to generate near time life cycle inventories. The mathematical structure used to structure the life cycle inventory was done following the methodology described by Heijungs and Suh in [29]. The data is linearized for every unit process using the manufacturing actor's LCA approach as described in [10]. Every unit process has a function and therefore it is possible to define a functional unit for every unit processes. To construct a Life Cycle inventory of a manufactured product, the system calls together all the specific inventories of every unit process

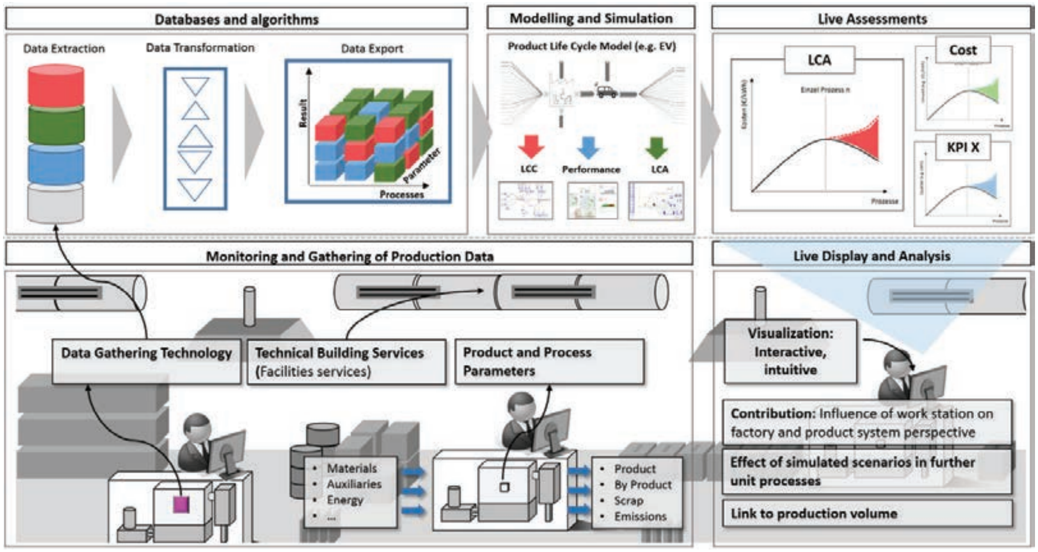


Fig. 2: Conceptual Framework of shop-floor Life Cycle Assessment

and builds the matrix of inputs and outputs for the production phase. This specific inventories can come either from real time data monitoring or from data stored in a data repository which in turn is composed of simulation results or data recorded from past events. These inventories created are afterwards consolidated and fed into a model that calculates life cycle environmental impacts of a given product system. The concept supports modelling not only production phase but also matches decisions made at the shop-floor with potential consequences taking place at different “places” within the supply chain.

The methodology comprises four parts: i. monitoring and gathering of production data at the SF, ii. data management, iii. modelling and simulation and iii. visual analytics. Data gathering is a key step of the shop-floor LCA concept. A suitable metering concept needs to be developed for the production systems under investigation. For the physical hardware recording the necessary measurable elements in the production system standard industrial sensors can be employed. As the methodology is based on the quick availability of decision supporting results, appropriate data gathering and processing hardware is required. RFID technology is in this regard useful for collecting product specific information that can be stored physically on the product. An important decision must be made for the appropriate communication protocol. The implementation of LCA at the manufacturing shop-floor level requires a continuous acquisition of precise and reliable data including material and energy flow. The data can be from various sources like sensors, controllers or enterprise systems like supervisory control and data acquisition (SCADA) or even a manufacturing execution system (MES). One major consideration is the various format of obtained data. In terms of unifying, it should be gathered and transformed to a one format or acquired by using standardized interface protocols like MTConnect [30] before further processing. The second step regards data management. Preprocessing data includes data cleaning, normalization, transformation, feature extraction and selection or various other techniques [31]–[33]. A major function of this techniques is to remove noise and redundancy, and find missing values [33]. Before choosing the right algorithm the loss of information should be considered as a result of condensing data and minimizing its stored space [31], [32]. Another major aspect is different types of data like time series or discrete values obtained from different sources, which should be considered before merging the data. The recorded data is processed on a database management system (DMS) running on the database server. The DMS provides storage of and access to the data by a formalized query language. While being fed by current production data, simulation is used for forecasting scenarios to support selecting most suitable strategies. Simulative approaches are used in this regard to fill the data gaps due for example to missing data from downstream processes. Simulation is used to fill data gaps from process parameters like demand of ancillaries, heat waste or even material removed. It calculates energy and material flows of possible scenarios with an appropriate resolution of data to be able to execute continuously LCA calculations. Simulation models depicts possible scenarios not only inside the factory but also for specific conditions in further life cycle phases. Finally, the LCI is fed into a product life cycle model is finally ready to match the temporal LCI to a background system provided by commercial environmental databases. Actual data is then sent to be visualized. The objective at this point is to show the impact of the current work station in the context of the product system being manufactured. Here the actor’s perspective approach presented by Löfgren and colleagues [10] provides a sound methodology to explicitly present the contribution of one specific work station the final product LCA results. The last step before the user interaction with the system is the visualization of the results. For that purpose, the results are then transferred to another database which is read by an interactive HTML5 web visualization system. With this visualization implementation all devices with a modern web browser that are connected to the wireless LAN network can display the results. As visualization media mobile devices such as tablets proved to be suitable. Mixed-reality devices also promise to have high potential to fulfill the visualization requirements once the technology becomes more broadly available.

4. Prototypic Implementation

To illustrate the applicability of the concept we implemented the methodology described in experimental factory at the TU Braunschweig [34] . We modelled the product life cycle of the processed product as shown in Fig. 3.

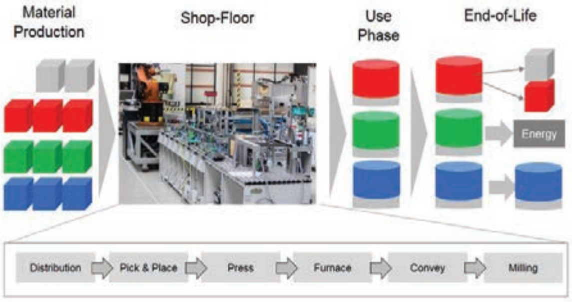


Fig. 3: Prototypic production line

In Table 2 a summary of the results from the simulation of the 6 different scenarios is presented. An energy and material flow oriented manufacturing system simulation (as in [20], [21]) was used for this purpose.

An example of the results visualization displayed at work station is presented in Fig 4. Notice in Fig. 4 that the results is shown as a combination of an already accumulated impact (cradle to work station) and is afterwards complimented with "predictions" built with simulated data.

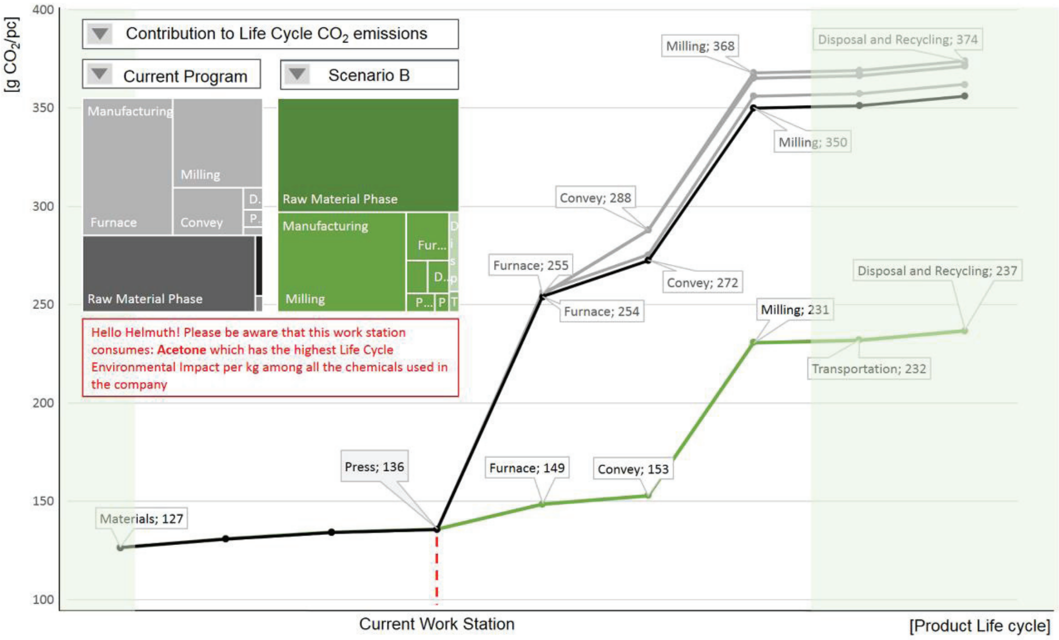
In this way information regarding specific impacts of the work station are shown that allows to provide advices for the development of measures considering the complete product system (for this case GWP) can change dramatically even influencing the contribution of the different life cycle phases.

Table 2. Simulation Scenarios Results.

Scenario	Description	Parts (pcs)	Time (s)	Energy (Wh/pc)
A	Base setup, one piece flow	92	7200	5.090
B	Batch of 10 for furnace, automated shutdown in between, ramp up 60 sec	96	7200	4.590
C	Doubled furnace capacity	98	7200	6.281
D	Doubled milling capacity	93	7200	5.072
E	Quality rate milling 95%	90	7200	5.206
F	C + D	165	7200	4.260

In Fig.4, for example shows at the workstation "press" how for different further scenarios (e.g. batch size in furnace) the cumulative environmental impact of the category selected. For the case in which the furnace is loaded as described in scenario B, the amount of energy for pc decreases substantially causing an overall reduction of life cycle impacts.

Also shown in figure 4. suggestions for a more efficient use of resources explained to the worker on a life cycle perspective. This is expected to give the operator of the work station more



Hello Helmuth! Please be aware that this work station consumes: **Acetone** which has the highest Life Cycle Environmental Impact per kg among all the chemicals used in the company

Fig. 4. Example of display at the Work Station Press

knowledge of the impacts caused by its workplace in a systems perspective helping him/her to become more aware about the environmental burden of their activities beyond the gates of the factory.

5. Conclusions

Although the example presented lacks complexity, it is nevertheless worth noticing that broadcasting LCA results at the shop-floor level is not only computational and technically feasible but also brings a set of assets for the organization. The feasibility of the system depends on the availability of data which is enable by measurement/sensor technology as well as by simulation approaches. While it is expected that the amount of automated data from both production environments and product use phases will increase in the future, the shop-floor LCA methodology presented in this paper provides a structured workflow for the integration of shop-floor data into the environmental impact of product systems. The methodology represents a step forward towards acquiring a broader and more consistent understanding of the concept environmental sustainability while monitoring manufacturing on a real-time basis. Thus, reducing environmental impacts becomes a natural cause of action such as quality improvement and cost reduction.

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