A Simulation Enabled Procedure for Eco-efficiency Optimization in Production Systems

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Abstract. Environmental sustainability in manufacturing has been experiencing increasing attention in practice and academia over the last decades. Manufacturing companies strive to improve their eco-efficiency, which is commonly understood as delivering high value products at lower cost and environmental impact. They need tools and methods to translate this strategic goal onto the operational shop floor level. This paper presents a procedure for optimizing the eco-efficiency of production systems, supported by a discrete-event material flow simulation model. Its application is shown in a case with a company from the Swiss consumer goods industry.

Keywords. Eco-Efficiency, Manufacturing, Sustainability, Simulation

1 Introduction

Sustainability considerations have gained importance in the public over the last decades. Especially for manufacturing companies, responsible for over 36% of worldwide CO2 emissions [1], increasing the energy and resource efficiency has become a major challenge and success factor. Reasons are steadily rising material and energy prices, increasing customer demand for environmentally friendly goods and legislative pressure holding companies accountable for their environmental impact.

Although measures to improve their environmental impact can be taken along the whole supply chain, SMEs typically lack the bargaining power to influence their supply chain partners. Improvement measures have to be found within their own operations for being the only area they can influence. The main issue for manufacturing SMEs thus is translating a strategic goal to increase their environmental sustainability into concrete improvement measures on a shop floor level, while still ensuring their profitability. This is understood as the optimization of their eco-efficiency [2].

Manufacturing companies need pragmatic analysis and decision support tools to solve this problem. This paper proposes a procedure to assess and optimize the eco-efficiency of production systems. The procedure is supported by a newly developed simulation approach, which couples the static material flow assessment (environmental perspective, MFA) with a dynamic discrete-event simulation (economic perspective, DES) in one model.

2 Project background and methodology

The findings presented in this paper stem from a two year Swiss national project called “EcoFactory”. It is funded by the Swiss Commission for Technology and Innovation and carried out by the BWI Center for Industrial Management (project lead), the Swiss Federal Institute for Material Sciences (EMPA) and the University of Applied Sciences HTW Berlin.

Case study research was chosen as the methodology in order to derive theories from practice [3]. As such, the project encompassed four case companies, as shown in Table 1. For the case selection, random companies were first approached for their interest in participating in the project. The four case companies were then selected for the sake of covering different industry sectors and company sizes. The purpose of the research can be categorized as theory building [4]. In a first step the state of the art in the field was assessed through exploratory literature reviews. Data from the case companies was further gathered mainly through semi-structured interviews. The research resulted in conceptual models for the simulation approach and the analysis procedure.

Table 1. Overview of case companies in EcoFactory project

Case Company	A	B	C	D
Industry	Consumer Goods	Packaging	Food	Metal Working
Size	55	115	800	3500

3 State of the art

Assessing and monitoring the economic performance of their production system has become a mature process for most manufacturing companies. The system boundaries for the analysis are clear and a broad consensus exists on which performance measures should be used for specific purposes. Further, the availability of data for the economic assessment is usually very good, since they can commonly be derived from data (semi-)automatically collected and updated from ERP or MRP systems.

An assessment of the environmental performance of a production system on the other hand is by far more challenging, since the environmental impact of a production system has different dimensions (e.g. air and water pollution, toxicity)and is driven by manifold aspects (e.g. energy and material consumption rates, support processes) [5]. Furthermore, there are different methods available to assess the environmental performance, each well suited for a different purpose (for an overview see [6]), while Life Cycle Assessment (LCA) represents the predominant one.

Thiede and Herrmann state that an integrated assessment of environmental and economic performance of a production system requires a system-oriented approach in order to identify the truly relevant fields of action for improvements [7]. Discrete-event simulation (DES) models have been acknowledged as powerful tools for in-

creasing the understanding of complex systems. They allow the user to gain insights into interactions between important variables in the performance of the system through their ability to reflect the dynamics of a system [8]. Since commercially available simulation tools do not yet consider environmental aspects, some effort has been undertaken in research during the last years to develop simulation models that aid the environmental assessment of production systems. A comprehensive overview of different approaches can be found in [9].
However, most developed approaches are still based on different model representations for the economic and environmental assessments. As such, they first use a DES model to investigate time-sensitivity and stochastic effects in regard to the economic perspective. Although based on the same object of reference, a material-flow assessment model is additionally required as a basis for the LCA of the manufacturing system, resulting in additional modeling efforts and is inconsistent when aiming at an integrated assessment of the production system.
For overcoming this gap, a simulation model needed to be developed that integrates both the environmental and the economic perspective in one unified model. The simulation model is preceded by a system analysis procedure reducing modeling efforts and ensuring that environmentally relevant consumption parameters are made available in the required granularity. The results will be explained in the following.

4 Project findings and results

4.1 System analysis

The developed system analysis procedure is based on the standard process of a simulation study, as originally formulated by Nance [10]. Figure 1 shows the basic steps of the system analysis, which will be described in the following.

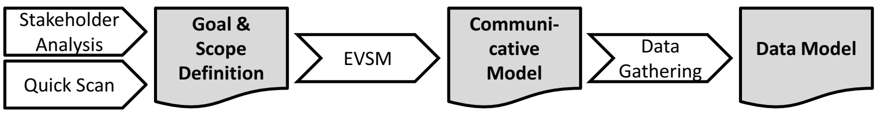

Fig. 1. System analysis procedure

The strategic goal to improve the eco-efficiency of a manufacturing company can be motivated externally or internally. Therefore, as a first step, it is important to understand the area of conflict the company is operating in. An extended stakeholder analysis was deemed a viable tool to identify which stakeholders impose pressure upon the company to improve their eco-efficiency. The most relevant aspects analyzed in this context are customers, suppliers, competitors, government, employees, society, technology and environment.
In addition to external pressures, manufacturing companies may have a proactive attitude towards the environmental sustainability of their business. In such cases, companies search for the activities and aspects that mainly drive the environmental impact of their production. In order to identify the production processes yielding the highest optimization potential, a qualitative analysis is conducted of the whole pro-

duction facility. For this purpose, the Cleaner Production Quick-Scan was adapted [11-12]. It is based on semi-structured interviews, checklists and a thorough factory walk-through. All production processes are assessed according to their economic and environmental optimization potential. The results of the Quick-Scan help to delimit the system that will later be analyzed in detail and modeled for the simulation. These two first steps lead to the Goal and Scope Definition, which serves as a basis and guidance for the further analysis and the whole simulation study.

For the in-depth analysis of the previously defined area of intervention, the Environmental Value Stream Map (EVSM) has been developed. It is based on the traditional Value Stream Mapping technique known from the Lean Production/ Just in Time Toolkit. The purpose of a traditional VSM is to illustrate the material and information flows along the value stream of a product in order to identify the sources of wasted productivity [13]. It has been extended to include an input-output perspective on each of the production processes in order to additionally capture their environmentally relevant aspects. The structure of the EVSM is shown in Figure 2.

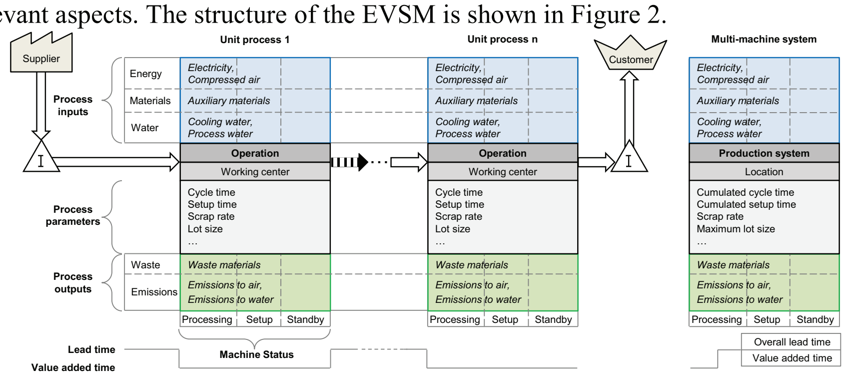

Fig. 2. Structure of the Environmental Value Stream Map [14][15]

The blue boxes on the top capture all environmentally relevant inputs into a production process, sub-categorized into energy, material and water inputs. The green boxes on the bottom capture all outputs of the process not related to the actual product or component produced. These are categorized into waste and emissions (air and water). As a result, the EVSM delivers a clear and accurate picture of all parameters needed to assess the eco-efficiency of the system. It is thus a suitable basis for the application of the simulation model that will be introduced in section 4.2.

Experience has shown that most environmentally relevant parameters, such as consumption rates of electricity, are only seldom available on a process level, so that measurements become necessary. For this purpose, a measuring procedure was developed together with the Institute for Machine Tools and Manufacturing of the ETH Zurich. Details on the measuring procedure can be found in [15-16].

4.2 Simulation model

To overcome the shortcomings of current simulation models, a new model was developed in close cooperation with the University of Applied Sciences HTW Berlin within the EcoFactory project. The model is based on a prototype architecture previously developed by HTW [17-18]. The approach focuses on integrating DES and MFA into one simulation model.

The model focuses on a cradle-to-gate perspective considering the environmental impacts of the production system. As such, the production facility is considered as the foreground system, which is explicitly represented and parameterized in the simulation model. The environmental impact of the upstream supply chain of the production is considered as the background system and not explicitly modeled. Within the simulation model, this aspect is accounted for through the integration of LCI data. Figure 3 shows the structural model of the simulation approach.

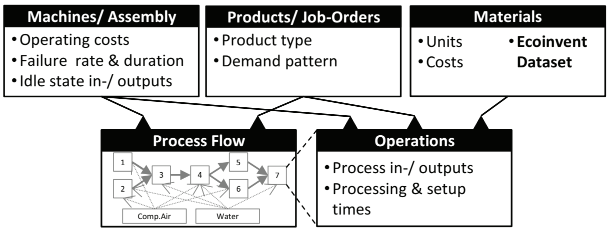

Fig. 3. Structural model of the simulation approach

As the illustration shows, the production system is modeled as a workflow of interlinked manufacturing operations. Each operation is determined by the workstation it takes place on (e.g. machine, assembly station), the product type being processed and the materials required as inputs (e.g. energy, water, auxiliary) or generated as outputs (emissions, waste). LCI datasets are imported for the definition of the material in- and outputs through an interface to the "ecoinvent" database, which is hosted and managed by EMPA. For this purpose, a search function for the LCI flows is incorporated in the simulation software. This interface also allows for the use of all LCA methods available in "ecoinvent" to support the evaluation of the environmental impacts. Hence, the structure of the simulation model is able to deliver a dynamic, job oriented LCA of the production system. The architecture further entails a definite attribution of workstations, products and materials. This enables the assessment of both the environmental and economic performance. For further details on the simulation software see [19-20].

5 Case study application

In this section, the application of the before described system analysis procedure and simulation model is shown on the example of case company A. The company counts 55 employees and produces made-to-order eyeglass lenses from specialist plastic billets. The billets are first milled to their required size and geometry before surface finishing and coating processes are applied according to customer specifications.

The stakeholder analysis and the Quick Scan showed that, while being an integral part of the company's proactive strategy, there is no significant pressure from stakeholders to reduce environmental impact. Reducing the material waste generation and electricity consumption were targeted as the main objectives. Figure 4 shows the EVSM of the company's production system as well as the simulation model in the graphical user interface of the software.

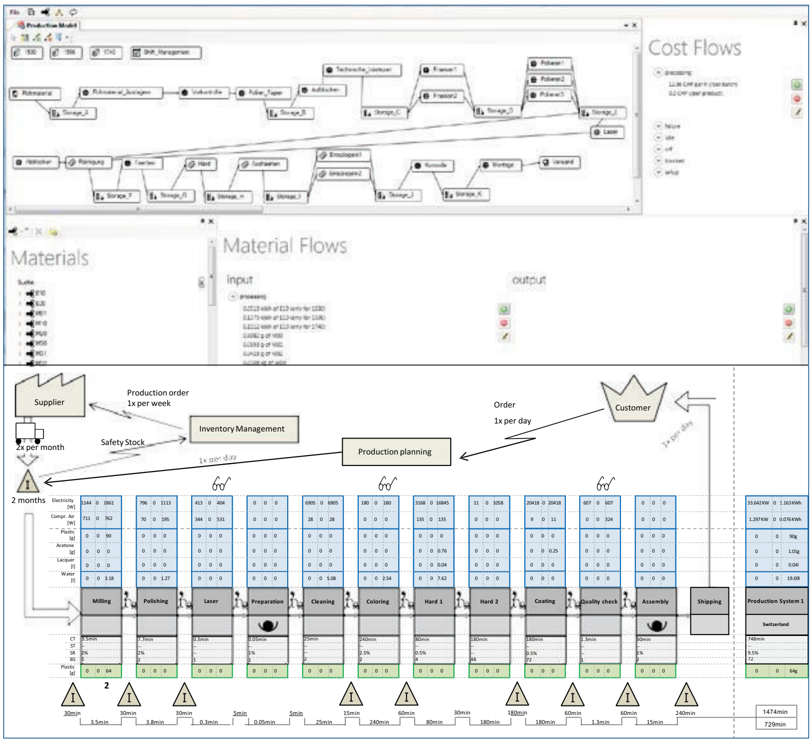

Fig. 4. EVSM and screenshot of the simulation model

The computed eco-efficiency per workstation for company A is shown in Figure 5. It is evident that the highest optimization potential lies in the antireflection finishing, milling and polishing processes. Figure 5 further shows an analysis of the eco-efficiency of the most relevant materials consumed within the production system. For this purpose, GWP100a (Global Warming Potential, in tons of CO2 equivalents) was chosen as the environmental performance indicator. This analysis shows that electricity consumption is the most relevant environmental impact factor, whereas the coating material use is the biggest cost driver. The simulation results further showed a rather poor capacity utilization of the antireflection finishing and polishing processes with idle times accounting up to 30-40% of total time respectively. An improved job-order planning for these processes, allowing to switch off the machines for longer idle periods, is being tested at the company. Based on simulation experiments, this measure has an estimated potential to reduce the overall electricity consumption by up to 10%.

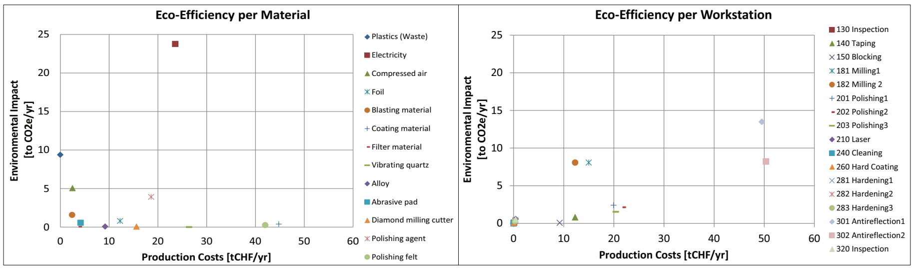

Fig. 5. Eco-efficiency of materials and workstations

6 Discussion and Conclusion

This paper presented a novel simulation approach, which combines discrete-event simulation with LCA in one unified model. Its architecture allows for a definite attribution of materials, workstations and products, delivering a higher degree of transparency to the production processes than current approaches. Further, a system analysis procedure was presented, designed to deliver all relevant data and information for building the simulation model of a production system with minimum efforts.

The main limitation to the presented approach is the commonly limited data availability at a process level, especially concerning environmentally relevant parameters. To unfold its full potential, the simulation model requires product-specific material consumption parameters on a process level. The lack of this data calls for dedicated measurements, which can result in significant efforts for the company. Nevertheless, at the case companies these measurements alone increased the awareness and transparency of consumption patterns within the production system and were by themselves deemed useful by the responsible production managers.

In summary, the application of the approach in company A resulted in time efforts of 10 days (6 days for the system analysis, 4 days for modeling activities), that were deemed acceptable by the company representatives. The simulation analysis pointed to an improvement measure estimated to reduce the electricity consumption in production by about 10%, while further measures are currently being evaluated.

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