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CONSIDERING ENERGY IN THE SIMULATION OF MANUFACTURING SYSTEMS

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ABSTRACT

In recent years, environmental aspects became one of the key interests in manufacturing. Accordingly, simulation studies had to include factors like energy or emissions. This paper aims to provide a comprehensive introduction to the state of the art in modeling of energy and emissions in simulation of manufacturing systems. We review existing literature to develop a landscape of common approaches and best practices. Typical goals and objectives of the reviewed simulation projects are summarized. Furthermore, we will evaluate the structure and life cycle phases of the examined manufacturing systems and look into the requirements and implementation of respective simulation studies. Finally, we will discuss open questions and future trends in this field of research.

1 INTRODUCTION

At the turn of the millennium, a major shift occurred in the manufacturing industry. Previously, manufacturing was focused primarily on economic aspects, but with increasing energy costs and increasing environmental consciousness environmental aspects moved into the spotlight in addition to traditional goals. This shift became apparent in the domain of simulation, when more and more simulation studies considered energy in addition to traditional factors in manufacturing and logistics (Figure 1).

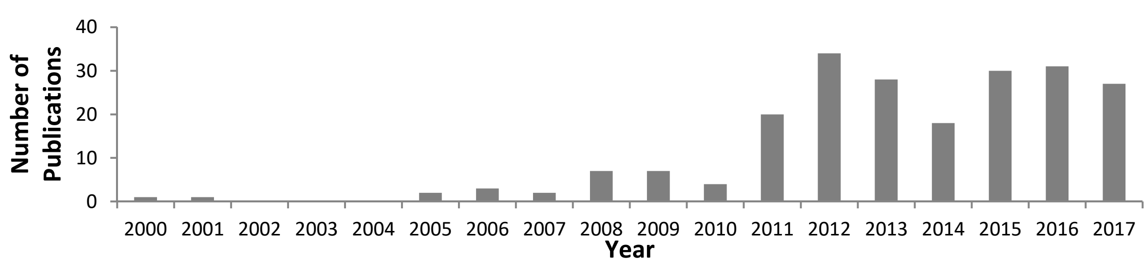

Figure 1: Identified publications on simulation studies in manufacturing and logistics factoring in energy.

The number of publications depicted in Figure 1 is derived from all relevant publications we identified. Our research process is discussed in more detail later on. Generally, our research indicates that environmental concerns have not gained interest in the simulation community before the turn of the millennium and only spiked substantial interest after 2007.

According to these publications as well as our experiences, a simulation study today may elaborate typical questions like: Can we switch some pieces of equipment in a factory temporarily to an energy saving power mode (e.g., Seewaldt et al. 2017)? What influence do energy-related process parameters have on the overall production process (e.g., Peter et al. 2017)? Which potentials for energy flexibility do exist in a given production system (e.g., Stoldt et al. 2017)?

This paper reports on findings of the workgroup on the Investigation of Energy-related Influences in SPL within the ASIM Section Simulation in Production and Logistics (SPL). This workgroup has reviewed literature on simulation projects that consider energy aspects in production and logistics. One main goal of the literature analysis has been to classify research projects and generate a map of existing work in this field. For this purpose, we have systematically reviewed journals, conferences, and doctoral as well as undergraduate theses to identify potentially relevant works. In total, approx. 40 journals and conference series have been selected based on their general themes, covering a broad range from simulation via logistics and production engineering to sustainability. The general work process comprises the following steps:

1. Gain access to relevant tables of content or lists of abstracts (particularly for proceedings within the scope specified above)
2. Page through all articles of a volume, proceeding or catalog
3. Select relevant articles based on their connection to material flow simulation with a parallel assessment of energy-related aspects with an application focus on production or logistics
4. Evaluate selected articles (see below) and disregard articles that show no actual application (i.e., conceptual works) or only extend previously identified works of a research group without adding new information to the map
5. Check the list of references for hitherto unknown sources or publications
6. Add findings to the map after brief discussion of the contents within the workgroup

Abiding by this process, we have evaluated more than 250 publications and added more than 150 references to the map. As pointed out before, we tried to avoid duplicate entries in our map. To this end, we only included multiple entries from the same research group whenever their content differed significantly. Because of this high number of publications, we will not be able to present the map's full list of references here and will instead only add exemplary references in the following sections. During evaluation, the following criteria have been employed to classify the work of individual research groups:

1. Goals and objectives of simulation projects with energy aspects (e.g., dimensioning of energy-relevant infrastructure)
2. Focus on the system life cycle (e.g., concept planning phase)
3. Focus on value creation chain (e.g., production)
4. Manufacturing principles (e.g., flow production)
5. Production type (e.g., mass production)
6. Industry sector (e.g., automotive)
7. Level of detail for modeling (e.g., machine components)
8. Architecture and paradigm for simulation (e.g., integration in discrete event simulation model)
9. Employed simulation tools (e.g., Siemens Plant Simulation)
10. Input data and information types employed (e.g., demand specification for production machinery)
11. Employed key performance indicators for energy aspects (e.g., energy consumption per system or system element over time)

In this paper, we will discuss some results produced in our survey. We provide an encompassing overview of the state of the art in simulation of manufacturing systems where energy is considered as a key aspect. We will elaborate what goals and application scenarios are typical, in which life cycle phases of a manufacturing system we often face questions pertaining to energy, and which kinds of production systems are regularly reviewed. However, we will skip over classifying the case studies with regard to industry sector and we will also omit the topic of product life cycle evaluation regarding energy, since these topics have previously been reviewed by us in Wenzel et al. (2017). With regard to the implementation of simulation studies that include energy aspects, we provide an overview of typical requirements and organizational questions that need to be answered for a successful simulation study. Additionally, we will review which tools and approaches are chosen to approach various types of simulation studies. This overview of the state of the art in simulation of material and energy flows will help researchers to identify relevant publications and simplify networking and exchange with research groups of similar interest.

Incorporating energy in a simulation study of a manufacturing system usually represents a unique challenge. Manufacturing systems are most frequently modeled using Discrete Event Simulation (DES). However, when we consider energetic aspects such as consumption or emissions, we observe continuous system changes. Different approaches have been proposed to tackle this challenge. One straight forward approach is to approximate the continuous behavior in a pure DES, for example by using energy levels for distinct tool states in manufacturing (Stoldt et al. 2016). If this is not sufficient, additional tools or simulation paradigms are used to complement DES. Typical setups or paradigms are:

1. Complementing DES by using the DES output as input for a specialized tool to evaluate energy aspects of the given challenge in a downstream energy evaluation
2. Using two complementary simulation models that operate either independently or are coupled with each other
3. Using a hybrid simulation tool that supports DES and additional continuous simulation paradigms

In this paper, we will not discuss these technical aspects in detail. For a summary we refer to Thiede (2012). He also provides a classification of simulation paradigms that is similar to our approach (see Wenzel et al. 2017) albeit less differentiated. According to his classification, which is depicted in Figure 2, external evaluations, coupled simulations, or integrated evaluations are typically used.

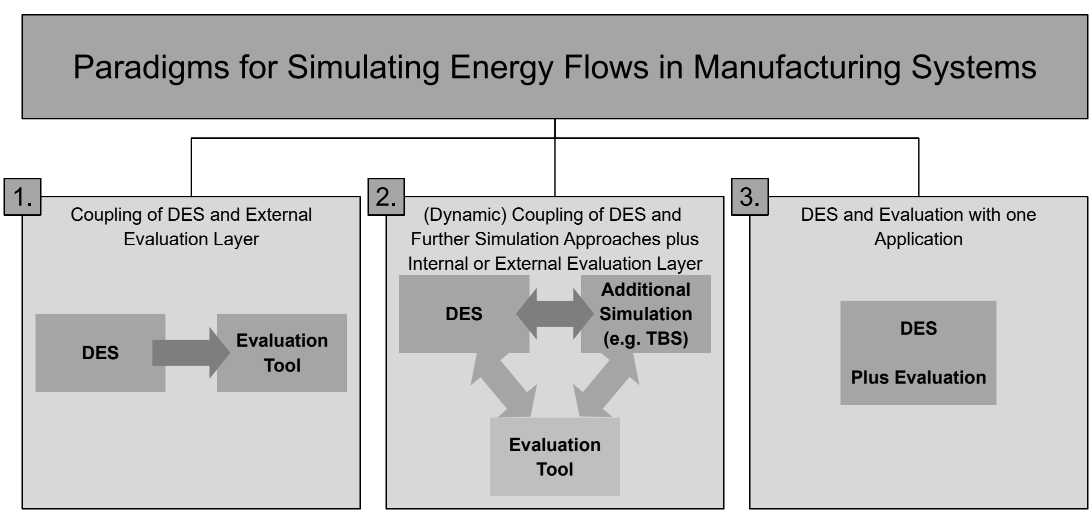

Figure 2: Paradigms for simulating energy flows in manufacturing systems based on Thiede (2012).

The paper is structured as follows: After this introduction we will discuss typical applications of simulation in manufacturing considering energy (Section 2). We will highlight typical goals and objectives and characterize typical simulation studies with respect to the considered manufacturing principle, the types (production types), and the life cycle phases of the studied manufacturing systems. In Section 3 we aggregate information on the implementation of these studies. As stated before, we will not elaborate on the technical aspects, but rather focus on typical requirements to successfully realize a simulation study, e.g., employed key performance indicators, additionally necessary input data, the level of detail for modeling, or the employed simulation tools. Finally, we will discuss as well as summarize our findings in Section 4.

2 APPLICATIONS

In this section, we describe different goals and objectives that simulation experts follow when considering energy-related influences in material flow simulation. Furthermore, we provide examples of manufacturing principles and production types that are common in case studies which utilize simulation with regard to energy-related aspects. At the end of this section, we also discuss which phases in the life cycle of a manufacturing system are considered in the reviewed publications.

2.1 Goals and Objectives

The literature analysis shows many goals and objectives concerning energy-related aspects that simulation experts follow. These aspects influence how to implement the simulation, which additional input data is required, and which key performance indicators have to be evaluated utilizing the simulation. The following goals and objectives have been identified:

- Design and dimensioning of energy-related infrastructure
- Reduction of the maximum load to reduce cost
- Peak shaving and load leveling
- Local optimization of the energy consumption of single machines
- Optimization of production equipment control
- Calculation and prediction of energy consumption
- Determination or prediction of energy costs
- Dimensioning of logistics and production systems under consideration of energy or emission targets
- Production planning and control under consideration of energy-related restrictions
- Support for or transparency regarding eco-friendly production and logistics
- Optimization of the supply chain with regard to cost and energy-related aspects

Most of these goals and objectives are related to economical savings: oversized energy infrastructure wastes money during investments and lowers equipment efficiency (e.g., Schacht 2014), peak shaving and load leveling allow for cheaper contracts with the electricity suppliers (e.g., Fuss and Beißert 2014), and local optimization of the energy consumption of single machines may aggregate to a significant saving if done for a whole production line (e.g., Schulz and Jungnickel 2012). Others, however, focus on predicting the energy consumption of production equipment for use in the design phase (e.g., Cataldo et al. 2015) or the energy costs in general (e.g., Diaz-Elsayed et al. 2013). Such information is valuable in "traditional" dimensioning of production equipment, especially when done dynamically (e.g., Neyrinck et al. 2015). More advanced studies do not just try to predict the consumption, but aim to test novel approaches to production planning and control that consider energy-related restrictions which may lead to more efficient (cost saving) production strategies (e.g., Seewaldt et al. 2017). The last group of goals and objectives targets environmental key performance indicators like the eco-footprint of a product and tries to achieve transparency for the stakeholders like the public, the government, or the environmentally conscious customer (e.g., Heilala et al. 2008). Supply chain optimizations (e.g., Circullies et al. 2012) constitute another group which is, however, not in the immediate manufacturing scope of this paper.

Depending on the goals and objectives, different key performance indicators and additionally necessary input data are required for the simulation study, which will be described in Section 3.

2.2 Characterization of Case Studies

In our analysis we have characterized previous case studies depending on three criteria. First, we use the manufacturing principles that according to the literature are classified depending on the spatial structure. We differentiate between five different manufacturing principles: the workbench principle, the on-site principle, the function or workshop principle, the cellular or group principle, and the flow principle (Lödding 2013).

Second, we consider the average size of the production run (lot size) and how often the product runs are repeated to categorize the production type. Based on definitions in the literature there are four main characteristics: one-time production, single or small lot-wise production, serial production and mass production (Lödding 2013).

Third, we examine the life-cycle phase of the simulated manufacturing system. Life-Cycle phases are divided into five main phases: planning and design, realization, start-up, operation, and termination/re-use (Attri and Grover 2012). In the following paragraphs, we will give examples on identified contributions that fit the defined characteristics for each criterion.

Regarding the manufacturing principle, we could not uncover any case studies that investigated on-site or cellular manufacturing principles. Most of the papers analyze manufacturing systems with flow or workshop principles, for example Barletta et al. (2014) provide an energy-based overall equipment effectiveness indicator. Furthermore, Frigerio and Matta (2016) discuss energy-efficient switching of machine tools and Ichimura and Takakuwa (2013) investigate material flow cost accounting. Whereas Hibino et al. (2014) use simulation to compare productivity and energy consumption in manufacturing systems, Schuh et al. (2014) analyze the effects of lot size planning on energy efficiency. Several identified case studies do not belong to any manufacturing principle although they analyze material and energy flows. These approaches aim mostly at the field of logistics and supply chain management. Many of these applications belong to the topic of distribution logistics with particular interest in CO_2 emission calculation and prediction (e.g., Circullies et al. 2012) or work on the optimization of energy consumption (e.g., Neyrinck et al. 2015). Some of these works concentrate on supply chain networks, giving insight into carbon footprint specification using the DES methodology (e.g., Gutenschwager et al. 2013; Kuhl and Zhou 2009).

The reviewed papers present case studies for each of the previously defined production types. Most of the works study serial production environments aiming to investigate two main aspects of energy flow: energy flexibility (e.g., Beier 2017) and energy efficiency. The latter one has been analyzed in connection with production control (e.g., Goy 2016) as well as with assembly processes (e.g., Oumer et al. 2016).

Regarding the life-cycle phase we have found that manufacturing systems with flow principle are analyzed in the planning and also in the operational life cycle phase. Production systems with workshop principle are mostly studied in their operational phase. According to our research, logistical and supply chain networks are almost without exception studied in their planning and design phase. In case of serial production systems, there are works that focus on the planning and operational stages as well, whilst in case of lot-wise production the majority of contributions focusses on the operational stage. There are a few works giving deeper insight into case studies about both design and operational life cycle phases at the same time (e.g., Marzouk et al. 2016; Matsuda et al. 2016).

3 INTEGRATING THE SIMULATION OF MATERIAL FLOWS AND ENERGY FLOWS

The previous sections have provided some insights in the application of simulation that considers both material flows and energy flows. Yet, how these different types of flow systems (the former discrete, the latter continuous) are integrated with each other in a simulation study depends on a number of factors. Multiple methodologies that aim to structure the entire process or parts thereof have been published in recent years (e.g., Dettmann et al. 2013; Solding 2008; Stoldt and Putz 2017; Thiede 2012). In order to supplement such methodical approaches, we have reviewed previously published case studies to identify which particular types of key performance indicators, levels of detail in modeling, additional input data, as well as tools have been used. These can be reference points for either more problem-specific or more generalized implementations of simulation studies.

Unanimously, the previously mentioned methodologies derive decisions on how to implement a simulation study from the project's task definition or parts thereof. Considering the categories analyzed in our review we have identified that these are related to one another in a simulation project (Figure 3). The key performance indicators as well as the level of detail for modeling are derived from the goals and objectives (see Section 2.1), but need to be defined in accordance with another, i.e., are mutually dependent. From these two (bearing in mind the goals and objectives), the additionally necessary input data can be specified as well as a suitable simulation tool can be selected.

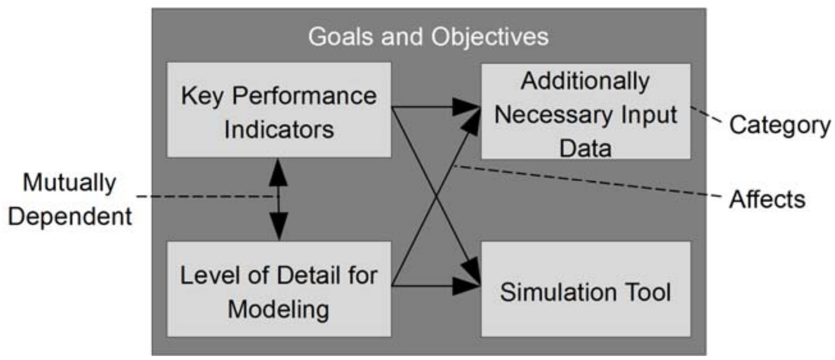

Figure 3: Relationships of the analyzed categories concerning the implementation of simulation studies.

All in all, we have identified eight classes of key performance indicators that are typically used in simulations of the kind discussed in this paper. As depicted in Figure 4, these can be distinguished by their time-dependence and by their focus on either the system under study or the flow items that pass through it.

Our research shows that the earliest approaches in this field seek solutions for simulating emissions (e.g., Heilala et al. 2008; Wohlgemuth and Page 2000) or energy costs (e.g., Solding and Petku 2005). Either of these are usually collected for the entire system, individual system elements, or averaged over all flow items passing the system. Originally, they all aim to calculate time-independent values for an entire simulation run, but more recent approaches also aim to calculate energy costs considering dynamic pricing or time-dependent procurement for entire systems (e.g., Weckmann et al. 2017). Alternatively, system-related, time-independent indicators that measure the value-adding energy consumption (e.g., Barletta et al. 2014) as well as the consumption per power state of system elements (e.g., de Oliveria Gomes et al. 2013) have been applied in practice. These allow for a more differentiated analysis of the origin of energy costs, however, only provide a static impression of a system. Measuring the energy consumption over time (e.g., Stoldt et al. 2016) requires more complex modeling but allows for investigating time-critical questions concerning the supply of energy in a system. Some case studies that include indicators of this kind also make use of derived key performance indicators, such as average consumption in 15-minute-periods (e.g., Fuss and Beißert 2014). Due to the growing research interest in energy flexibility, some studies also measure an energy-related self-sufficiency ratio or similar indicators (e.g., Beier 2017). Key performance indicators for measuring the energy consumption for individual flow items or entire classes of flow items during a simulation run are often but not exclusively found in supply chain studies (e.g., Johansson et al. 2009). Our review indicates that typically no time-dependent, flow-item-related indicators are used. This is understandable, as flow-item-related indicators are typically an input for the analysis of a system's overall performance or for the comparison of multiple system configurations.

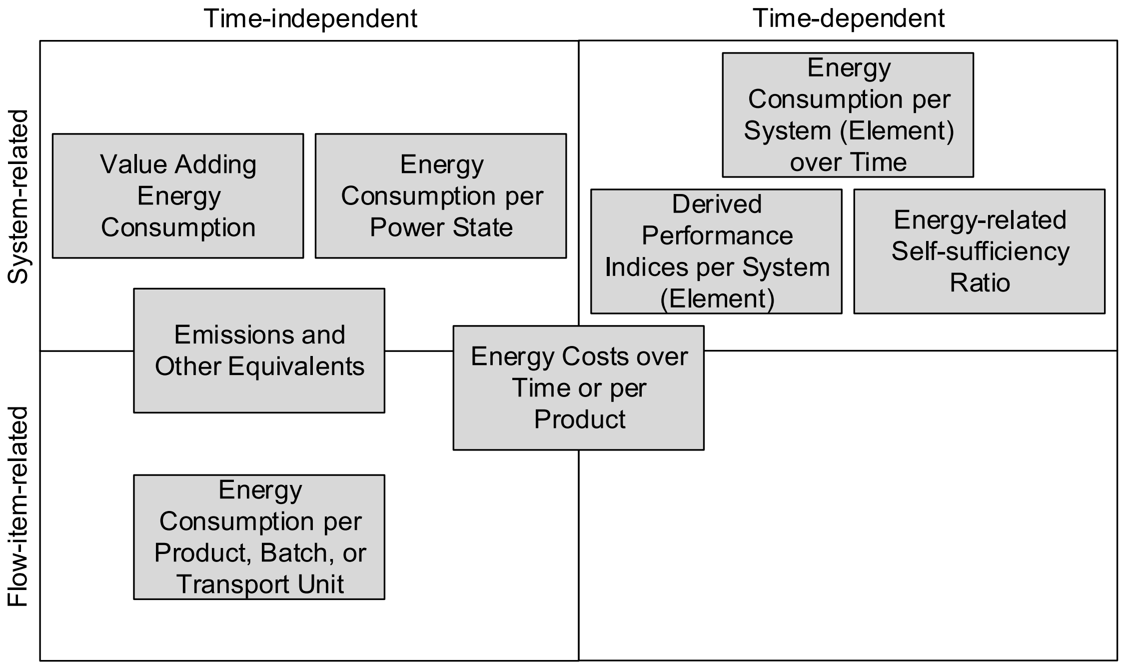

Figure 4: Key performance indicators in the integrated simulation of material flows and energy flow.

Relating to the level of detail for modeling, we have identified simulation studies that use the following levels of detail when modeling both material and energy flows:

- Production or logistics networks (e.g., Jain et al. 2012)
- Production site or (flight/ship/sea/train) terminal (e.g., Kaffka et al. 2015)
- Production areas within a single factory building (Rahimifard et al. 2010)
- Lines, processes, or machines (e.g., Beier 2017; Jain et al. 2012; Peter et al. 2017; Stoldt et al. 2017)
- Machine components (Eberspächer and Verl 2014)

Which level of detail for modeling is chosen, usually relates to the task's focus. Most of the works we have identified consider entire lines or single processes and machines, especially those relating to production in a closer sense. Supply chain investigations, however, tend to be considerably more abstract, modeling production or logistics networks as systems of black box or gray box elements to study the transports between these. This, again, mirrors the more common utilization of equivalents of some kind in such studies. Modeling individual machine components is not particularly popular despite the fact that many energy efficiency improvements originally take effect on this level. The reason is likely that the improvements can be abstracted on a higher level as a change of processing times, change of energy demand, etc. These represent adjustments to the model's logic or parametrization that can be introduced during simulation at substantially lower effort than building a model on a component level would require.

All simulation studies in this field require input data to parametrize and simulate the consumption of energy of individual system elements. According to the goals and objectives, all simulation studies we have identified require time-dependent or time-independent energy demand specifications for production machinery, transport systems, or warehouse systems. Only a few simulations use physical models to simulate the consumption of energy, but even these require some of the former data for parametrization. Order- or product-specific input data that relate to the energy demand have been used, but whether this is necessary depends primarily on the simulated system and the level of abstraction. For instance, if a machine is simulated on a component level using a physical model, the demand can be calculated based on the actual process. However, if a more abstract modeling approach is chosen, the demand may need to be parametrized according to the flow items processed. Besides the demand-related data, emission equivalents (e.g., kg_{CO2} per hour of operation) and energy prices or energy price models constitute typically required input data. In some instances, the behavior of energy sources and input data to simulate it is also necessary. Lastly, despite the political dimension of energy efficiency in general, no simulation study employed information on existing legal frameworks.

Thiede et al. (2013) have previously reviewed the support for various software tools for their suitability to support simulation studies of the kind discussed in this paper. Yet, most tools have some means that allow them for being extended so that appropriate functionalities can be added if they are not capable out of the box. A result of our review is that at least 26 commercial as well as even more self-developed simulation tools have been used in published simulation studies in accordance to the architecture paradigms mentioned in Section 1. Furthermore, in a lot of simulation studies Siemens Plant Simulation is used. This fact coincides with the software's popularity in Germany and the high concentration of German research groups in this field (see Wenzel et al. 2017). Other international research groups use a wider range of tools. Works that follow a more detailed simulation of the energy demand and supply in a system regularly employ tools that allow for the combination of discrete event and continuous simulation, such as MathWorks MATLAB or AnyLogic.

4 DISCUSSION AND SUMMARY

Looking at the overarching picture, we conclude that integrating considerations of energy in simulation projects is a well-established approach. It is well-supported by research and available tools. The current state of available methods covers most aspects that are currently of interest. Nevertheless, changing future demands will most certainly cause various kinds of progress. Looking at the actual implementation in the industry, we see significant prospects for growth. We see two main reasons for this: on the one hand, companies face the typical challenge in simulation studies – the availability of the required input data; on the other hand, the interest in straight forward energy savings is currently decreasing. This dwindling interest is caused by a shift to other topics, since energy is again more affordable than in the past. With this in mind, it will be interesting to see how legislation will change in the future with steadily growing political interest in environmental aspects.

We consider the following topics to be key challenges in the future. With regard to potential legislation changes, it remains to be seen how well-prepared companies are in an evolving environmental landscape. This is especially true, since we currently observe a nearly complete negligence of legal considerations besides emissions in simulation research and a complete focus on economic questions pertaining to energy aspects. Another trend in industry is the shift from energy savings towards energy flexibility. Especially green energy sources like solar and wind cause much more variability in energy production. Additionally, small and local energy producers introduce new challenges in energy distribution. A flexible approach with regard to energy, supported by simulation, can be a key factor in gaining competitive advantage. Accordingly, Stoldt et al. (2018) discuss the relevant trends and developments in factory planning with regard to energy flexibility. Finally, we want to highlight one area where we anticipate potential gains and future research. At the moment, most simulation projects examine the simulation and optimization of existing manufacturing systems and their operation with regard to energy consumption and emissions. The initial design and implementation of these systems is rarely considered. Consequently, developing energy-efficient and -flexible systems might benefit from including these questions and simulation earlier in the process.

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