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CONSIDERING ENERGY-RELATED FACTORS IN THE SIMULATION OF LOGISTICS SYSTEMS

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ABSTRACT

Traditionally, aspects such as emissions and energy consumption have to be taken into account for environmental and economic reasons when it comes to transport. In other areas of logistics, such as production logistics and intralogistics, the energy aspect is also becoming increasingly important. Existing literature has been recently reviewed in a contribution of the Arbeitsgemeinschaft Simulation (ASIM) to the Winter Simulation Conference 2018 (Uhlig et al. 2018) to develop a map of common approaches and best practices for manufacturing and logistics systems. In the paper presented here, as a complement we are focusing on the application of energy simulation in logistics to give a comprehensive overview and present exemplary case studies. Furthermore, we show a classification of approaches to combine energy aspects with simulation. Finally, we will discuss open questions and future trends in this field of research.

1 INTRODUCTION

Uhlig et al. (2018) already argued that at the turn of the millennium more and more simulation studies have considered energy aspects in the simulation of manufacturing and logistics systems. To substantiate this argumentation, the workgroup on the Investigation of Energy-related Influences in SPL within the ASIM Section Simulation in Production and Logistics (SPL) has evaluated more than 250 publications on simulation projects that consider energy aspects in production and logistics and generated a map of existing work in this field with more than 150 references. The general work process, the map structure, and the consideration of energy in manufacturing systems are discussed in Uhlig et al. (2018). The paper presented here complements the contribution published in 2018 and discusses energy aspects in the simulation of logistics systems.

"Logistics refers to the process of planning, implementing, and controlling the efficient, effective flow and storage of goods, services, and related information from point of origin to point of consumption while meeting customer requirements" (Swamidass 2000). Logistics implies transportation, handling, and stocking inside of an enterprise (*intralogistics*) and outside of an enterprise in consideration of suppliers and customers (*supply chain*). Therefore, our focus on the value added chain is procurement (inside and outside), distribution (inside and outside), intralogistics and warehousing, packaging and bottling as well as disposal and recycling. Relevant industrial sectors are trade, logistics and traffic logistics. The level of detail for modeling refers to entire logistics networks as well as to factory and terminal (e.g., airport, seaport, inner harbor, train) and intralogistics aspects in enterprises.

For this area of application, we provide an overview of the state of the art considering energy as a key aspect. The paper is structured as follows: After this introduction we discuss different applications in logistics. First of all we give a short literature overview of typical applications of simulation in logistics considering energy (Section 2). In Section 3 we describe different approaches for simulation of discrete event logistics and continuous energy aspects that are used in the simulation applications discussed in Section 2. In Section 4 we highlight two case studies from the simulation of a supply chain and an inner harbor terminal. Finally, we discuss and summarize our results in Section 4.

2 APPLICATIONS IN LOGISTICS

In this section, we give a literature overview of energy simulation in Logistics. Following, we show exemplary simulation case studies from the ASIM working group SPL, in which energy aspects are applied. Lastly, we show a classification of approaches to combine energy aspects with simulation.

2.1 Literature Overview

In this subsection, the research process is described methodologically, as well as by examples chosen to create transparency and comprehensibility and to show the topic's wide range of contents. This subsection ends with two exemplary results that were found to be interesting by the authors, upon which further analysis can be carried out. Building on the map presented by Uhlig et al. (2018), the focus is narrowed to logistics only, to support the intended quantitative and qualitative analysis. Therefore, the map is reduced with the following approach:

- Identification of classifications that already support the intended focus (e.g. *industrial sector*: *trade*, *logistics* or *transport logistics*).
- Highlighting articles following this classification as to-be-kept.
- Assessment of all other articles by title and abstract. In the case title and abstract are not sufficient, the full text is taken into account.

Following this procedure, the original map has been reduced to 25% of its original amount of articles. Regarding the numbers of publication per year, a similar trend as already discussed by Uhlig et al. (2018) can be observed: roughly 90% of the publications have been published in the last ten years, peaking at 2012/13 and showing a slight decrease for the most recent years. This could indicate a relation between the trends in manufacturing and logistics.

While applying the above-mentioned method, the following aspects become apparent: Because of the large number of paper authors, a certain discrepancy in the understanding of key terms is inherent. The term *Supply Chain* shall be noted exemplarily: While some authors tend to use it as a synonym for linked production systems (distributed: compare Rabe and Deininger 2012 or even contained: Jain et al. 2012), others mean the realization of the linkage between contained production systems (Cirullies, Schwede, and Toth 2012). A clear distinction between supply chain management and procurement is difficult to express.

We cater to this inherent limitation of linguistic classification by the guiding principle to include work that considers energetic aspects of logistical processes or logistical equipment. At a few occasions, this is not explicitly mentioned nor excluded in the regarding article. In those cases, the authors take the liberty for an educated guess, which of course might offer some margin for subjective influences. These were whatsoever assessed to not be critical.

Cirullies, Schwede & Toth (2012) can serve as an example for understanding supply chain as the linkage between contained production systems. A typical automotive supply chain is depicted: "Although applied multi-sourcing strategies allow short procurement distances, in some cases parts need to be shipped from a different continent, which necessitates multimodal transport". Such supply chains can be associated with certain risks as well as complexity, which justifies the use of simulation. The authors focus on transportation modes (container ship, cargo plane, train or truck) and link them with respective parameters originating from Life Cycle Assessment (LCA) approaches (ISO 14040/44).

Grundmeier et al. (2015) on the other side investigate the operation of electric transport vehicles used at container terminals. They intend to enable the evaluation of new logistic strategies, especially intelligent strategies for battery exchange in order to have them charged at price-optimal times, which might influence the vehicle operation. Nevertheless, transportation tasks constitute the core-business. A combined observation of the logistical process and the energy usage can offer insights to interdependencies and other influence factors. Furthermore, a short-term forecast of energy demand by battery charging is discussed.

Packaging and bottling take a special status when distinguishing between production and logistics, as the distinction between value adding or not becomes rather fuzzy. Even though it can be viewed as a production process, it is predominantly characterized by transportation and handling processes. Forster (2013) emphasizes the role of resource input and product respective utility output in bottling and packaging systems. Simulation offers advantages for optimization approaches concerning controlling strategies that will lead to a smoother production flow and furthermore implement enhanced integration of energy and other resource consideration.

The non-definitive classification of the aforementioned articles with corresponding key performance indicators (KPI) is shown in Table 1.

Table 1: Article classification for exemplary papers.

Article	**KPI**	**Phase in Value Adding Process**
Cirullies et al. (2012)	-Emissions, Environmental Impacts	-Procurement
Grundmeier et al. (2015)	- Energy Usage (abs. or rel.) per Product /-Variant/ Transport Unit - Energy Usage (abs. or rel.) per Unit of Time per (Sub-)System - Deduced KPI of (Sub-)System (e.g. Peakload, Output, …)	-Intralogistics
Forster (2013)	- Energy Usage (abs. or rel.) per Unit of Time per (Sub-)System	-Intralogistics
Kaffka et al. (2015	- Energy Usage (abs. or rel.) per Product /-Variant/ Transport Unit	-Intralogistics

The generated map classifies all relevant papers that were identified by thorough literature search. As the search was conducted by the ASIM workgroup, consisting of several experts, it seems legitimate to draw certain conclusions from the analysis of the mapped articles for this particular field of research.

3 ENERGY SIMULATION IN LOGISTICS

Logistics simulation most commonly relies on discrete event simulation (DES), since typical measurements of interest like inventories or transport times can be effectively captured using this approach. Therefore, the system behavior can be modeled using discrete system changes like start/end transport or increase/decrease inventory. However, when we consider energy or emissions as additional factors, we often encounter effects that need to be modeled continuously. For example, we might want to measure fuel consumption of vehicles to choose the most fuel efficient route or to determine optimal rules for charging automated guided vehicles (AGV).

3.1 Approaches for Energy Simulation in Logistics

In general, there are four approaches to tackle this challenge (Figure 1). The first approach circumvents the challenge of continuous system changes by employing discretization. To this end, a continuous factor is modeled using a simple functional approximation between two events. For example, by mapping a given level of energy consumption to a given state we assume a linear dependency, e.g., a vehicle in the state transporting consumes a certain amount of fuel depending on the time span between start and end of transport, and a given consumption level. The obvious advantage of this approach is that it can be implemented easily using existing DES tools. For many projects this leads to reasonable results, although its accuracy is limited by its granularity. For example, Keramydas et al. (2017) use this approach to design and plan globalized supply chains where CO_2 is considered in addition to traditional costs measures.

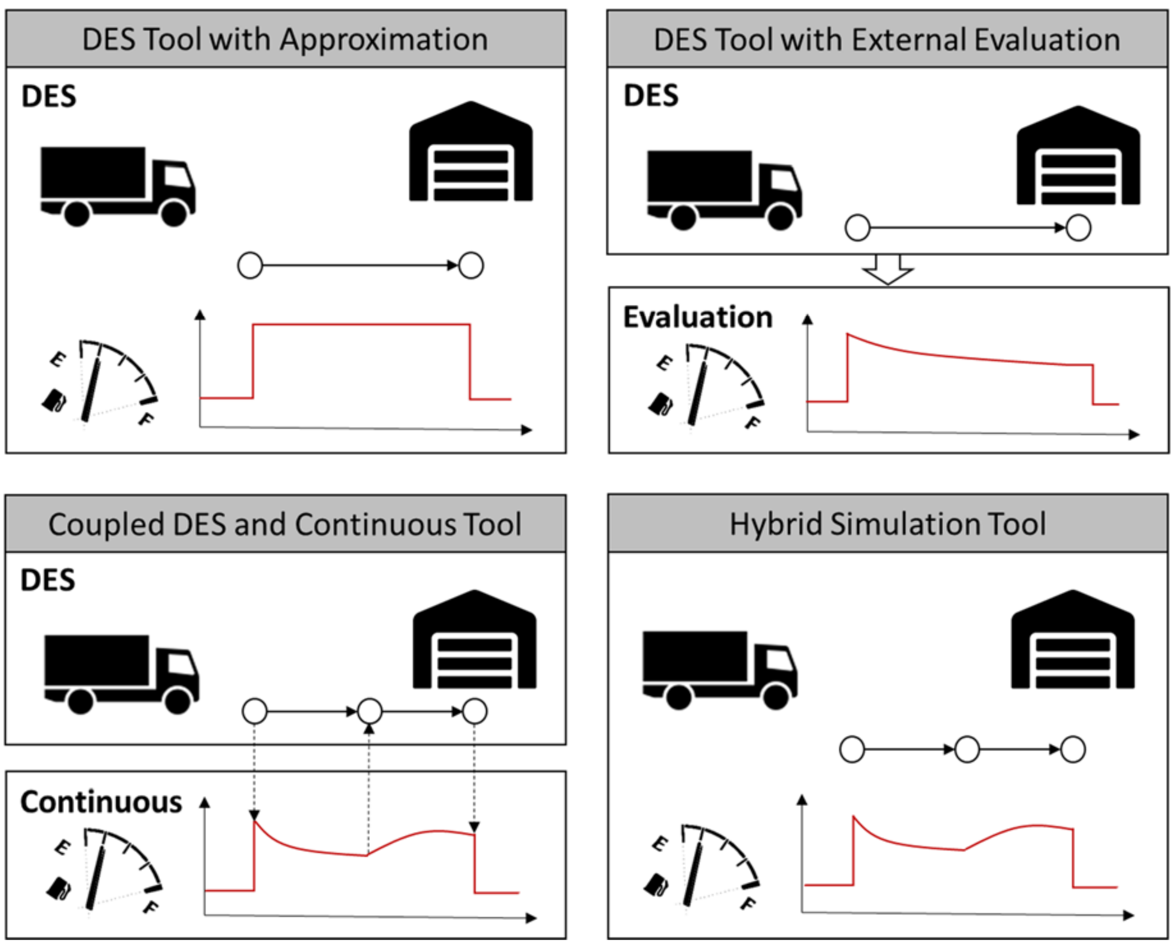

Figure 1: General approaches to include energy aspects in logistics simulation.

When more fidelity is required, the classical DES approach should be complemented with a continuous modeling approach. Thiede (2012) discusses these combined approaches. Fundamentally, we can use three strategies to extend the purely discrete modeling approach: A complementary evaluation tool, coupling the discrete event simulator with an additional model, and a hybrid modeling approach.

The complementary evaluation tool relies on the idea of feeding the DES results into an external evaluation tool. This additional layer computes values of interest to enrich the raw simulation results. For example, this layer could provide a more detailed calculation of fuel consumption by including additional factors like an altitude profile for a route used by a vehicle and additional continuous models for accelerating and decelerating. In a sustainability study for local pharmaceutical business retail by Longo (2012), for instance, Excel was used to further evaluate the output of the DES tool. While this approach can provide a high fidelity, it is limited with regard to dynamic decisions based on energy factors. Since the evaluation tool only enriches the DES results after its execution it cannot provide feedback during the simulation run. To achieve this kind of dynamic interaction we need a closer coupling of both approaches.

To this end, we can couple two models by dynamically exchanging messages between them. In this case, our fidelity is only limited by the granularity of communication events. A common setup for this approach is to couple a DES with a continuous MATLAB model. For example, Wenzel et al. (2015) discuss a SimAssist platform to couple MATLAB with the DES tool Plant Simulation to simulate the material flow in a VW factory. The main advantage is that we can rely on already established tools from both domains. However, we have to provide an appropriate interface in both tools to establish a successful communication and synchronization. This can be technically challenging and inefficient with regard to runtime.

Probably the most elegant solution is the use of a hybrid simulation tool, that supports mixed models out of the box. This approach allows, as far as possible, for seamless integrating discrete and continuous modeling elements. In contrast to coupled models it is much more difficult to find tools that support this approach. It is also challenging to provide a common environment for both worlds, since they stem from fundamentally different approaches. Often the tools in this category historically evolved to a hybrid tool by extending to the other approach. On the one hand, MATLAB as traditional continuous modeling tool today has also features for discrete events. On the other hand, DES tools like AnyLogic now also include libraries for continuous models. For historical reasons, there are few users that are familiar with both paradigms and, therefore, adaption of these tools is difficult. For example, most of the DES users feel quite unfamiliar with MATLAB, and AnyLogic cannot provide a similarly complete library support for continuous modelling as MATLAB.

Obviously, a hybrid modeling approach promises the highest fidelity based on a dynamic interaction of discrete and continuous modeling elements. Nevertheless, it is important that there are fundamental limits to combining discrete and continuous world models. An instantaneous change of state can be hard to synchronize with a continuous process.

3.2 Tools in Energy Simulation

This section gives an overview about the current state of art when it comes to simulation tools in logistics research as it was retrieved from the entries of our logistic focused literature map. Figure 2 (left) shows a rather heterogeneous usage of tools. The largest share (*Other*) represents those tools that were used in only one article of the aforementioned collection of relevant literature. This is contrary to the findings in the original map which included a focus on manufacturing and showed a clearly favored simulation tool (Plant Simulation), which is usually applied in automotive contexts.

Regarding the popularity of the simulation approach, an analysis can be carried out based on the work presented in Section 2. As shown in Figure 2 (right), in 65% of the considered articles DES was chosen to be the most suitable. This coincides with our experience. Nevertheless, the gap to the second-ranked was not expected to be this large, as the field of logistic simulations is wide-ranging.

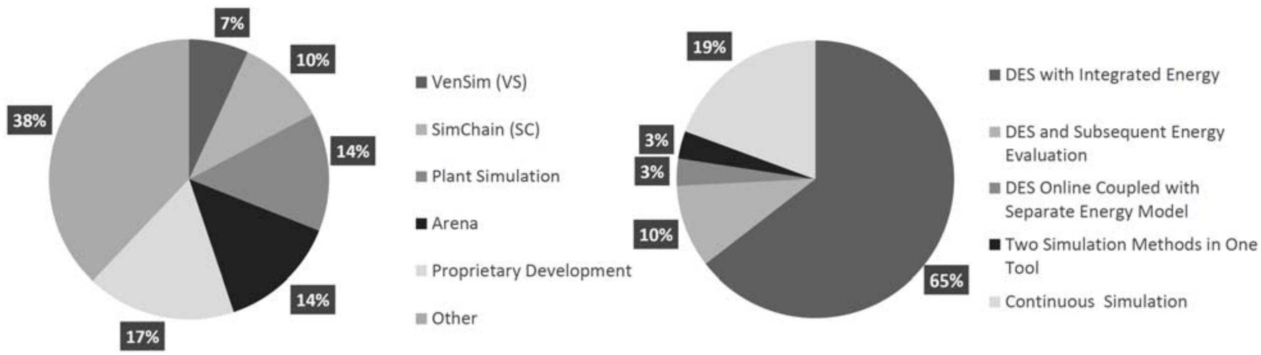

Figure 2: Simulation tools used (left); simulation approaches (right).

4 CASE STUDIES FROM ASIM SPL

In this section, we present two case studies from the ASIM SPL working group that consider energy in their simulation model. The first example addresses a macroscopic view in the simulation of supply chains and the second example covers the microscopic view, when processes and the handling of containers is examined in a harbor terminal.

4.1 Fast Moving Consumer Goods Distribution

For this case study, the German business of the company Barilla including the affiliated company Wasa has been analyzed, starting from the production sites over the distribution centers (DCs) to the local delivery points. Both operate in the so-called Fast Moving Consumer Goods (FMCG) field. Three different distribution scenarios have been considered to assess design alternatives of the distribution chain concerning CO_2 emissions, costs, and service levels (for a detailed description see Rabe et al. 2015).

The simulation tool applied for this project was SimChain (Gutenschwager and Alicke 2004), which is based on the commercial discrete event simulation software Plant Simulation. SimChain enables to simulate a supply chain on strategic and operational level. In the last years, SimChain has been extended to consider the measurement of CO_2 emissions together with logistics features influencing these emissions, such as multi drop delivery including tour planning algorithms.

The distribution chain consists of 586 locations served with more 13,218 orders for Barilla products and 8,006 orders for Wasa products from the year 2012. In the as-is case, the distribution chains of Barilla and Wasa run independently from each other. The goods of Barilla are transported from Parma with trucks to the DCs in Langenau and Mannheim. From the DCs the goods are delivered by trucks of a third party logistics provider (3PL) to the local customers. The goods of Wasa are produced in Celle, from where they are delivered by trucks of 3PLs to the local customers.

On this base, two alternative scenarios of the distribution chains of Barilla and Wasa have been analysed that both include merging the material flows, in order to explore if and to which amount such a merging would positively influence the cost, the service levels, and the emission of the distribution chain.

In the first alternative scenario (A), the goods of Barilla are transported by trucks to the DCs in Langenau and Mannheim with the same order quantity as in the base scenario. From the DCs the goods are delivered to the local customers. The Wasa goods are transported from the production site in Celle to the DC in Langenau to utilize this DC as distribution channel for the local customers. This scenario is illustrated in Figure 3 left. In the second alternative scenario (B), the Barilla goods are transported by trucks from the production site in Parma to a DC in Neuss. Additionally, the Wasa goods are transported from the production site in Celle to the same DC in Neuss in order to merge the distribution networks of Barilla and Wasa completely. The scenario is illustrated in Figure 3 right.

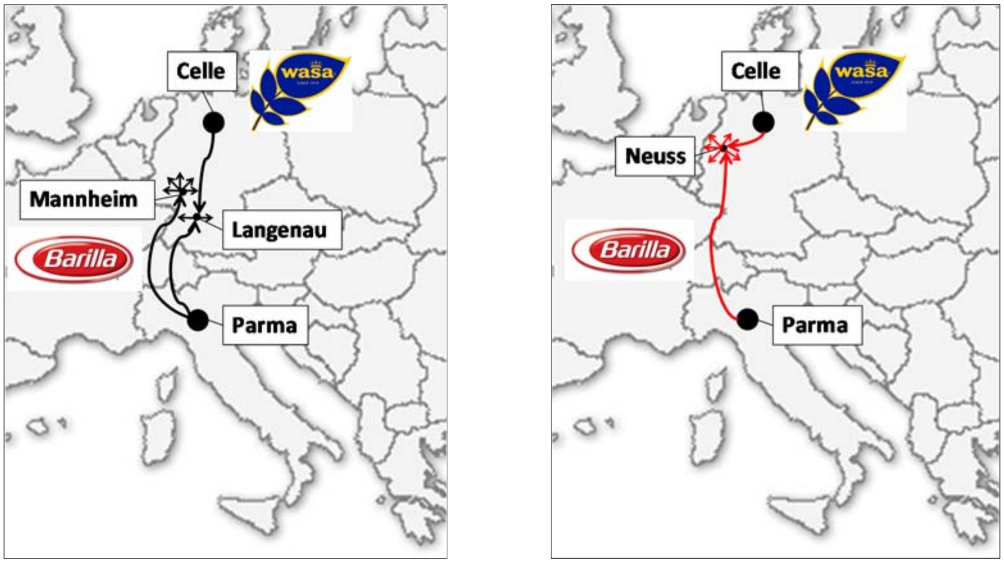

Figure 3: FMCG distribution: Alternative scenarios A (left) and B (right).

In contrast to the original expectations, the as-is situation showed the best results in terms of CO_2 emissions and transport costs. This scenario also has the lowest service level for replenishment for the trip of the trucks from site to DC. Alternative A delivers the second best results for CO_2 emissions and costs. Nevertheless, the CO_2 emissions are 8.3% and the costs are 9.4% higher than in the base scenario. The service level for replenishment is the highest in this scenario. The alternative B provides the poorest results for all three factors, compared with the other scenarios.

4.2 Energy Consumption in Multimodal Transshipment Terminals

Another example that considers energy consumption in logistics has been applied in the simulation of multimodal transshipment terminals (Kaffka et al. 2015). The simulation model is based on the simulation environment TerminalSim, which was developed by Kaffka et al. (2014) and is based on Enterprise Dynamics 8 (Figure 4).

For the simulation, energy consumption measurements were carried out on different crane models with different ages. In addition to the energy consumption measurement, a detailed process recording synchronized to the energy consumption measurement was carried out in order to be able to allocate the energy consumption gained to the individual sub-processes. A crane cycle is divided into the components load and empty travel, spreader lowering and lifting as well as load intake and discharge.

The crane handling building blocks of TerminalSim were then extended by the results of the energy consumption measurement of the various cranes. Key performance indicators that are calculated during the simulation are handling time, handling distance, energy consumption (in kWh) and CO_2 emissions. The KPI are then allocated by type of container.

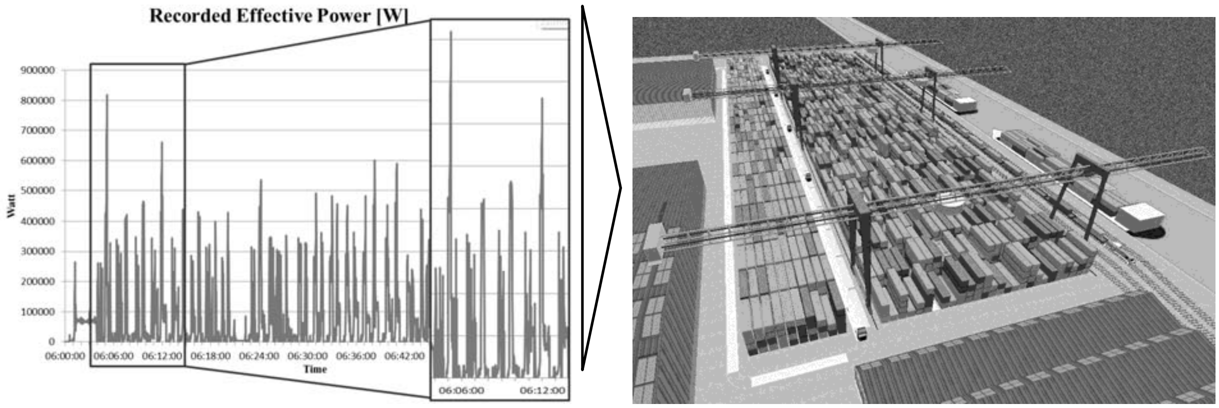

Figure 4: Results from data collection and screenshot of TerminalSim.

Within the scope of the project presented, the total consumption of a multimodal transshipment facility has been allocated at container level depending on various influencing parameters. For this purpose, simulation models with the corresponding influencing parameters were created and consumption values were derived for individual handling situations. Although the actually measured energy consumption could be adopted, the total consumption over one year with simultaneous allocation at container level could not be determined in this manner. For this reason, a one-year simulation study was carried out.

During the simulation study, energy consumption and factors influencing it were successfully determined in a multimodal transshipment terminal. The results have shown notably that the distance of the transshipment is responsible for high consumption. The weight of the containers, on the other hand, can be neglected. In order to save energy and costs, it is important to reduce the handling distance as far as possible. In addition, repositioning must be avoided, as any additional movement is generating further consumption.

5 DISCUSSION AND SUMMARY

We have presented current practices and approaches of energy simulation in logistics. We conclude that, in comparison to manufacturing systems, there are distinctly fewer applications found in literature. However, the current state of the art covers various applications, from supply chain simulation on a macro-level to intralogistics applications on a micro-level. The analysis of the tools used shows a heterogeneous image in which no tool is used predominantly. With regard to the supply chain, the integration of energy aspects can be used for the sustainable design and improvement of supply chains. When it comes to the standardization for sustainability assessment of the supply chain, the validation of typical library values of LCA assessments can be supported by simulation. Furthermore, component-specific LCA can be derived from the digital representation of these components using simulation.

We presented two examples for the consideration of energy factors in logistics in practical case studies from a supply chain and a container terminal. The application cases have shown that the collection of data for energy consumption and emissions is a main challenge when it comes to generate a realistic simulation model.

With regard to current trends, we expect that the progressive electrification will bring new technologies to the market in the field of transport, such as autonomous driving and electric trucks. This offers new application cases and opens a new field for further investigations. In intralogistics, autonomous systems such as AGVs, robots, and drones, are also applied and will increasingly move into the focus of research.

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