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A CASE STUDY FOR SIMULATION AND OPTIMIZATION BASED PLANNING OF PRODUCTION AND LOGISTICS SYSTEMS

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ABSTRACT

This paper introduces a practical approach for the comprehensive simulation based planning and optimization of the production and logistics of a discrete goods manufacturer. Although simulation and optimization are well-established planning aides in production and logistics, their actual application in the field is still scarce, especially in small and medium-sized enterprises (SMEs). This is largely due to the complexity of the planning task and lack of practically applicable approaches for real-life planning scenarios. This paper provides a case study from the food industry, featuring a comprehensive planning approach based on simulation and optimization. The approach utilizes an offline-coupled multilevel simulation to smooth production and logistics planning via optimization, to optimally configure the production system using discrete-event simulation and to optimize the logistics network utilizing an agent-based simulation. The connected simulation and optimization modules can enhance the production logistics significantly, potentially providing a reference approach for similar industry applications.

1 INTRODUCTION

Simulation is a well-established planning aide for planning purposes in production environments (Michaloski et al. 2011), both for production planning and control (Kádár et al. 2004; Mula et al. 2006) and for optimizing factory processes (Kuhn 2006; Stahl et al. 2013). Despite the availability and acknowledged potential, the practical application is still scarce, as both a literature review (Jahangirian et al. 2010) and practical experience in the field of planning projects in the manufacturing industry show. A major hurdle is the perceived difficulty of designing models and acquiring proper data as well as the scarcity of reference applications with significant shown benefits. This paper is aimed at contributing to the understanding of potential benefits of simulation applications for practical planning purposes, especially for small and medium sized companies (SME), that find it particularly hard to cope with complex planning situations and the application of advanced planning techniques. The paper is based on a complex planning case for a food manufacturer in Europe, in which a multi-module simulation based planning method was developed and applied. The cased study results are discussed .

The paper is structured as follows: After an introduction of the case study and a general introduction of the planning approach, the three major modules of the approach are presented. The paper will finish with a summary discussion of the results and an outlook on future research.

2 CASE STUDY INRODUCTION AND APPROACH OVERVIEW

The case study is based on a food manufacturer in Europe that produces goods for supermarket chains and wholesale, also located in Europe. The planning task that is meant to be aided by the simulation based approach presented herein, is the factory planning of a new factory with updated production technology and processes as well as a significantly increased production capacity to support the expected growth in the company's business. The goals for the planning mainly consist of calculating the necessary amount and capacity of production and logistics resources, while at the same time improving the productivity of the system, which in turn minimizes the investment and operational cost for the new plant. Figure 1 offers a simplified overview of the main production process.

Figure 1: Simplified process overview of the production facility of the case study.

The planning comprises a smoothing of the production to optimize the capacity utilization, the configuration of the production and logistics system, as well as an optimized planning for the supply-chain network of the company. These planning aspects require different simulation characteristics and methods to optimize and model the real-life system. In this approach the abovementioned planning aspects have been segmented into three major modules, displayed in Figure 2.

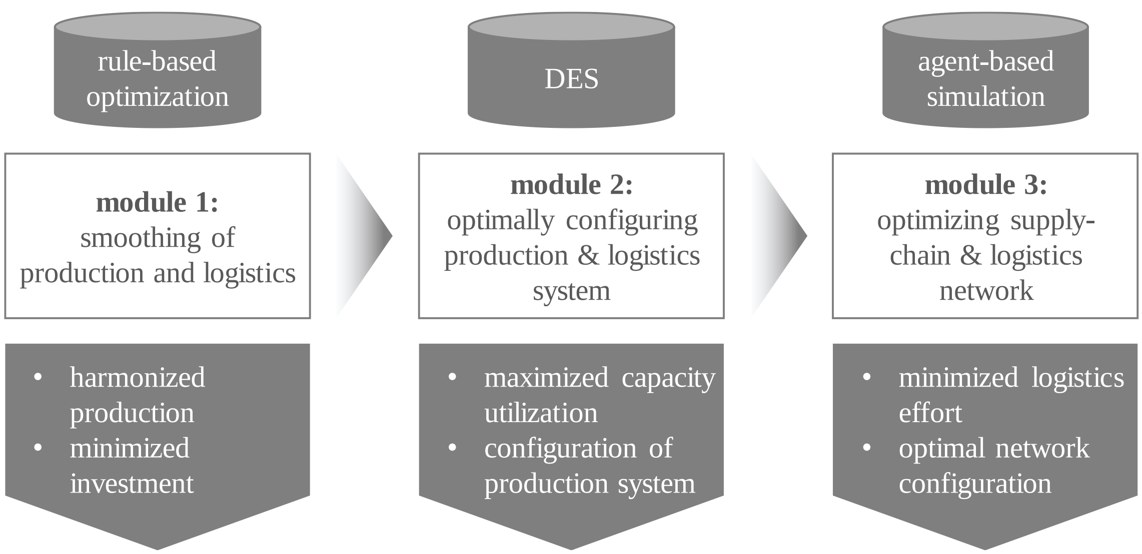

Figure 2: Overview of the simulation-based planning approach, including the goals of each module.

This approach represents a multilevel simulation with an offline coupling – an online coupling is not necessary since the simulation results are only required successively. Each of the three method modules receives the results of its precursor as input data, beginning with module 1. Thiede offers an overview for multilevel simulation options in planning environments (Thiede et al. 2016). The three method modules will be presented successively – for each component the basic concept, related work and the implementation and results will be presented.

3 SMOOTHING OF PRODUCTION AND LOGISTICS THROUGH OPTIMIZATION

The first module of the planning method is the smoothing of the production and logistics workload via a rule based optimization. The basic idea behind the developed smoothing approach is to eliminate spikes in sales volumes in order to not confront the production and logistics system with workload exceeding the capacity that would necessitate costly measures to cope with – see Figure 3. Shifting/pre-drawing start-of-production dates requires prolonging the production process by prolonging a maturing process and/or the finished goods storage.

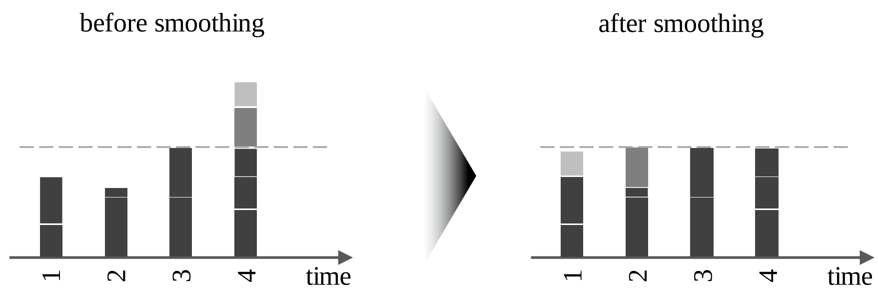

Figure 3: Example for smoothing principle – two peak orders are pre-drawn to harmonize the workload.

3.1 Related Work

External fluctuations in demand, together with amplifying effects in supply chains – e.g., the Bullwhip-Effect – can lead to significant inefficiencies in production systems. Thus, the smoothing of production workload is a way to significantly improve the efficiency of production systems. Possible methods of achieving a smoothing effect are:

- The Heijunka approach from the Toyota Production system, which achieves a harmonized production by employing local control mechanisms such as KANBAN control (Veit 2010).The approach is most effective in volume production applications, such as the automotive industry, were it originated from.
- A smoothing method based on a multi-criteria optimization of production schedules is another way of achieving schedules that increase the efficiency of production systems (Sobottka et al. 2017). However, the complexity of considering the capacity in log-term planning horizon is a challenge for optimization based methods, which are by nature computation-intensive.
- Rule based approaches that time-shift production volumes are another way of smoothing production. Tegel for example has developed a "Goal-Chasing-Heuristic" that builds smoothed plans from scratch (Tegel 2012). The algorithm fills "tacts" (timeslots) with orders with a given capacity limit for each tact, while trying to minimize the unused capacity in each tact. Orders that exceed the remaining capacity of a tact are scheduled in one of the following slots.

In the case considered herein, the planning has to start with a given plan – containing sales volumes and delivery dates – that have to be optimized for the production and logistics system by a suitable smoothing method. Thus, the following rule based approach has been developed.

3.2 Approach and Model

The future sales volumes – i.e., sales in the upcoming months – are being forecast by analyzing contracts, negotiations with costumers and taking into account sales trends of the past. Due to the nature of this specific food industry, well over half the annual sales volume is sold via special promotions – these have to be negotiated with the customers, supermarket chains and forecasting those requires considerable experience from the planners. The optimization rules have been developed by the company's planners in the past and are a reflection of what kinds of sales peaks have to be tackled and how much the volumes may be time-shifted – i.e., produced ahead of the delivery date – restricted by technological and quality constraints. Over the years, the planners have accumulated this knowledge derived from considerable insight into the complex system behavior. In the course of optimization workshops the rules were formalized. The capacity restrictions pertain to two major facility groups: packaging machines and a storage and treatment facility, in which the unfinished products are matured under specified conditions for multiple days. Accordingly, the optimization is split into two phases, plus a third to transfer the results into feasible production lots:

- Phase 1: the smoothing of special promotion sales volumes in order to reduce capacity peaks for packaging machines according to product-specific rules
- Phase 2: the smoothing of both promotion and standard sales volumes according to volumes exceeding the available/desired production capacity
- Phase 3: the resulting scheduled production quantities are quantized into production and transport lots in a way that optimizes the utilization of transport containers and production facilities

In Phase 1 the rules are solely experience based and they decide for each individual product, how incoming promotion-sales volumes should be segmented and scheduled for production prior to the delivery date. This ensures a more even workload for the packaging and requires finished goods to be stored longer in the finished goods storage. Phase 2 is focused on reducing overall peaks in workload for the production and logistics system. An ABC-Analysis is conducted for the products: for type A and B products the forecasted production volumes – including the results of phase 1 – are analyzed for volumes exceeding a set mean capacity value for each product. For type C products this analysis is conducted for entire groups of products. Once the excess-volumes have been identified, the algo week tries to shift the volumes to an earlier date – trying to shift only as much as necessary and only as much as their respective expiration dates allow for. If excess volumes cannot be shifted they remain as a residual peak and have to be addressed by capacity enlarging flexibility measures, e.g., overtime or additional shifts, or by increased production capacity. Since the resulting production quantities after Phase 2 are calculated decimal numbers, they have to be quantized into production lots that correspond to the capacity of transport and handling equipment, which in turn is necessary to hold the unfinished products during the long treatment processes. For this last phase, an algorithm was developed, that aims to distribute the scheduled quantities of products to production lots, trying to fit the volumes determined by Phase 1 and 2 as accurately as possible, while maximizing the number of full transport-storage devices, e.g., resulting in fully packed trolleys.

3.3 Implementation and Results

The developed method was implemented in *Java Eclipse Neon* that offers an object oriented programming and high processing performance. The orders are read via a table with scheduled orders or order forecasts and every order, including its characteristics – e.g., product type, technological properties – is converted into a data object within the smoothing method for fast computing. To validate the underlying model and to evaluate the impact of the smoothing algorithm, the method was applied to historical sales and production data from the past three years. After the validation, the historical data was extrapolated taking into account scenarios for future growth – the smoothing method was then applied to this resulting data to evaluate, how many relatively expensive packaging stations (Phase 1) and production units (Phase 2) could be saved by providing a certain amount of relatively cheaper conditioned maturing-storage space and finished goods storage. The results show that the rule based smoothing method is able to replicate and slightly surpass the performance of the rule based smoothing of promotion sales volume (Phase 1) that had been compiled by planners manually – see Figure 4.

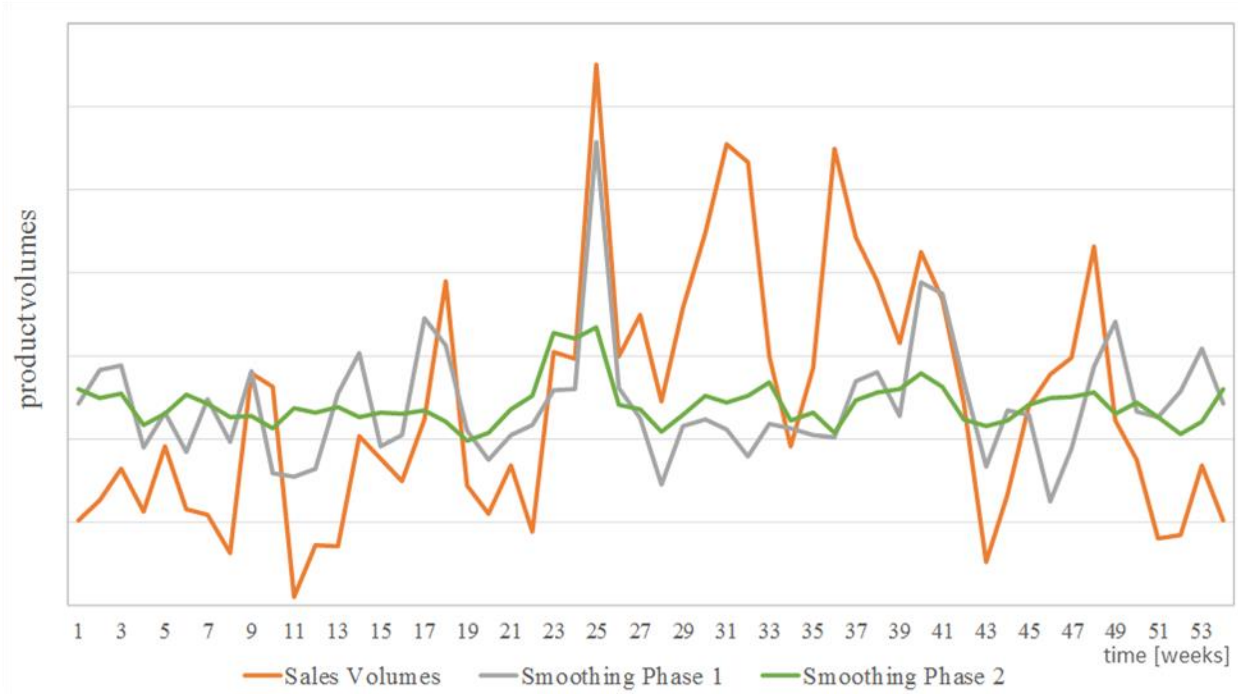

Figure 4: Impact of the smoothing method on scheduled product volumes: Smoothed Production Trend vs. Original Sales Volumes.

This reduces the number of additional packaging machines needed in the future. In addition to that the Phases 2 and 3 are able to reduce the necessary capacity in the multi-stage production process by ~40%, compared to an unsmoothed production plan. Given the very expensive production equipment, this translates to considerable savings – in the order of several million Euros of investment – both in investment for the future plant and its expected operational cost. The smoothing requires additional storage capacity in a process that only requires minimal conditioning and the associated investments of which are considerably lower. Thus, provided the restrictions are observed, the optimization is economically sensible. The detailed results show that these improvements are achieved by only shifting the modest amount of ~9% of the entire sales volume in the course of three years. This keeps the optimization costs both in equipment – larger maturing process facilities – and waste energy and storage low. Although the smoothing method was also used for the dimensioning of the production equipment – i.e., packaging machines and maturing process facilities – a second important application will be the operational planning.

4 CONFIGURING THE PRODUCTION AND LOGISTICS SYSTEM

The smoothed scheduled production volumes are subsequently used as input for the second module of the simulation based planning approach: With the help of a discrete-event simulation (DES) both the multi-stage production system and the storage-, commissioning and logistics system of the new production plant with increased capacity are being configured.

4.1 Related Work

Simulation means conducting experiments with a model of a – typically complex – real-life system. In the context of planning in production, a form of dynamic, discrete-event simulation (DES) (Law and Kelton 2000) is the most common option (Sokolowski and Banks 2012). In this kind of simulation the time lapse of processes is considered at certain points in time, determined by events, such as the start and end of process steps, movements or decision processes. A simulation can be combined with optimization methods, e.g., mathematical optimization and metaheuristics, to simultaneously simulate processes and improve the system performance. This is especially interesting, when simulation is used for planning tasks in production and logistics systems. One option is to use simulation as an evaluation function for the optimization, another option is to include an optimization algorithm for a specific task within the simulation procedure (März et al. 2011) – the latter will be used in the presented planning approach.

4.2 Approach and Model

The production and logistics system consists of three major sections (see Figure 1): A preliminary production step with a short duration is separated by a warehouse storage from the second step, a multi-stage production process that lasts several weeks, during which the unfinished product is being treated, matured and processed. A further maturing and storage step leads to the third major step, the packaging, storage and commissioning. For each of these three steps a simulation was developed to optimally configure the key properties that define the cost and performance of the production and logistics system. As with the smoothing module, this module is also intended for later use in the operational planning of the factory.

Part 1 – Preparatory Step: In the short preparatory step, the smoothed production schedule is used as an input and converted into delivery schedules of the suppliers. The incoming deliveries are then transformed into detailed, daily production plans within the simulation. The goal of the simulation is to determine the necessary number of machines and staff for this first production step and to provide a realistic input for the following simulation by accurately replicating the detailed production planning algorithm of the factory. The actuating variables are the number and performance characteristics of the machines, the number of production staff plus the working hours per day – i.e., the shift schedule.

Part 2 – Multi-Stage Production Process: In this step, the unfinished goods are being batched into production lots and put onto specialized transport, storage and treatment trolleys. An optimization algorithm within the DES was developed to maximize the capacity utilization of the trolleys. The trolleys then proceed through a multi-stage process in specialized treatment units that lasts several weeks and is determined by the product types. For this process another optimization routine was built into the DES ensuring the product-quality by guaranteeing certain process characteristics – e.g., minimum time spent in a process step – and simultaneously maximizing the capacity utilization of the treatment cells. The major tasks of the simulation for this second step are to determine and minimize the number and capacity of necessary treatment cells and to provide the following simulation with realistic data by accurately simulating the future process of the actual production system. The optimization algorithm embedded within the simulation analyzes upcoming orders at a production step where raw material is being cut into pieces as intermediate products. Most important among the analyzed characteristics are the order delivery date and the product type of the final product. The algorithm then tries to fill up specialized movable racks in which the intermediate products are being kept during most of the remaining production process. The algorithm utilizes a small sorting buffer to optimize the capacity utilization of the racks. Since some of the production steps are conducted in very expensive treatment cells, which can only be filled with the special racks, this local optimization through sorting also has a positive effect on the number of required treatment cells, thus protracting the dates at which further treatment cells will have to be installed in the planned factory.

Part 3 – Packaging, Storing and Commissioning: In this last step the products are being packaged into small units, stored in different storage facilities according to the product type and finally commissioned and shipped to the customer. The DES is meant to simulate the entire process but the major goal is to optimize and configure the main storage facilities and most of all an automatic small parts warehouse that holds the majority of the products. A major challenge in this module was to accurately simulate the complex interactions of multiple packaging machines, conveyors, automatic rack transport vehicles, the utilization of storage space and the commissioning process – with each of the ~300 of products and variants requiring a specific process variant. An optimization algorithm within the DES was developed to minimize the number of transports and actuations within the automatic small parts warehouse. The algorithm tries to batch as many products into one transport by combining and sequencing transport requests with the same product types during a day. By minimizing the transports the requirements and thus the investment of the future storage system can be reduced.

4.3 Implementation and Results

The three part simulation was implemented with the commercial DES software *Plant Simulation 13*. The extensive parts of customized production and logistics logic described in chapter 4.2 have been encoded in tailor made methods in sim talk, the code language of Plant Simulation.

The simulation for **Part 1** processes 1,7 million moving material entities – in a simulated time of three years, which is kept constant for the remaining simulation parts – and emulates the behavior of a system of 15 machines plus handling equipment. It was also used to evaluate an alternative, more advanced production technology for the preliminary production step, which, as a result of the evaluation, will be installed in the newly built production plant.

The simulation for **Part 2** processes ~3 million moving product entities and simulates the behavior of 40 production cells. The optimized batching method is able to increase the utilization of critical capacity by 3% – this further reduces the number and capacity of necessary production cells that could already be reduced by the smoothing method (see chapter 3.3). Figure 5 shows an exemplary capacity utilization trend including the warm up phase starting from an "empty production".

The simulation for **Part 3** emulates the behavior of 20 packaging machines, a palette storage, an automatic small parts warehouse and multiple commissioning machines plus an extensive intralogistics transport network. Utilizing the developed optimization routines within the DES, the transport and handling operations in the storage facility could be reduced by ~20%, thus significantly reducing the requirements for the rack transport vehicles, corresponding to significant investment reductions for the new plant. It is important to note that all the optimization logic elements within the simulation module will have to be used in the future operations of the production plant, either in the form of a standalone simulation that is used as an operational planning tool or implemented into the control logic of the subsystems of the actual production and logistics equipment.

5 OPTIMIZATING THE LOGISTICS NETWORK

The last module of the simulation based planning approach is aimed at optimizing the logistics network and network strategy of the food manufacturer. Different network-scenarios are designed and evaluated with an agent-based simulation of the logistics performance for each variant. This simulation module receives the scheduled and shipped products from the production simulation (see chapter 4).

5.1 Related Work

Globalization has led to an internationalization of production – even medium sized companies organize their operations in networks of interconnected production sites, suppliers and customers (Shi and Gregory 1998). Production networks as systems of factories with matrix connections and corresponding interrelations require a network management – the single production sites cannot be treated in isolation (Rudberg and Olhager 2003). The geographic allocation of production sites, the allocation of resources and strategies to produce, organizing the global supply of goods and deliveries, modes of covering regional markets or methods of seizing regional opportunities and benefits are among the global footprint related decisions, companies with production networks have to take (Laqua and Wey).

In order to take these decisions effectively, performance measurement systems for the networks are a key element for planning (Arif-Uz-Zaman and Nazmul Ahsan 2014). Considering the simulation of production networks and especially the transport and logistics aspect, which is the focus in this paper, agent-based simulation are a suitable way of considering the complex systems with heterogeneous behavior within the system (Leitão 2009). There are also reference applications for simulating the autonomous behavior of elements in supply chain networks with agent-based simulations (Macal and North 2009).

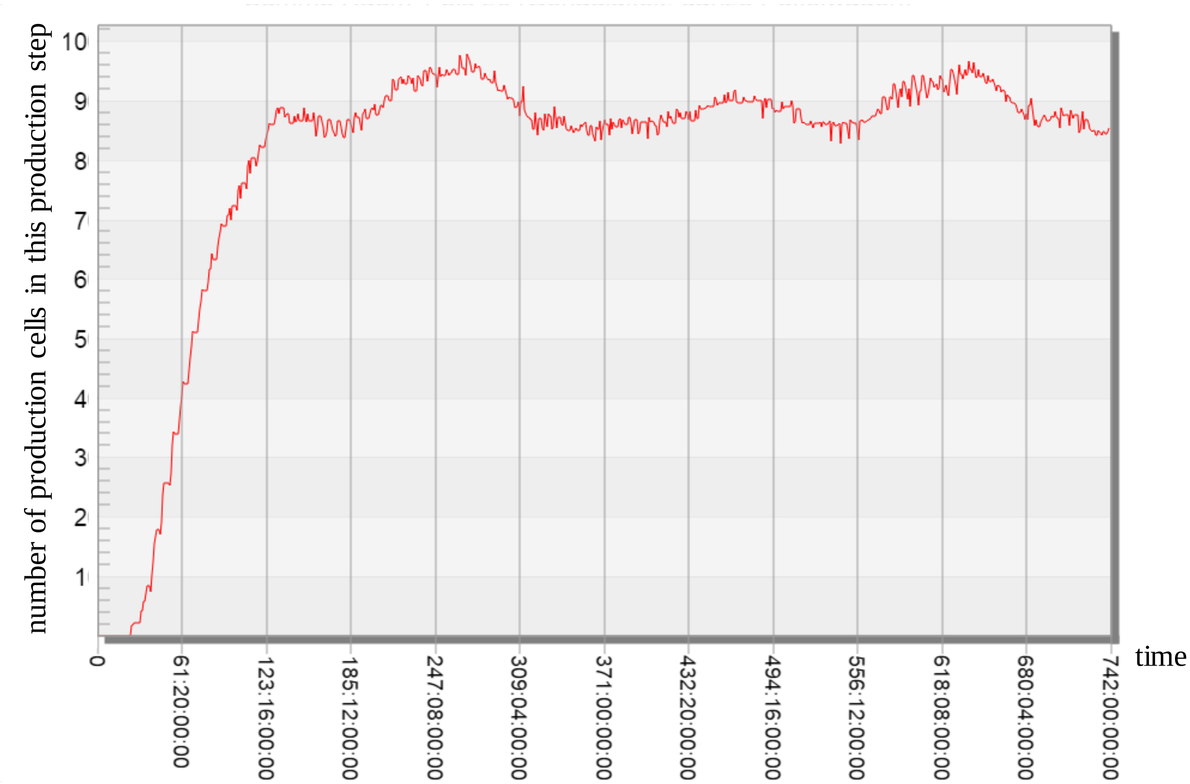

Figure 5: Example – results for the required capacity trend for one of the production steps.

5.2 Approach and Model

The production network of the case study consists mainly of the production facility itself, multiple suppliers in Europe and multiple customers, which are supermarket chains in Europe. The transports are conducted with trucks – the deliveries to the production facility are executed by the suppliers and the finished goods are shipped to the customers by the producer. The simulation model contains all of these components and uses the scheduled production volumes as input. The start-of-production dates are converted into corresponding supplier delivery dates – the supplier delivery dates are modelled after the existing supplier contracts, with extrapolated volumes for future planning periods. The shipping dates are a direct input from the production simulation module (see chapter 4). The geolocation of both suppliers and customers is used as an input for this simulation module. There are two basic scenarios being evaluated: Scenario A with two specialized production sites, that are largely specialized according to product types but which also exchange unfinished goods, and scenario B with a single, larger production site – see Figure 6. In both scenarios the supplier- and customer network is identical. Within these basic scenarios different locations for the production site(s) were also evaluated. For this last planning module the aim is to compare the logistics performance of the scenarios to support the strategic decision where to locate the future production sites and whether or not to integrate the existing sites into the future supply network or to concentrate the production in one centralized plant. The objective function consists of key performance indicators, developed together with the company's management. The key indicators are: costs (costs of production, logistics costs a quality costs), network indicators (lead-time, delivery service level), production site indicators (site performance, infrastructure) and sustainability indicators (CO_2 Emissions, usage of renewable energy). These indicators were built into the simulation model in order to provide decision support. More detailed information on this module has been published (Biegler et al. 2017).

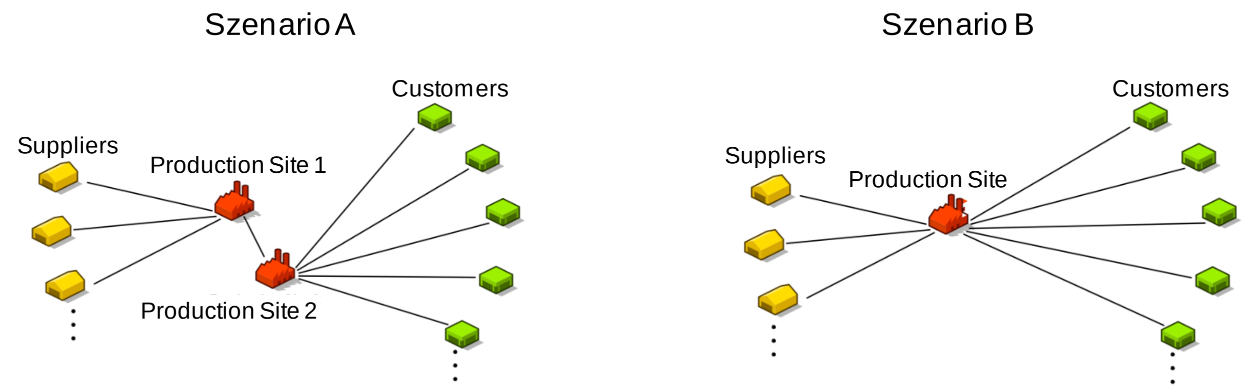

Figure 6: Overview of major logistics network scenarios.

5.3 Implementation and Results

The simulation was implemented in the commercial multi-method simulation software *AnyLogic 7.3.1*. The transport network simulation is modelled in the agent-based module – suppliers, customers, trucks and manufacturing facilities are modelled as agents with a custom behavior. The geospatial aspect is covered by the built in Geographic Information Systems (GIS). Using the GIS, *AnyLogic* is able to simulate realistic routes and transports for every truck automatically. Input-Excel files are used to read the locations of suppliers, customers and the manufacturing facilities. Figure 7 shows the basic structure of the supply-chain network in *AnyLogic*.

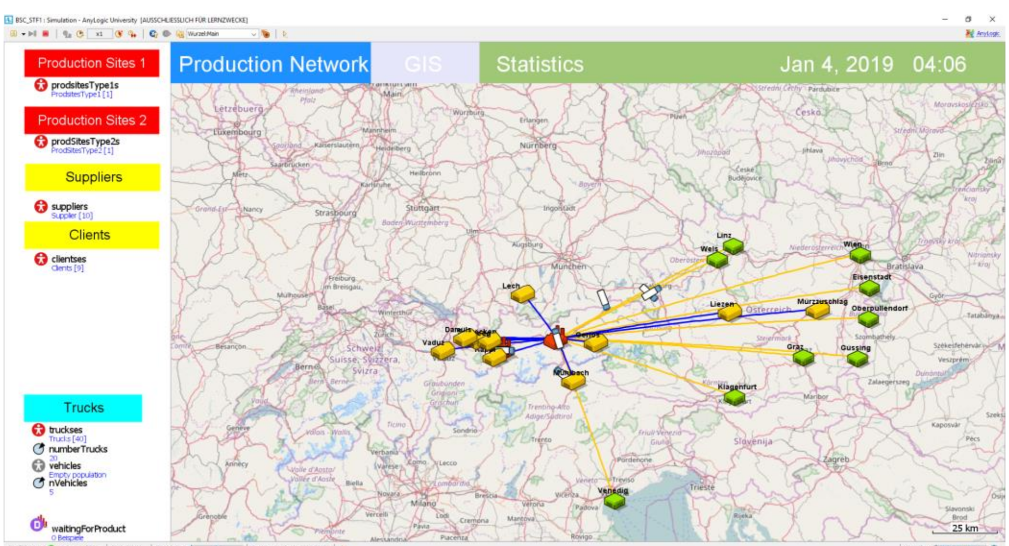

Figure 7: Overview of the AnyLogic simulation model.

The results (see Figure 8) indicate that scenario B with the centralized production achieves a higher overall performance, according to the key indicators. The most important difference is the 1 million kilometers shorter annual accumulated transport distance, with an associated reduction of CO_2 emissions by 13%, all within a simulated time of two years. The reduction is mainly due to the eliminated transports between the production sites and the changes transport lengths between the production plant. its suppliers and its customers.

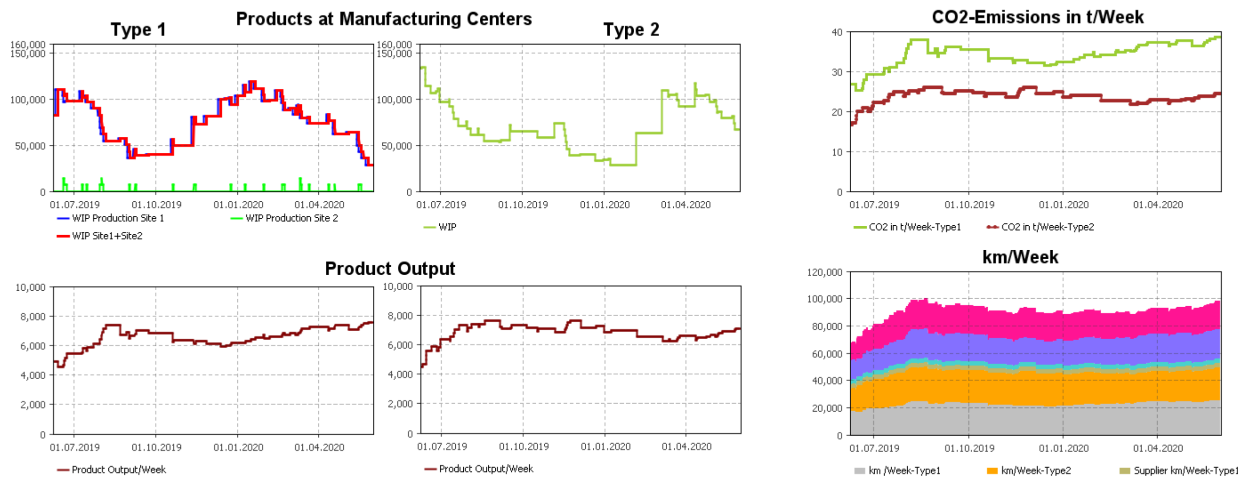

Figure 8: Example – overview of the results screen for the network analysis.

6 CONCLUSION AND OUTLOOK

The results of the factory planning benefitted significantly from the application of the simulation based planning approach. Through the smoothing module, the necessary capacity for expensive and critical production resources could be reduced by 40%, which is equivalent to millions of Euros of saved investment for the new factory, while at the same time also improving the capacity utilization and thus minimizing the operational costs. The results of the second method module, the DES based configuration of the production and logics system, achieve an additional 3% reduction of the capacity demand. The configuration also enabled a targeted investment plan for the new factory, detailing when and how many new production machines/cells have to be installed in the future. It was also possible to reduce the capacity demand for transport and handling operations of the automatic storage facility, again equivalent to a significantly reduced investment requirement. The last module of the method, the supply-chain network optimization, was able to support the design of a supply chain network configuration with a 20% reduced transport distance, while simultaneously informing the search for an optimized factory location. In addition to supporting the factory planning, the method provides planning aides for an optimized operations planning for the future plant.

It is however important to note, that the three-phased smoothing method with its optimization results in heightened risk. Pre-drawing production volumes may lead to overproduction in case the forecasted promotions are cancelled. However, at the same time the risk of negative repercussions of interrupted production – e.g., due to equipment outages – is reduced. It is currently impossible to quantify both effects on risk due to the lack of available data; the planners at the company, with whom the results were developed, are aware of the situation and are able to provide human oversight for the planning and optimization in order to mitigate the risk.

The validation for the three modules could not be based on historical data since the underlying models describe a future state with (partially) changed production technology. Thus, the modules and their functions were validated together with experienced planners from the company, to ensure the modules provide feasible results and do work realistically and, most of all, as intended. The robustness of the obtained results was addressed by using multiple different data-sets representing slightly different future scenarios for each module. However, before their final implementation, the optimization methods will be tested in pilot trials during the ramp-up phase of the new plant – this offers the chance to fine tune the optimization modules.

The presented approach is applicable to other complex, discrete goods production environments – however, the simulation models have to be created anew for each new application case. Thus, combining the optimized smoothing of production planning with a simulation based optimization for the production planning and control in an integrated planning method is a major goal for future research work within this project. Enlarging the goal system of the optimized planning of production and logistics, especially towards sustainable manufacturing and energy efficient production, is another future research goal. An Advanced Planning System (APS) functionality has already been developed (Sobottka et al. 2017) and will be expanded by the longer planning horizons of a smoothed long term planning.

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