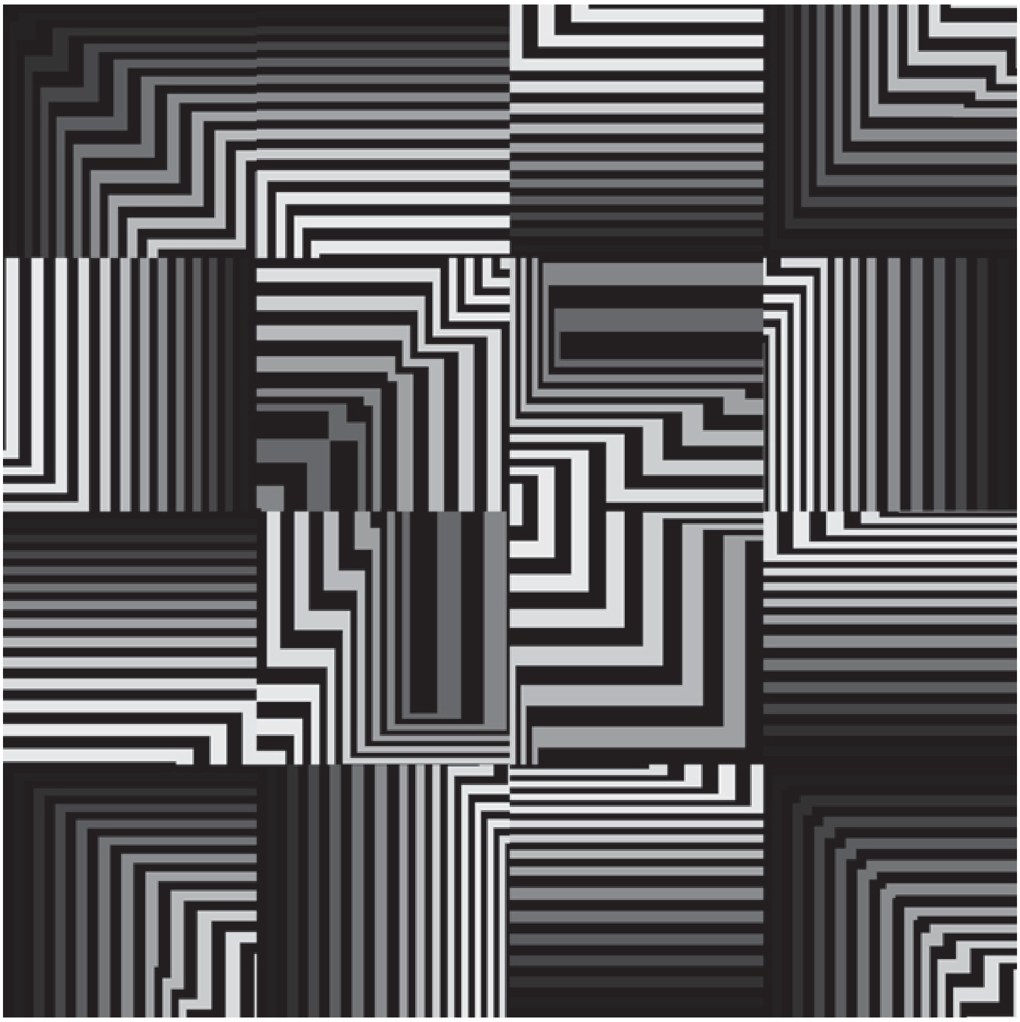
SNE SIMULATION NOTES EUROPE

SNE Special Issue
Simulation in Production and Logistics



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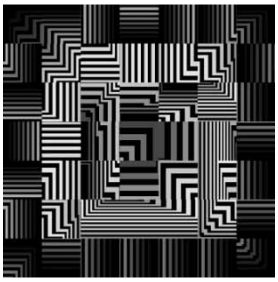
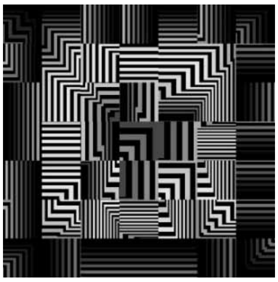
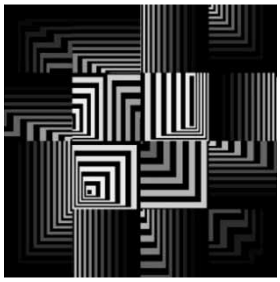
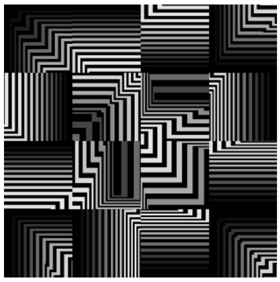
Editorial

Dear Readers, We are glad to present SNE 30(4), the SNE Special Issue Simulation in Production and Logistics, with selected outstanding contributions of the 18th ASIM Dedicated Conference "Simulation in Production and Logistics" (ASIM SPL'2019). We thank the special issue editors for their excellent editorial work (for details, see the special issue editorial).

Thirty Years SNE - we are pleased that for SNE Volume 30 Vlatko Čerić provided his algorithmic art as design for SNE cover pages. The artist and simulationist Vlatko Čerić has chosen four algorithmic art pictures from the series LABYRINTH for covers of SNE Volume 30. The cover of this issue SNE 30(4) presents LABYRINTH no. 21, – below readers can view all four cover pictures for SNE Volume 30, LABYRINTH no. 6, no. 7, no. 17, and no. 21. We thank again Vlatko Čerić for his co-operation.

Felix Breitenecker, SNE Editor-in-Chief, eic@sne-journal.org; felix.breitenecker@tuwien.ac.at

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Editorial Special Issue SPL 2019

SNE 30(4) comprises a selection of outstanding contributions of the 18th ASIM Dedicated Conference **Simulation in Production and Logistics** (ASIM SPL'2019), which took place in September 2019 at the Fraunhofer Institute for Machine Tools and Forming Technology (IWU) in Chemnitz, Germany.

Every two years, this conference – as Europe's largest conference on simulation in production and logistics – is organized by the ASIM Section *Simulation in Production and Logistics* (SPL) and presents trends, research results, developments, and significant industrial applications. The conference in Chemnitz has focused in particular on energy and sustainability, human work and workforce planning, and applications in factory control and logistics. An increased interest in data science and artificial intelligence in the context of simulation has clearly been visible.

The consideration of energy aspects in the simulation of manufacturing systems stands above all in the context of operational efforts for carbon-neutral production and sustainability. *Wörrlein et al.* investigate in the application of AI for predicting the energy consumption of machining jobs. For this, the authors present a hybrid system model that emulates aspects of the real system using a conventional simulation model in combination with a model generated from machine learning. *Dettelbacher et al.* use simplified simulation models, which are compatible with a low amount of data acquisition in different scenarios for the simulation of energy demands in aluminium die cast operations. This is in recognition of the fact that many companies often have a poor database for complex simulations.

Turek et al. describe a method for the analysis of power demand and load peaks of material handling components, combining the discrete event material flow model of a high-bay warehouse system with a power calculation model developed within the MATLAB environment. *Auf der Landwehr et al.* present a simulation approach and model, capable of reproducing shopping activities within the context of grocery retail. By employing this model, it is possible to assess the environmental influences of offline and online shopping concepts for urban areas in terms of sustainable operations and emission outputs.

Three selected contributions focus on human work and personnel deployment. The paper by *Zülch* provides an expert overview of the state of the art of personnel deployment simulation and its inclusion into the digital factory. The author states that the focus is mainly on anthropometric and physiological questions and on the working environment and sees the need to include aspects of occupational psychology and sociology.

März & Mielke introduce a simulation-based personnel planning and sequence optimization in mixed-model assembly lines. Their optimization approach considers workforce availability and qualification and reduces excessive overload peaks for workstations. *Leiden et al.* present a simulation framework to model production lines and interactions with shop floor workers relating to occupational safety and health. By adapting their framework to new challenges such as social distancing in pandemics, they address a very topical and relevant issue.

Studies on logistics concepts and the design and control of handling technology and conveyor systems are a traditional application field of simulation, which still contains many interesting innovations. *Habl et al.* introduce methods to solve the shuttle vehicle scheduling problem in high-powered automated vehicle storage and retrieval systems (AVSRSs), which require a much more complex control due to their increased flexibility and dynamics. In a series of simulation experiments, they show the performance improvement of horizontal transportation in various configurations of this new type of AVSRS. *Filz et al.* develop and validate a simulation-based data analysis framework for the planning of flexible manufacturing systems following a matrix-structured manufacturing systems design approach.

Many contributions of the conference offered surprising views beyond the typical application aspects and observation levels of simulation. An excellent example of these provide *Gnerlich et al.* by presenting a novel approach to simulate construction process disturbances with agent-based Petri nets using a building information model for expert construction time analyses.

The editors express their gratitude to all authors for their great effort and cooperation. For this SNE issue, they have revised and in many cases considerably expanded their original conference contributions, thus providing interesting insights into current considerations and the spectrum of scientific discussion. Furthermore, the editors would like to thank the reviewers for their substantial and precious support towards a special issue of high scientific quality. Last but not least the editors thank the SNE Editorial Office for the support in compiling this special issue.

The editors hope that you will enjoy this SNE issue, that it contains valuable suggestions and that it will encourage you to participate actively in the next conference, which will take place in Erlangen from 15th to 17th September 2021, see www.asim-fachtagung-spl.de.

Sincerely, the SNE 30(4) Special Issue Editors

Markus Rabe, TU Dortmund;
Andreas Schlegel, Fraunhofer IWU Chemnitz
Sigrid Wenzel, Universität Kassel
in the name of the ASIM Dedicated Conference SPL

Simulation-based Data Analysis to Support the Planning of Flexible Manufacturing Systems

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Abstract. A matrix-structured manufacturing system represents a flexible manufacturing system that combines volume- and variant-flexible production and strives for efficiency. The system is a modular, cycle-independent manufacturing concept in which all workstations are linked by a flexible transport system. Due to the function of the manufacturing system, the requirements at the individual workstations are not known in advance. Therefore, the planning of the material supply according to requirements is a relevant target value in the planning and design of such a flexible manufacturing system. In order to support the planning, the characteristics of material supply can be investigated with the help of an agent-based simulation. However, the simulation results must be examined in more detail in order to be used for planning flexible manufacturing systems. Therefore, data analysis can be used to derive necessary knowledge from the simulation data. In this context, the aim of this paper is to support the planning of flexible manufacturing systems by developing and validating a simulation-based data analysis framework.

Introduction

The line-oriented production is the main production principle in numerous industrial companies. Considering these companies in detail, a variety of challenges can be identified. Among these are a strongly fluctuating demand, decreasing product life cycles and an increasing amount of variants [1].

These influences increase the flexibility and efficiency requirements for the production system. The concept of a matrix manufacturing system (MMS) helps to meet the aforementioned challenges with a high degree of flexibility and scalability [2]. Figure 1 provides the graphical comparison of both manufacturing systems.

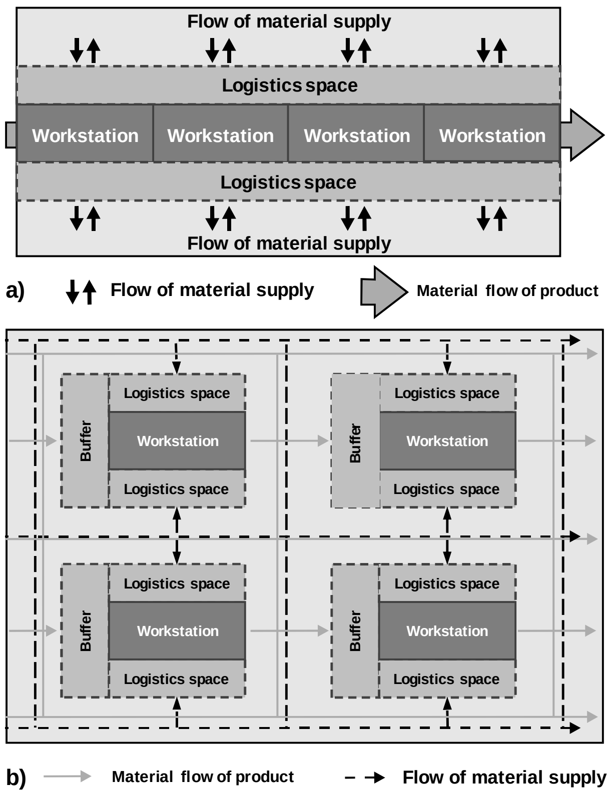

Figure 1: Comparison of (a) line configuration and (b) matrix manufacturing system [3].

The matrix-structured manufacturing system is composed of modular and decoupled workstations (WS), which are internally connected by a flexible transportation system (Figure 1).

The material flows are coordinated by an intelligent production control system within the manufacturing system.

An elementary component of every production system is the internal material supply, which provides the required components. This process has significant influence on the efficiency of the whole production system. The network-related structure of the MMS consists of an uncoupled modular and redundant WS design. This design leads to multiple demand locations for the same material or modules. Therefore, the destinations and individual routing of the materials are not known beforehand. The assignment of products to the WS is performed by the production control system at short notice and is particularly dependent on the specific circumstances within the manufacturing system. This limits the planning of material supply and reinforces the need for responsiveness and flexibility [3].

The design of this manufacturing approach causes numerous dynamic and stochastic effects. These increasing uncertainties of the system have a direct effect on the material supply strategy. To overcome these challenges already during the planning phase, this paper develops a methodology that uses simulation results as a basis for data analytics to identify and control relevant system parameters in an early planning stage of a flexible manufacturing system using an MMS as an example.

1 Planning of Matrix Manufacturing Systems

In order to specify the MMS planning challenges in more detail, the requirements on material supply strategies are explained in Section 1.1. In addition, Section 1.2 discusses different approaches to simulating MMS and derives the need for further research with a specific focus on the material supply strategy within the MMS.

1.1 Requirements on Material Supply Strategies

The material supply is a central component of the MMS, because – in contrast to line configuration – no materials are stocked at the individual work stations. Therefore, in order to determine the material supply requirements within the MMS, the influencing factors on the one hand and the design on the other hand must be determined. Due to the fact that the material supply belongs to the logistics system, it is part of the higher-level production system.

Thus, the characteristics of the production system define the framework conditions for the design of the material supply. Furthermore, the characteristics of the material spectrum to be provided have a major influence on the design of the material supply. These include logistical (e.g., frequency of use), physical (e.g., volume) and handling (e.g., bulk material) properties of the material spectrum to be provided [4]. In order to gain a better understanding of the differences between the line configuration and the MMS, Table 1 shows the central characteristics of the respective manufacturing system configurations.

Requirements	Line configuration	MMS configuration
Delivery locations	single	multiple
Material bundling	dependent on assembly order	hardly possible
Short-term capacity planning	fixed	Variable / dynamic

Table 1: Comparison of selected design parameters for line configuration and MMS [3].

The design of the MMS network structure of unlinked modular workstations and the multi-redundant structure lead to several possible delivery locations for the same material or modules. This requires a simple WS layout, which enables an easy design of the supply of the respective WS. Furthermore, the source-sink relationships are dependent on the respective system status and the selected production control logic in an MMS, because they need to react variably and dynamically. This results in different supply locations for individual workpieces (WP) within a system. Due to the missing planning base as a result of the dynamic system behaviour, a bundling of required materials for supply is hardly manageable [3].

Once the material is fed into the production system, the WS on which the product is processed are not known as they are determined by the production control system on short notice and depending on the individual situation. This leads to a renunciation of short-term material supply planning [3].

In addition, due to the lot size of one, the number of transport operations within the MMS increases. Due to the architecture of the MMS as a network structure, there is an overlap between the product transport and the material supply.

Assuming a high number of transport processes, the risk of blockages on the transport routes increases significantly, resulting in increased uncertainties in the overall manufacturing system. In this context, deadlocks can occur especially in close-meshed layouts. For example, decentrally controlled automated guided vehicles (AGV) trigger a circular closing and completely block each other. This must be prevented; otherwise, the entire system will be blocked due to missing material supply and product transport [5].

1.2 Simulation of Material Supply Strategies within MMS

Simulation is applied to support the planning process of production systems. For this purpose, simulation is used especially in industry and research as a method of representing and imitating real systems as a function over time [6]. Simulation is often used to validate, analyse, and optimise flexible systems, such as production logistics systems [7]. In manufacturing, methods of simulation are used for a wide range of tasks. Most common are layout design, planning, analysis, and optimisation of manufacturing systems [8]. Furthermore, simulation offers the chance to analyse cause-effect relationships within the system and to represent the system behaviour in a comprehensible way [6, 8].

Greschke et al. introduce a methodology that strives to combine flexibility and profitability for assembly lines. Therefore, identical cycle times of all products are eliminated and the process is kept smooth. By focussing on a systematic assignment of several operations to specifically equipped WS and by controlling the corresponding distribution to ensure the dynamic configurability of the system, the MMS design is implemented [2].

Following this approach, Schönemann et al. more specifically focus on the main principles, elements, and control strategies of the MMS. Therefore, a simulation approach is introduced and discussed to evaluate different MMS control strategies. A use case is applied to validate the simulation approach for the planning of MMS. However, no detailed consideration is given to material supply strategies within the MMS [9].

Buth et al. focus on agent-based simulation approaches to increase the flexibility of manufacturing systems by using industrial grade software tools. The authors, therefore, introduce a generic methodology for implementing agent-based logic on an MMS use case [10].

Focussing more specifically on logistics, Kern et al. introduce five different material supply strategies for the future modular final assembly in automotive manufacturing. Applying this concept in a use case of pre-assembly at a German automobile manufacturer, a space reduction of 15 % could be achieved. However, the performance of the concept has not undergone any validation [11].

Filz et al. built up on the concept of Schönemann et al. [9] and expanded the MMS simulation approach with a focus on material supply strategies. Therefore, different material supply strategies are modelled and analysed with regard to predefined key performance indicators in an agent-based simulation environment [3].

Nevertheless, none of these approaches regarding the agent-based simulation of MMS anticipate decision support under consideration of uncertainties for the planning of material supply strategies within an MMS. Moreover, none of these approaches can help to understand and gain insight from various simulation runs. Consequently, the planning process of highly flexible systems like the MMS cannot be supported by previously validated planning parameters of the material supply system.

2 Data Analysis Framework for Planning of Flexible Manufacturing Systems

Previous investigations regarding simulation of flexible manufacturing systems, such as the MMS, show that these systems are highly dynamic and hardly predictable. This impedes the planning process of such systems. In order to support the planning process from an engineering perspective, decision support for relevant planning parameters is necessary. Therefore, a framework is presented in the following that supports the planning process of flexible manufacturing systems by applying a data analysis model on simulation results. The aim of this model is deriving knowledge based on simulation data in order to draw conclusions and to gain insight into interdependencies between different parameters, providing decision support for the planning of such manufacturing systems. In this context, decision support is understood as a target-oriented analysis of the simulation results under consideration of the stochastics and uncertainties of the manufacturing system for the most robust derivation of sensitivities and, thus, design parameters for the manufacturing system.

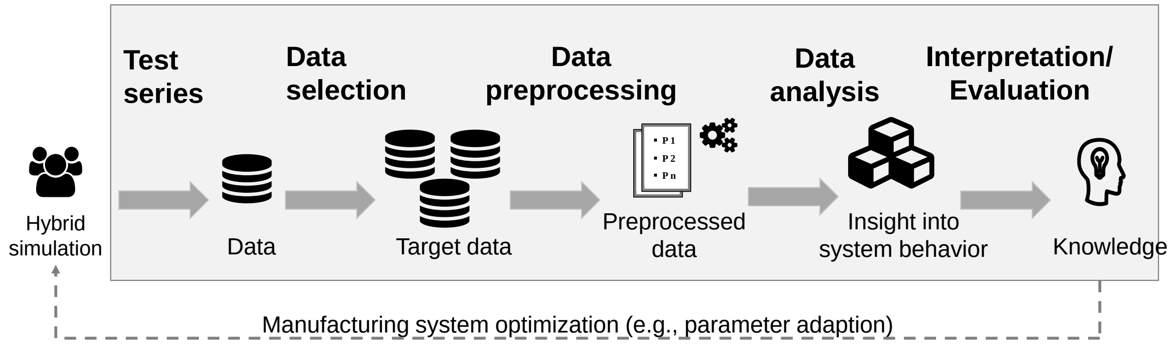

Figure 2: Data analysis framework for planning of flexible manufacturing systems (based on [12]).

The framework is based on the knowledge discovery in databases approach of Fayyad et al. as a standardized and widely-used procedure [12]. Moreover, it is extended to the specific requirements and application of simulation-based data.

The data analysis framework for planning of flexible manufacturing systems within this paper consists of several steps that are shown in Figure 2.

Initially, a simulation model has to be built. Since the focus of this paper is on the data analysis of simulation results, the development and validation of a simulation model is neglected.

Within the first step of the developed framework for simulation-based data analysis, necessary data for further analysis have to be generated. Therefore, various simulation test series have to be carried out for data generation. Since the manufacturing system is subject to stochastic and dynamic behaviour, the data used for analysis need to reflect the most representative system behaviour. Therefore, several target parameters that are relevant for the planning of the specific system have to be detected. In order to gain a deeper understanding of the system behaviour and the influence as well as interactions of the individual parameters, a parameter variation with corresponding simulation runs has to be carried out. Thereby, the behaviour of the individual parameters as well as the entire system can be monitored. In order to create the basis for a subsequent analysis, it is necessary to have a sufficient number of simulation runs that cover all necessary parameter combinations. Furthermore, the simulation results must be saved in a way that allows for subsequent analysis.

After acquiring simulation results, the target data need to be selected. For this purpose, the data are analysed regarding their importance for a larger scheme or system (e.g., utilisation of manufacturing system).

In this context, clustering methods can be used for unsupervised learning or classification for supervised learning approaches. The advantage of a clustering approach lies in the fact that automated and comprehensible thresholds between different parameter ranges can be defined. The choice of approach depends on the respective application [12].

The target data sets identified in this process will be used for further analysis. Moreover, the previously identified data sets are examined for their effect on the target value. Therefore, a correlation analysis of the parameter regarding the target value (e.g., utilisation of manufacturing system) is performed. The parameters with the highest correlation coefficient regarding the target value are considered for further steps.

Furthermore, the collected data need to be preprocessed to ensure data quality. Thus, the data must be converted into a format that allows for further processing. This includes, for example, the xlsx or CSV format. With the help of data structuring, the collected data are transformed into processable data types. In addition, the data need to be formatted to make them suitable for further analysis. Nevertheless, the data are filtered with respect to the analysis aim (e.g., selection of material-supply-related data).

The data analysis is supposed to offer insights into interdependencies between different parameters and their effect on the overall manufacturing system. For this purpose, the sensitivity of the parameters regarding the target value is analysed. Principally, different methods of data analysis can be used for this, such as data mining. On the one hand, this can be used for quantifying and ranking the effect of individual parameters on the target value. On the other hand, the identified parameter ranges can be used to obtain information on how such a system is to be planned in order to obtain optimal utilisation or performance.

In this context, for example, box plots as statistical methods can be used to analyse the distribution of the parameters with regard to their target value. A boxplot is a diagram to display the distribution graphically. With the help of a boxplot a first impression about the location and the distribution of data in a certain range can be given [13].

Within this developed framework, the data analysis aims at determining the optimal parameter combinations and their ranges. By using data analysis methods, parameter interdependencies can be identified and be provided as input and support for planning purposes. The tool is designed for the usage by different application groups such as planning or quality engineers.

With the help of the data analysis, knowledge as decision support is available, in which exact influences of individual parameters as well as parameter ranges and sensitivities are defined to reach the optimal target value.

For the improvement of the planning process of flexible manufacturing systems, the acquired knowledge can be used to improve the simulation model as a feedback loop as well as to support the overall planning process of efficient and flexible manufacturing systems.

3 Application of the Decision Support Model on a Matrix Manufacturing System

Since the MMS is highly flexible and dynamic, it is a hardly predictable system. This sets particularly high demands on the material supply system in terms of flexibility and responsiveness. Therefore, the previously introduced framework for decision support for flexible manufacturing systems is applied to the planning of the material supply strategy within the MMS.

For this purpose, an existing hybrid simulation model for the MMS with a focus on different material supply strategies will be used for simulation-based data analysis. The simulation model is based on existing work by Filz et al. [3].

After implementing the simulation model, multiple simulation runs are performed with a focus on the respective material supply strategy to generate test series. Therefore, a parameter variation is carried out that considers central planning parameters of the logistics system. During this process, the overall utilisation of the production system is set as a target value that describes the average working time of all individual ressources (e.g., machines) within the entire manufacturing system.

Each simulation run was carried out with 500 products. In total, about 3,000 simulation runs were carried out that cover the combinations of the selected parameters. Moreover, the simulation results were saved in an Excel spreadsheet for further processing. Table 2 gives an overview of the selected parameters for the parameter variation with their respective minimum and maximum values as well as the iteration steps.

Parameter	minimal value	max.imal value	Step size
Amount of products in system	6	13	1
Amount of AGV	2	18	1
Velocity of AGV [m/s.]	0.5	1.5	0.1
Loading time AGV	25	35	2
Unloading time AGV	25	35	2

Table 2: Selected parameter variation for test runs.

Within the framework, the target data are identified in a first step. In this use case, a k-means clustering method with six clusters is applied in order to identify the target data sets with a high utilisation of the manufacturing and logistic system. In addition, clustering is used to provide a transparent separation between the data. Therefore, a threshold at 0.19 for the overall utilisation of the manufacturing system is set. Consequently, only data sets that lead to a utilization of the manufacturing system over 0.19 will be used for further analysis (Figure 3a).

Furthermore, a correlation analysis of the filtered data is performed to identify the parameters with the highest impact on the target value of the overall manufacturing system utilisation.

Figure 3b displays the results of the correlation analysis in a ranked order. Based on this, the parameter “Amount of AGV” has the highest correlation coefficient with 0.62, followed by “Velocity of AGV” with 0.22 and “Amount of products in system” with 0.11.

For the purpose of data preprocessing, the selected data are checked for formal criteria such as data type in a first step. Within the preprocessing, the removal of noise or handling missing values within the target data sets is extremely important in order to be able to carry out the necessary calculations efficiently and in a target-oriented way.

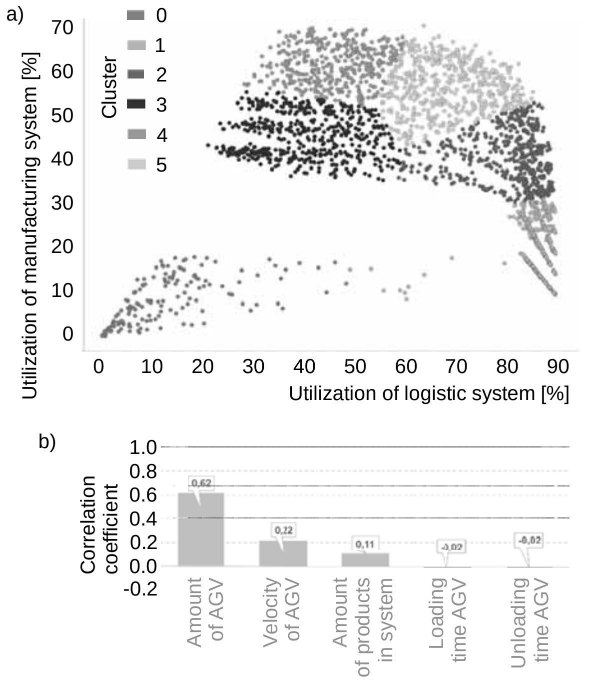

Figure 3: Identification of target data:
(a) Data clustering for defining threshold;
(b) Ranking of parameters based on correlation coefficient.

Within the data analysis step, a sensitivity analysis is performed. The previously selected parameters are analysed with the help of a boxplot to further identify at what range the parameters need to be set to ensure a high utilisation of the manufacturing system. Figure 4 displays the boxplots of the identified parameters in relation to the target value as a basis for sensitivity analysis.

Figure 4a graphically displays the behaviour of "Velocity of AGV" with the regard to the "Overall utilisation of the manufacturing system". The results show that the parameter values fluctuate between 0.2 and 0.7 of the utilisation of the manufacturing system.

However, the median changes only slightly during the increasing velocity of the AGV. Therefore, the parameter is seen as not very sensitive. With regard to the results, the highest utilisation of the manufacturing system can be achieved with a "Velocity of AGV" between 1.1 and 1.3.

With the help of Figure 4b, the sensitivity of "Amount of products" can be analysed. The simulation study assumed that a minimum of 6 and a maximum of 13 products are simultaneously in the system. The results show that with a higher amount of products the utilisation of the manufacturing systems increases. However, it should be pointed out that further research has shown that there is saturation for about 11 products; otherwise, there will be longer waiting times at the WS that lead to a decreasing utilisation of the system, and a higher number of transportation systems (e.g., AGV) is required. This increases the risk of deadlocks.

Figure 4c displays an increasing utilisation of the manufacturing system with increasing "Amount of AGV". A saturation of the utilisation can be determined between 9 and 11 AGV. This results in the fact that an additional provision of AGV does not lead to an increase of the utilisation of the manufacturing system and can, therefore, not be recommended.

After the individual parameters have been analysed with regard to their behaviour on the target value, the next step is to determine the optimal parameter combination. Within this use case, the assumption is made that the utilisation rate in such a flexible manufacturing system should be over 60 percent. To determine the optimal parameter combination, a decision tree is used to optimise the overall utilisation. With regard to the planning of the material supply within a flexible manufacturing system, the results show that the combination of 9 to 11 AGV with a velocity between 0.75 and 0.95 m/s seems to be the most robust combination. Ideally, there will be 9 to 11 products within the system at the same time.

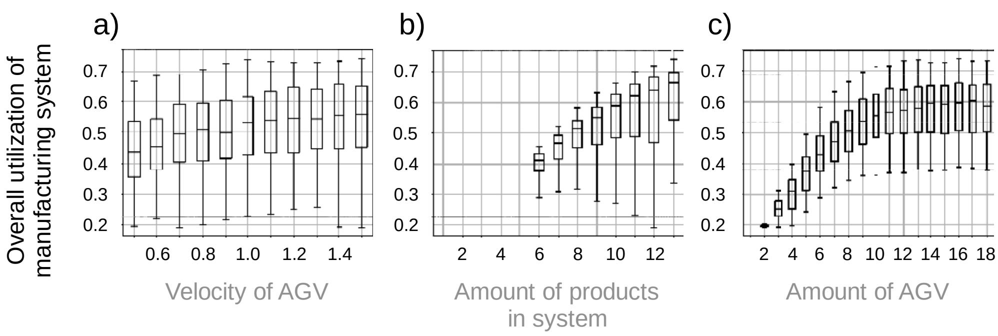

Figure 4: Sensitivity analysis of target parameters in relation to target value.

4 Conclusion and Outlook

Within this paper, a data analysis framework for planning of manufacturing systems was developed and implemented in a use case regarding the material supply strategy within the MMS. The use case shows the consistent implementation of the framework from the running of simulation test series to data analysis of the generated results. With the help of the developed framework, the parameters "Amount of AGV", "Velocity of AGV" and "Amount of products" could be identified as particularly important for the overall utilisation of the manufacturing system. Especially the parameter combinations of 9 to 11 AGV with a velocity between 0.75 and 0.95 m/s and 9 to 11 products were identified as optimal to achieve a high overall utilisation of the manufacturing system.

Since the use case only considered five parameters, test series with parameter variations of all subsystems are necessary to overall improve the manufacturing system. Therefore, it is necessary to analyse the combination of the parameters in order to be able to determine this influence on the target value. Moreover, only one material supply strategy for MMS was analysed. In addition, further research is needed regarding the usage of data mining algorithms for planning of flexible manufacturing systems. Using this approach, parameters with significant influence on the target values of the entire system can be identified at an early planning stage. This may, for example, enable greater consideration of interactions with the environment and can be used for the sustainable planning of manufacturing systems.

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Vehicle Coordination and Configuration in High-powered Automated Vehicle Storage and Retrieval Systems

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Abstract. The growing demand for increased flexibility and throughput capacity of automated warehouses is driving the implementation of rail-guided automated vehicle storage and retrieval systems (AVSRSs). A new type of AVSRS is capable of further increased performance by utilizing multiple vehicles along one rail instead of using only a single vehicle per aisle and tier. In this work, we introduce the shuttle vehicle scheduling problem (SVSP) in AVSRSs and present methods to solve the SVSP. We conduct a series of simulation experiments to show the performance improvement of horizontal transportation in various configurations of this new type of AVSRS and discuss main benefits of deploying high-powered AVSRSs.

Introduction

Automated vehicle storage and retrieval systems (AVSRSs), also known as shuttle systems, provide a flexible and efficient way for storing small transportation units. Due to the complete decoupling of horizontal and vertical transports executed by shuttle and lift vehicles, AVSRSs with aisle- and tier-captive shuttle vehicles achieve, in combination with unit lifts, the highest throughput capacity. Depending on the warehouse geometry in this version of AVSRS, throughput is limited by either the lift or the shuttle vehicles, i.e., the number of tiers and the length of the aisles [1]. By deploying additional shuttle vehicles on each tier as well as lift vehicles in each shaft, a further increase in throughput can be achieved in such systems if the coordination of several vehicles is successful. This results in a new version of AVSRS in the field of high performance that can meet the increasing requirements in terms of dynamics and flexibility of AVSRSs. Beyond the increased throughput of newly planned high-powered AVSRSs, existing systems can also be adapted flexibly and with little effort by deploying additional vehicles that can react to changing conditions.

In this work, the potential of high-powered AVSRSs is revealed by means of the horizontal transport on one tier of an aisle. First, an overview of existing research literature in the field of AVSRSs is presented. In order to conduct robust and efficient operations of several shuttle vehicles on a tier, strategies for the coordination of the vehicles are required. After the problem statement, solution approaches are presented and illustrated by means of a selected control strategy. The implementation of the control algorithm in a simulation model allows for subsequent performance testing, in various configurations, of a tier in an aisle.

1 Literature Review

The throughput calculation of AVSRSs that is associated with the configuration and design is the subject of numerous scientific studies and can be carried out using either analytical or simulation-based models. For example, the FEM Guideline 9.860 contains an analytical model for calculating the throughput of AVSRSs with vehicle and unit lifts. In particular, special cases such as double-deep storage or the use of several unit lifts in the aisle are considered [2]. Analytical models for AVSRSs with unit lifts and one shuttle vehicle on each tier are developed in [3] and [4]. The modeling of the individual tiers is based on queuing systems and is validated by means of discrete event simulation. The analytical determination of the throughput is, therefore, a suitable method, although it is mainly used for basic systems.

[5] develops a tool that enables the throughput calculation of various system configurations by using the Monte Carlo simulation.

[6] presents a simulation model for analyzing, in a short time, rack configurations with several lifts per aisle, in order to identify the optimal configuration. [7] conducts a simulation study to investigate the effects of different variables on the achievable throughput capacity of AVSRSs with unit lifts. Hence, a simulation-based throughput calculation is increasingly used if a large number of configurations and more complex systems are being investigated.

In principle, the throughput of AVSRSs is significantly influenced by their control. However, especially in the case of basic configurations of AVSRSs with unit lifts, the transport processes often do not require complex controls, or can often be defined by simple priority rules. An exception is the AVSRS with unit lifts considered in [8] with two lift vehicles moving in the same lift shaft. The vehicles are controlled by a block sequencing algorithm that optimizes the sequence of the transport jobs with the help of heuristics. [9] takes up this approach and supplements it by taking into account the acceleration and deceleration processes of the vehicles. In lift configurations with more than one lift vehicle per shaft, simple priority rules reach their limits and more complex control strategies are required to enable an efficient and robust operation.

Until now, AVSRSs with several vehicles on a tier have not been considered in literature, whether in regard to the achievable throughput or to the necessary control strategies.

2 Coordination of Multiple Shuttle Vehicles on a Tier

The coordination of several shuttle vehicles on a tier is a challenge for the control applied. In the following, the associated problems and possible solutions are presented and, finally, a selected control algorithm is described.

2.1 Problem Statement

In high-powered AVSRSs, several shuttle vehicles that move along the same railing system are available for horizontal transport on the individual tiers of an aisle. To ensure robust transport processes, it is necessary to coordinate the shuttle vehicles in such a way that block events and collisions are prevented.

At the same time, the control must ensure that waiting times and empty driving times are minimized, thus making the transport processes efficient. This challenge, which we define as Shuttle Vehicle Scheduling Problem (SVSP), is divided into the three successive problems of job allocation, sequencing and execution.

While the presented SVSP has not yet been considered, the Crane Scheduling Problem (CSP) is a comparable scheduling problem that occurs in the area of gantry and overhead crane control and has often been discussed in literature.

In addition to the CSP, the SVSP can also be regarded as a special case of general machine scheduling – it can, thus, be assigned to NP-hard problems and formulated equivalently [10]:

> n jobs $\{j_1, j_2, \dots, j_n\}$ must be processed, whereby
> m shuttle vehicles $\{s_1, s_2, \dots, s_m\}$ are available.

Basically, the optimization aims at minimizing the processing time of the considered jobs and, thus, maximizing the throughput on the tier. The following questions must, therefore, be answered in the SVSP:

- Which shuttle vehicles are, in principle, allowed to carry out the job concerned? (preselection of the shuttle vehicles)
- Which shuttle vehicle takes over which job and in which sequence or at what time? (allocation of the jobs to the shuttle vehicles)

2.2 Solution Approaches for the Shuttle Vehicle Scheduling Problem

In order to solve the SVSP on the tier, we rely on work carried out in the area of CSP. [11] evaluates and classifies possible strategies for preselection and allocation (Figure 1). Adapted to the SVSP on the tier, the following preselection strategies can be formulated:

- *Location-based restriction*: The tier is divided into zones that are assigned to the individual shuttle vehicles. Jobs that span several zones can, thus, only be fully processed by several vehicles.
- *Task-related restriction*: Shuttle vehicles are either responsible for the supply and disposal of one or more lifts or carry out assisting transport tasks, such as relocation or preliminary transports.
- *No restriction*: All jobs can be processed by all shuttle vehicles.

The preselection assigns each job j_i of the job list J to all shuttle vehicles which are in principle able to execute it, i.e., each shuttle vehicle s_i receives a list of jobs $j_i \dots j_j \in J$. The individual lists can overlap depending on the preselection strategy. This is the basis for the second step, in which the jobs are finally assigned to the shuttle vehicles using an allocation method, and the sequence for the job execution is determined for each vehicle.

According to [11], one option to conduct the job allocation is by means of block sequencing or dynamic sequencing. In this case, the concepts of block sequencing and dynamic sequencing, in conjunction with rolling scheduling, are both based either on optimal solution methods or on approximate solutions using heuristics. In both cases, a defined number of jobs are planned in parallel (simultaneous assignment). The use of optimization methods, such as the Branch-and-Bound method, guarantees that the shortest possible schedule is found for the different jobs. Heuristics and Metaheuristics aim to obtain a solution as close as possible to the optimum in acceptable computing time [10].

Another approach for the job allocation is the use of priority rules in dynamic sequencing. In this case, only the next pending job is assigned to a shuttle vehicle (successive assignment) that

- has been the least used until now,
- completes its current job the next and becomes available,
- is closest to the job start location, or
- is chosen randomly.

2.3 Control Algorithm for Coordinating Multiple Shuttle Vehicles

The investigation of a potential performance increase on the tier of an aisle in AVSRSs firstly requires the selection and implementation of a control algorithm. For this purpose, *no restriction,* i.e., each shuttle vehicle is able to carry out any job on the tier (see section 2.2), is chosen for preselection.

For job allocation, the block sequencing algorithm based on [12], originally developed for the control of overhead cranes, is used and is now adapted to the application on the tier of a high-powered AVSRS.

Functionality. Based on block sequencing and, thus, depending on the selected block size, a number of jobs are planned in parallel (job allocation) and then executed by the shuttle vehicles.

After the last job is completed, the job block is removed from the job list and the next block is planned in the next iteration.

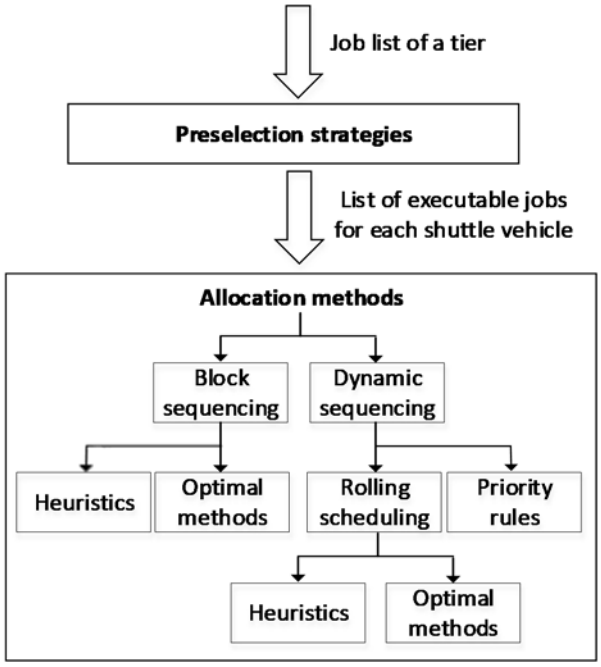

Figure 1: Classification of strategies to solve the SVSP-based on [11].

Job allocation. The job allocation of a block consists in assigning, with subsequent sequencing, a job to a shuttle vehicle by determining a start time for this job. Then, the algorithm iteratively spans a solution tree, whose nodes contain all possible partial schedules. In each iteration, the algorithm tries to add further pairs (shuttle vehicle – job) to the existing nodes and to append the newly created nodes, until the respective schedule is complete. The complete schedules correspond to the leaves of the solution tree and represent the feasible combinations of pairs. Finally, the schedule that is complete and requires the smallest processing time is selected for job execution.

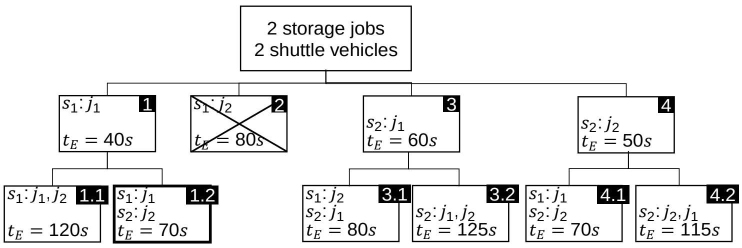

Figure 2: Examplary solution tree with two jobs and two shuttle vehicles.

Figure 2 shows a basic example of the assignment of two jobs to two shuttle vehicles. In the first iteration, there are four possibilities to assign a job to a shuttle vehicle. For the next iteration, the node with the smallest processing time is selected (schedule 1) and completed by two assignment alternatives.

Then, an analogous procedure is carried out for nodes 3 and 4, whereas node 2 is no longer pursued as it is dominated by schedule 1.2. Finally, the schedule with the smallest processing time is selected (schedule 1.2) and transferred to execution.

Job execution. After the scheduling of the block, the execution is carried out by the shuttle vehicles. For each job, it is first determined whether it can be executed immediately or whether waiting times must be observed in order to prevent block events with other shuttle vehicles. If the job has to be executed immediately, the trajectory planning and travel to the starting point of the job take place. Otherwise, one or more waiting positions or intermediate stops must first be determined and driven to in order to avoid interferences with other shuttle vehicles.

Applied heuristics. The number of possible solutions or schedules grows exponentially with the block size and causes the computing effort to increase accordingly. To limit the computing time, a heuristic is used that

- deletes incomplete schedules whose processing times are already bigger than that of a complete schedule (see Figure 2),
- removes a defined number of nodes from the tree, which has a certain total amount of nodes. Nodes or schedules with the smallest number of scheduled jobs or – if the number of jobs is identical – requiring a higher processing time are removed.

3 Simulation-based Analysis

A simulation model was created using the discrete event simulation environment Plant Simulation to investigate the throughput of a tier in a high-powered AVSRS. The model allows different configurations of the tier and aisle respectively, and is afterwards described. The results are subsequently presented and evaluated.

3.1 Simulation Model and Parameters

The simulation model contains one tier of an aisle in an AVSRS and has the following components (Figure 3):

- Rack with storage bins (free or occupied by a transportation unit)
- Railing system with an extension on either side of the tier for vehicle evasion (evasion buffer)
- Shuttle vehicles (with kinematic parameters based on [2])
- Lifting systems with two transfer buffers for storage and retrieval

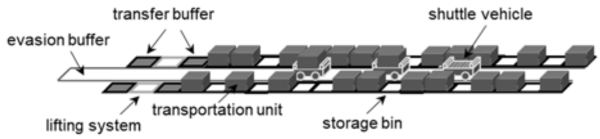

Figure 3: Section of a tier in an aisle of a high-powered AVSRS.

The analyzed configurations of the tier in the simulation study are shown in Table 1, where the lifting systems serve as the boundary of the simulation model. The listed configurations contain 200 storage bins (100 storage bins in each longitudinal direction of the aisle), as this is a common number of bins per tier in practice, and differ in the number of deployed lifting systems and their positioning within the aisle.

Configuration	Number of lifting systems	Position of lifting systems	Number of storage bins
1	2	Start of aisle	200
2	2	Center of aisle	200
3	4	Start and center of aisle	200
4	4	Start and end of aisle	200

Table 1: Considered configurations of the tier.

For the simulation-based throughput analysis, the number of shuttle vehicles goes from 1 to 5 in each configuration. The resulting 20 experiments are performed with five replications.

3.2 Results

In this section, the results of the conducted simulation study are presented and discussed on the basis of the described simulation model.

Comparison of different configurations. Figure 4 shows the obtained throughput with respect to the number of deployed shuttle vehicles for each configuration. Basically, throughput increases initially by deploying additional shuttle vehicles and decreases when four or five shuttle vehicles are deployed on the tier. This relies on the rising evasive moves, especially at the lifting systems, when the number of vehicles is increasing. Although unneeded vehicles could park in the evasion buffers, meaning that throughput should not be reduced by the further increase in the number of vehicles, this possibility is not taken into account by the heuristics in the scheduling process.

By positioning the two lifting systems in the center of the aisle (configuration 2), the shuttle vehicles can approach the lifting systems from both sides without time-consuming evasive moves, thus enabling the highest throughput throughout. When placing the two lifting systems at the beginning of the aisle (configuration 1), significantly longer distances and interferences between shuttle vehicles at the lifting systems lead to the lowest throughput. A slight increase in throughput is achieved when two lifting systems are positioned at the end of the aisle, as well as two lifting systems at the beginning of the aisle (configuration 4). A further increase in throughput can be achieved by positioning two further lifting systems in the center of the aisle (configuration 3), since shuttle vehicles can now approach the lifting systems from both sides again.

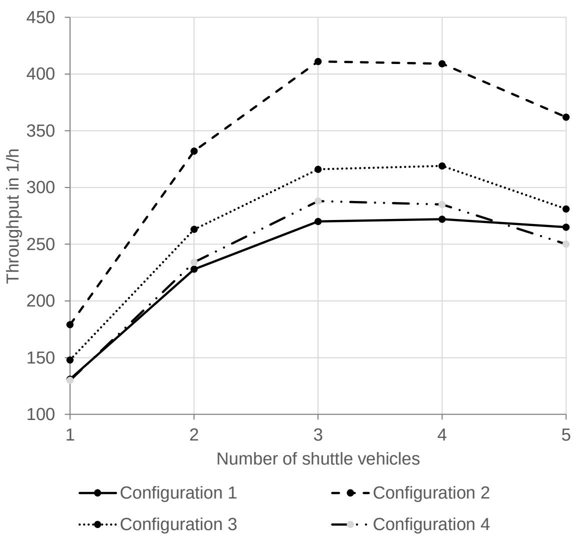

Figure 4: Achieved throughput depending on the number of shuttle vehicles and aisle configurations.

Increased performance by deploying additional shuttle vehicles. Figure 5 shows the increase in performance for the number of shuttle vehicles concerned by applying configuration 2. Consequently, the deployment of one additional shuttle vehicle increases the throughput produced by the deployment of a single shuttle vehicle by 85 %. Two additional shuttle vehicles further increase the throughput by about 24 %, until finally, by deploying five vehicles, there is a reduction in throughput of about -11 %.

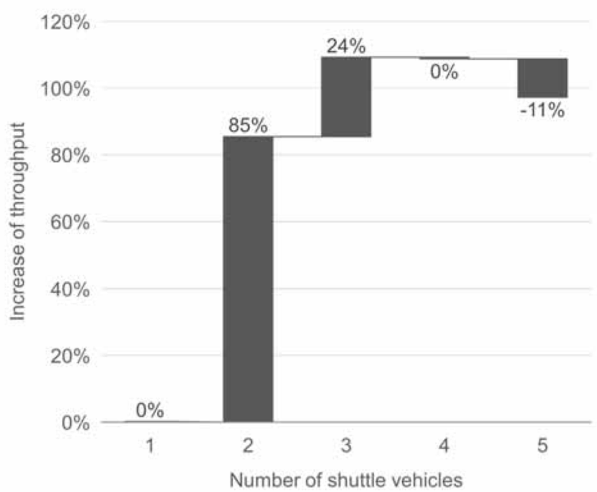

Figure 5: Increased capacity by deploying further vehicles on a tier of an aisle (configuration 2).

4 Conclusion and Outlook

High-powered AVSRSs represent a new version of AVSRS with increased flexibility and dynamics. However, these systems require a much more complex control to run the system in a robust and efficient manner. In this sense, the SVSP was introduced for this work; solution approaches, based on existing literature in the scheduling of gantry and overhead cranes, were also presented. By implementing the control algorithm in a simulation model, an increase in throughput was demonstrated by deploying several shuttle vehicles on a tier. Depending on the configuration of the aisle, the throughput decreases again when deploying too many shuttle vehicles. Even if the applied heuristic limits a complete enumeration and the exponential increase of the solution space, the control algorithm requires long computing times due to block sequencing, especially with an increase in the block size and and in the number of shuttle vehicles.

Further control algorithms could provide a remedy through alternative solution methods and, at the same time, enable real-time capability of scheduling in order to apply the method found in industrial practice. As demonstrated in the simulation study, the number and positioning of the lifting systems within the aisle have a decisive influence on the degree of increase in throughput. Equivalent to horizontal transport, the performance of vertical transport could also be improved by deploying several lift vehicles in a common shaft. Since the SVSP also occurs in a modified form, the same control algorithms can be applied. However, the interfaces between horizontal and vertical transport play a key role, since they have to be coordinated.

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Simulation-based Assessment of Grocery Shopping in Urban Areas

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Abstract. This study proposes a simulation approach for modelling, assessing, and quantifying travel distances caused by stationary grocery shopping activities as well as e-grocery deliveries on the last mile. Utilizing an integrated emission calculation model, the simulated travel values are converted into relevant emission output factors to assess the individual impact of e-grocery deliveries compared to individual shopping trips by private consumers for different scenarios. While e-grocery does not yield an emission saving potential for low penetration rates less than 20 %, up to 41.5 % of the total emission outputs can be economized when home deliveries are employed for a moderate share of the urban population.

Introduction

Technological advancements as well as the digitalization trend have a major influence on human behavior, interaction, and communication patterns. Especially in the transport sector, new technologies entail alternative business models, strategies, and shopping habits, which have a huge potential to disrupt existing mechanisms and standards. Consistently, urban freight transport has to evolve constantly in order to cope with the adapted shopping habits of (potential) consumers as well as the environmental concerns and objectives of all involved stakeholders [1]. High traffic volumes resulting from commercial as well as private transportation activities account for perseverative congestions and extended travel times as well as environmental contamination caused by vehicle emissions.

Accordingly, the development and implementation of new, emission-free drive concepts as well as the fortification of alternative means and modes of transport have become a major point of concern, especially in Europe [2]. While commercial traffic is dominated by last-mile delivery operations, a major share of traffic loads and traffic-related emissions arising from private traffic in Germany or the United States of America is related to grocery shopping activities [3, 4]. To exploit the opportunities and overcome the challenges of shifting consumer habits and new digital technologies, the food retail organization has initiated a major transformation within the recent years.

While first approaches to online food retailing, also known as e-grocery, already became evident in the 1990s, the concept has gained increasing popularity in many markets, particularly in the last decade [5]. As the consumer behaviour is changing rapidly, home delivery concepts for grocery and food products are promoted and likely to gain more popularity in the near future [6]. Besides of economic benefits in terms of operational efficiency and economies of scale, an increasing utilization of e-grocery, with delivery tours substituting private shopping errands, can potentially aid in reducing traffic loads. Furthermore, this can yield advantages regarding emissions in urban areas, where last-mile logistics, traffic volumes, and environmental pollution have become major points of concern [7].

However, as the individual environmental benefits of e-grocery directly depend on the infrastructural, behavioural, and operational context, few studies have assessed and quantified its particular effects compared to stationary grocery shopping, yet. To cope with concept-specific peculiarities and behaviour-dependent variables such as individual usage rates, shopping trip proportions, store selection, and basket composition, which are not entirely adaptable to and testable in a real-world setting, a configurable simulation model can serve as a valuable investigation tool for evaluating the environmental impacts of stationary grocery shopping compared to grocery deliveries in terms of emissions.

Moreover, this approach aids in investigating and examining the impact of future mobility trends such as vehicle electrification [8] and convergence of mobility and logistics [9] on the ecological value of e-grocery as well as stationary grocery shopping. Hence, this publication aims to provide a conceptual simulation framework that is capable of comparing stationary shopping and e-grocery, whereby the latter will be examined by means of home-delivery operations from a food fulfilment center, as this is a prevailing and most common business model for online grocery provision on an international scale [10, 11].

While hybrid delivery concepts (e.g., Click and Collect) are increasingly gaining importance on an international scale, they are not (yet) operated by the major German retailer that serves as reference and validation object for our simulation study. Similarly, returns in the simulated operation model are handled in terms of reception checks, meaning that deliveries are checked upon the delivery reception and, if necessary, returned directly with the delivering carrier [10]. Accordingly, return operations do not result in additional transportation activities or traffic loads and will not explicitly be considered in this study.

By developing and employing a sophisticated simulation model for analyzing the individual emissions caused within the context of e-grocery and stationary food retailing, all relevant details (e.g., mileage) and dynamic structures like behavioral influences (e.g., mode of transport choices) within the respective system can be reproduced and quantified. While the model proposed in this paper focuses on an exemplary urban district in the center of Hanover, Germany, the simulation approach can also be adapted for other metropolitan areas, providing a uniform approach to assess the environmental value of e-grocery for different specificities.

1 Related Work

Motivated by the growing importance of e-grocery during the last decade, several studies have attempted to assess, quantify, or benchmark the economic, social, and environmental impacts of various grocery fulfilment methods. Hardi and Wagner investigated the CO_2 emission balance caused by grocery deliveries as well as private shopping activities in a given city district in Munich, Germany [12]. By employing a Monte Carlo simulation approach, taking into account real-world geo-data, randomly selected target households, delivery probabilities, and individual routing methods, they calculated and analyzed break-even points for energy consumption and CO_2 emissions based on simulated vehicle distances and individual power efficiency factors. The results of the study indicate a significant emission savings potential of the e-grocery concept compared to individual stationary grocery shopping activities in the area of investigation. However, the calculation and simulation approach is static and neglects dynamic confounders and influencing factors such as individual shopping behavior (e.g., outlet choice depending on shopping type, chained trips) as well as delivery time windows, ultimately limiting the practical relevance and reliability of the results.

Concerning a holistic view on behavioral as well as concept-specific variables influencing the environmental impacts of online grocery retailing compared to stationary shopping, van Loon et al. developed a framework taking into account that individual consumer shopping characteristics directly influence the environmental footprint of the fulfilment concept [13]. Based on the proposed framework, they built a Life Cycle Assessment model to analyze different online retail methods for fast-moving consumer goods (FMCG) in the United Kingdom, indicating that consumer behavior as well as structural conditions such as routing and fulfilment properties are critical success factors for the sustainability of e-commerce when comparing it to stationary shopping. While their study provides a comprehensive overview about the key impact factors influencing the climate change potential of online FMCG retailing on a general basis, their results depend on the individual input parameters and, hence, are exclusively valid for the area under investigation. Their approach, therefore, lacks a general modelling or simulation framework that can be uniformly adapted to various contexts and scenarios.

Other contributions to the specified research area include studies from Coley et al., who have made an empirical analysis of contrasting food distribution systems in terms of carbon emission outputs resulting from local farm shopping as well as a large-scale vegetable box system [14]. Durand and Gonzalez-Feliu, who assessed three e-grocery fulfilment scenarios in terms of mileage reduction, showed the effectiveness of a hybrid concept, combining home deliveries and proximity reception points [15].

Moreover, approaches to solve different routing problems in urban areas have been proposed by Blas et al. [16] and Mayer et al. [17], whereas Rabe et al. provide insights into the use of discrete event simulation in a supply-chain context [18].

Less recent publications on computer simulation for assessing, quantifying, or benchmarking the environmental impacts of home delivery concepts include studies from Cairns, Punakivi and Saranen, Punakivi et al., and Kämäräinen et al., who applied different modelling and simulation approaches such as route mapping in various international contexts in order to virtually compare distances covered in terms of e-grocery and stationary grocery fulfilment [19, 21, 22, 23].

Generally, these studies uniformly indicate potential advantages of e-grocery. However, they again neglect dynamic system properties and interdependencies such as behavioral variables as well as stochastic influences and fail to model the respective fulfilment system on a holistic scope, ultimately diluting the overall validity, significance, and transferability to the real world. Moreover, the utilized modelling and simulation approaches are case-dependent. Therefore, they cannot be transferred to different contexts and cities, implicitly illustrating the value of a uniform, parametrizable simulation model.

Table 1 provides a synopsis on the related work in the field of e-grocery simulation research. A large share of contributions is related to the assessment, evaluation, or quantification of potential economic, social or environmental impacts of an increasing e-grocery utilization [12, 15, 20], the analysis of behavioral influences on operational performance and concept efficiency [13, 22, 24], or the provision of a comprehensive status quo concerning grocery home delivery concepts as well as research [25, 26, 27].

Regarding grocery logistics concepts related to fulfilment or delivery activities, several studies propose, conceptualize, or examine various concepts in different contexts, whereby the majority of publications are concerned with benchmarking or comparing the impact of these concepts on given target variables (e.g., emissions, costs) [15, 22, 23, 28]. To provide a more comprehensive and concise overview, we have classified the studies based on their research scope and main objectives, namely the provision of an explorative research overview (Research Overview), the evaluation of different e-grocery concepts (Concept Evaluation), the assessment of sustainability attributes related to e-grocery (Sustainability), the evaluation of the economic viability and profitability of various e-grocery business models (Profitability), the approach to assess, benchmark, and quantify e-grocery through simulation (Simulation Approach) as well as the aim to determine logistical influences caused by different delivery models and strategies (Logistical Influence).

Source	Method	Topic	Research Overview	Concept Evaluation	Sustainability	Profitability	Simulation Approach	Logistical Impact
[6]	MM	CB	◎	◒	◎	◒	◒	◎
[7]	LR	CO	●	◒	◒	●	◎	●
[10]	LR	CO	●	◒	◎	◒	◎	●
[11]	CS	FD	●	●	◒	◒	◎	●
[12]	SM	EI	◒	◒	●	◒	●	◒
[13]	MM	EI	◒	◒	●	◎	◒	●
[15]	CS	EI	◎	●	◒	◒	●	●
[20]	LR	EI	●	◒	●	◒	●	●
[21, 23]	CS/SM	P	◎	●	◒	●	●	●
[23]	SM	FD	◎	◒	◒	●	●	●
[24]	DS/SM	DSS	●	◒	◒	●	●	●
[25]	MM	EI	◒	●	●	◒	◒	◒
[26]	SU/SM	DSS	◒	◒	◎	◎	●	●
[27]	LR	CO	●	◒	●	●	◎	●
[28]	SM	EI	◒	◒	●	◎	●	●
[29]	MM	DF	●	◒	◒	●	◒	●
[30]	CS	FD	●	●	◒	◒	◎	●
[31]	CS	FD	●	◒	◒	◒	◒	◒
[32]	DS	PS	◒	◎	◒	●	◒	◒
[33]	SM	DSS	◒	●	◒	●	●	●
[34]	LR	FD	●	●	◒	●	◎	●
[35]	CS	CO	●	●	◒	●	◎	●
[36]	DS/SM	DSS	◒	◎	◒	◒	◒	●
[37]	MM	DSS	●	◒	◒	◒	●	●
[38]	CS	FD	◒	◒	◒	◒	◒	●
[39]	MM	FD	◒	●	◎	●	◒	●
[40]	LR/CS	CO	●	◒	◒	◒	◎	◒

Consideration: ● = full ; ◒ = partial ; ◎ = no consideration

Table 1: Overview of e-grocery research based on or related to computer simulation and general concept reviews for different methods (SM = Simulation modelling; MM = Mathematical modelling; LR = Literature review; SU = Survey; CS = Case Study; DS = Data screening, LR = Literature Review) and topics *(*FD = Fulfilment Design; P = Profitability; EI = Environmental impact; CB = Consumer Behaviour; DSS = Decision Support System; PS = Pricing System; DF = Demand Forecast, CO = Conceptional Overview)

2 Research Approach

To provide a simulation framework capable of quantifying mileages and emissions caused by e-grocery as well as stationary grocery shopping activities realistically, we adapted a three-stage research design.

The definition of the area under investigation as well as the choice of an appropriate simulation modelling software and the selection of an adequate research approach constitute the conceptional foundation for the simulation modelling approach and have been aligned with the objectives of this study. In turn, the simulation model, including all conceptional and functional components, parameters, as well as development routines, provides concept-specific results on vehicle mileages. Subsequently, these are transferred to a comprehensive emission model to generate insights on the environmental impact of e-grocery and stationary shopping in the given context.

Initially, we used the java-based multipurpose software AnyLogic (Version 8.5.1) to design and develop an agent-based simulation model for reflecting shopping-related mileages caused by private as well as commercial traffic in the district *Mitte* of Hanover, Germany. The simulation results served as a basis for the emission calculation, founded on emission factors and structural vehicle data, by the European Environment Agency [41] and the city of Hanover [42].

Overall, this approach allows for a more dynamic, flexible, and thorough comparison, as simulated mileage results can be directly complemented or adapted in order to reflect behavioral and technological scenarios that exceed the actual scope of consideration of the simulation system. Both, simulation model, simulation results as well as emission model and its results were supported and backed up by means of information acquired during an in-depth literature review (i.a., employing data from literature presented in Section 1). Moreover, following an iterative development approach, we constantly verified and validated model components as well as results with data from a major German grocery retailer to ensure a high degree of validity and reliability. In this regard, several test cycles for mileage outputs have yielded a maximum deviation of 5 % of the simulated mileages compared to distances tracked by the retail organization for its real operations. A synopsis on the research approach is given in Figure 1.

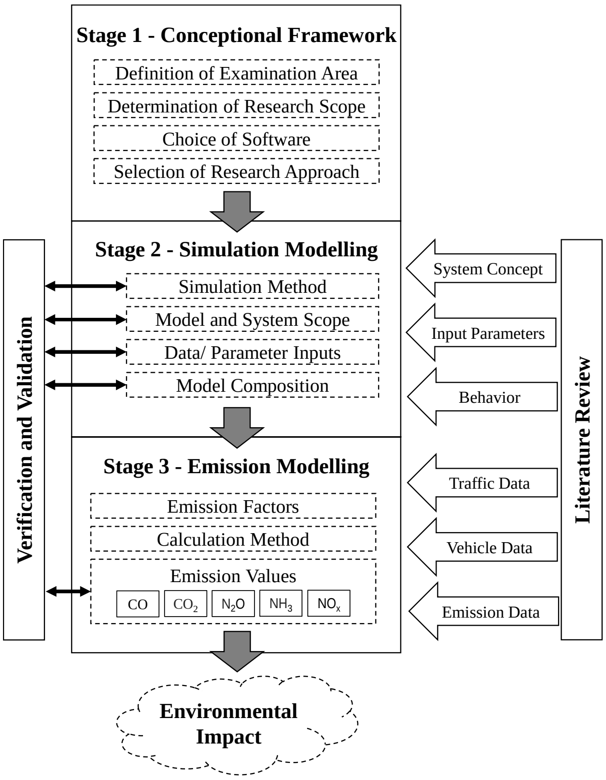

Figure 1: Three-stage research approach.

3 Simulation Model and Components

In accordance with the complexity of the problem and the need to model and replicate interdependencies between customers, supermarkets, delivery conditions, and behavioral influences (e.g., supermarket selection, trip chaining), an agent-based modelling (ABM) method was selected to reproduce the real-world system for the area of investigation. In contrast to microscopic simulation techniques such as discrete-event simulation (DES) or macroscopic simulation such as system dynamics (SD), it enables two-direction interactions and can effectively emulate interactions between individuals in a given system, ultimately reproducing global system dynamics by means of networking effects resulting from the modelled agent interactions. This approach appears particularly suitable to reflect behavioral influences and components with geographical reference [43]. The main advantage of ABM in the context of our study is its immanent capability to capture emergent behaviors that are decoupled from the properties of the individual agent (e.g., tour planning and (re-)scheduling) [44].

While other traffic simulation and analytical solution approaches such as SD, DES, Spreadsheet Simulation, or Monte Carlo Simulation are commonly used within the field of supply chain, traffic, and logistics simulation [45, 50], ABS features several benefits within our research. Despite its versatile applicability, Spreadsheet Simulation is rather suitable for models with a simple data structure. Moreover, it limits the data storage capabilities and is less efficient in simulating large or complex systems [45]. Due to the given pro-activeness of the agents, ABS requires a parallel-CPU system or a computer network to avoid sequential state changes across agents leading to reactive agent behaviours similar to entities in a DES [46]. Even though ABS and DES are both Turing complete [49], meaning that their theoretical modelling power is equal when sufficient memory and computational time are given, they are distinctively different regarding their flexibility and efficiency in modelling different types of systems. ABS is not just capable of capturing emergent behaviours resulting from interactions between agents, but generally more efficient in simulating systems with frequently interacting entities [46]. As the focus of our study is placed on the deduction of generic system insights (vehicle mileages) rather than the investigation of detailed interactions (e.g., communication between agents), ABS seems favourable over pure DES-only approaches [51]. Concerning SD modelling, ABS and SD are very similar techniques, whereby ABS takes bottom-up and SD a top-down approach. In fact, "the set of all SD models is a strict subset of the set all ABS models" [52], which is also referred to as the Agency Theorem for System Dynamics [53]. However, due to the given system complexity and the number of involved entities as well as unknown parameters, the bottom-up approach of ABS was likely to support the overall modelling process and, therefore, was more preferential for this study than SD. In line with the ABM approach, in which all relevant entities were modelled as particular active objects, the time-advancing mechanism is discrete and based on the interactions of agents, with each inter- or intra-network-related communication flow element accounting for a time-progression step in the simulation system [54]. In this context, communication flows, including process as well as decision elements outlined in Figure 4, are stored as events and integrated by an event list.

To reduce computing times, enable multiple simulation runs to account for stochastic variances in specific parameter values (Monte-Carlo approach), and increase the degree of generalizability, credibility, and transferability of the simulation results, the scope of the model is restricted to the district Mitte in the city of Hanover. With 1,604 households, the simulation covers about 22 % of the entire population (7,230 private households) in the area of investigation [42]. The simulation model provides outputs in terms of kilometers covered by private as well as commercial vehicles, allowing to quantify simulation insights and to flexibly convert simulation results into emission outputs to assess and evaluate the environmental impact of given shopping concepts [55].

To increase the quality of the simulation in terms of reusability and transferability [56], the entire model was developed on a parametrizable data basis to enable a context- and scenario-independent adaptation of the modelling framework. Additionally, a configurable behavior model was integrated to specify e-grocery utilization depending on the contextual and structural system condition, ultimately aiding in the simulation of more-realistic scenarios (e.g., due to given constraints like minimum order values, e-grocery will presumably be used more often for bulk purchases). Output-relevant input parameters within the model as well as reference values for the examination area are shown in Table 2.

Parameter	Value	Unit	Type
Shopping Frequency	51	Percentage	Fixed
Car Possession	56	Percentage	Fixed
Bulk Purchases	42	Percentage	Fixed
E-Grocery Utilization	5/20/42	Percentage	Variable
Multi-shop Purchases	Yes	Boolean	Fixed
FFC Location	52.447220, 9.697536	Coordinates	Fixed
Delivery Fleet	5	Vehicles	Fixed
Carrier Capacity	18	Orders	Fixed
Service Time per Order	Mean: 7 SD: 2	Minutes	Stochastic
Loading Time per Order	Mean: 2 SD: 1	Minutes	Stochastic
Trip Chaining Share	26	Percentage	Fixed
Public Transport Share	25	Percentage	Fixed
Vehicle Speed	Mean: 30 SD: 5	Km/h	Stochastic
Working Days	6	Days	Fixed
Working Hours	7.8	Hours	Fixed

Table 2: Simulation model parameter values and classification.

Concerning the conceptual composition of the model, nine agent types have been defined to reflect relevant entities, interactions, and relationships for both shopping concepts. The agents' behaviour is controlled by means of statecharts, defining the decision-making processes within the given agent types and the system environment.

Figure 2 provides an overview of the class diagram for stationary retail and e-grocery. All class elements represent agent types (indicated by the stereotype <<agent>>). The agent type "Main" includes the visualization of the simulation by providing a GIS map (Figure 3), while the "Household" agent type depicts consumers and "Grocery" all super- and hypermarkets in the area under investigation. At runtime, one single instance of the agent type "Main" exists, whereas 1 to *n* agents of the type "Household" and "Grocery" can be instantiated and utilized within the "Main" agent. Each "Household" has access to 0 to 1 "Car" agents for its shopping operations, which are responsible for the actual journey from household to supermarket. The "Purchase" agent represents a data type required for communicational flows. It is assigned to 0 to *n* "Households" to reflect a household's choice to make none up to several purchases at simulation runtime.

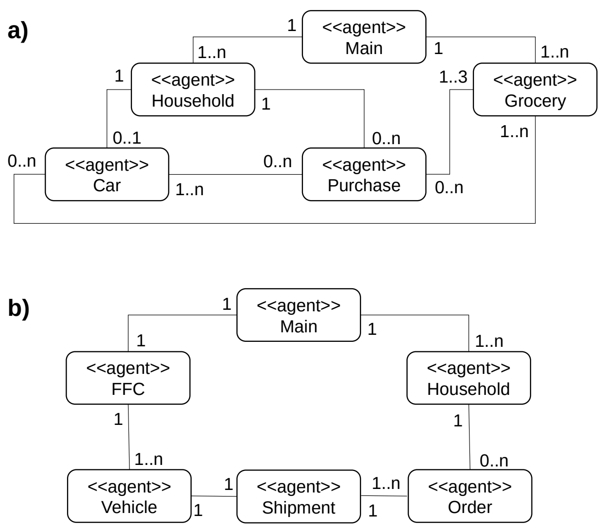

Figure 2: Class diagrams for (a) stationary retail and (b) e-grocery.

In contrast to the class diagram for stationary grocery shopping, the framework for e-grocery contains six agent types. Again, the "Main" agent is responsible for displaying the agent types "Household" and "FFC" (Food Fulfilment Center) at simulation runtime.

Generally, 1 to *n* "Household" agents as well as one "FFC" agent can be instantiated. The "FFC" agent receives orders from the "Household" population, which are depicted as communicational "Order" agents. Subsequently, the "FFC" aggregates all incoming "Order" agents to a "Shipment" agent, which is handed over to the "Vehicle" that is responsible for delivering the orders to the final customer ("Household").

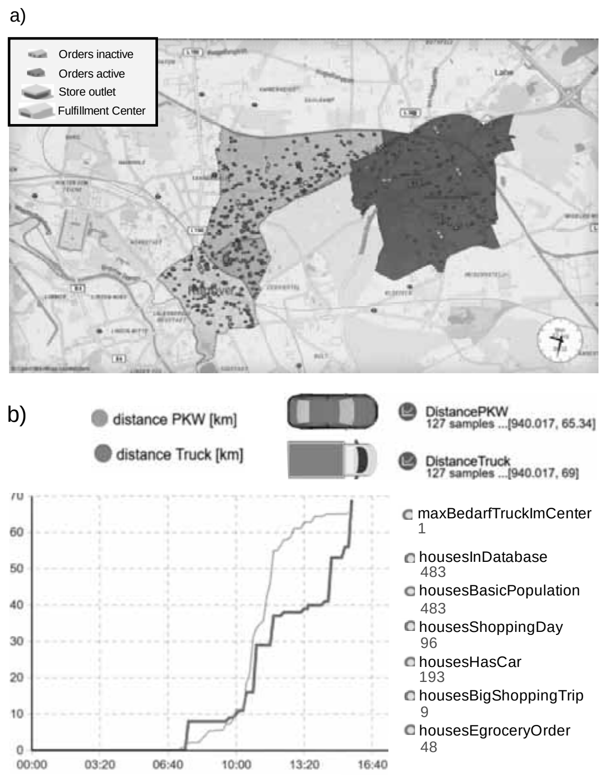

Figure 3: Traffic flow:
(a) simulation visualization on GIS map and
(b) statistical diagram for vehicle mileages.

While virtual abstract agents (e.g., Shipment, Order) act as supporting units for communicational flows in the simulation model, physical agents (e.g., Vehicles) are placed in a geospatial environment and feature both, communicational properties as well as process-related characteristics. Navigation and routing procedures are conducted by means of a clustered k-Nearest-Neighbor (kNN) algorithm [57], which is a non-parametric approach utilized for classification and regression, ensuring realistic and efficient delivery operations. Due to their stochastic decision nature, kNN algorithms are generally very robust compared to other routing methods when it comes to solving vehicle routing problems based on noisy training data [47]. Moreover, they allow for solving large problems with high computational complexity.

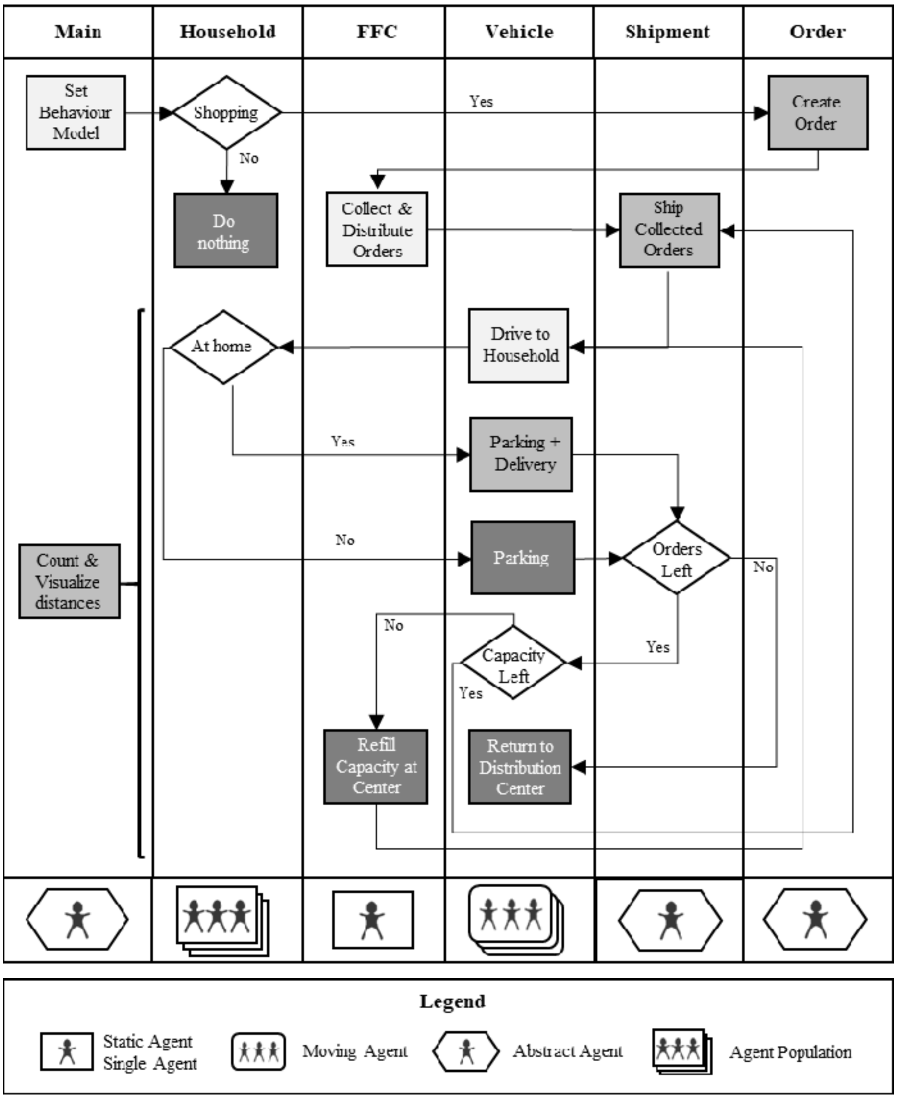

Figure 4: E-grocery simulation process flows.

Besides other routing and classification heuristics such as savings heuristics, insertion heuristics, or sweep heuristics, despite of relatively high computational costs, nearest neighbour heuristics are commonly used to define starting solutions for various routing problems, including the capacitated vehicle routing problem with time windows, as present in our research [48]. As a structure to define spatial relationships, kNN aids in enhancing the model network capacity and features efficient implementation processes [47].

In the context of our adapted kNN algorithm, first, a limited range is specified to assess the availability of customers within a given delivery area. In turn, the nearest customer (i) is set as a starting point for identifying the nearest remaining customer (i) in the given range.

As soon as no remaining customers are available within the set boundaries, the algorithm automatically increases the range until a customer that still has to be delivered in a respective time window has been found or all customers have already been registered in a delivery network. The road network is based on OpenStreetMap (OSM). Routes between household agents are chosen in line with a distance-based cost function, assigning each edge of the routing network with a cost based on the distance between starting point and endpoint.

In terms of process flows, the simulation model comprises two agent networks, representing the concepts of stationary grocery shopping as well as e-grocery. As shown in Figure 4 and Figure 5, for each concept, the simulation model is initiated by setting up a behaviour

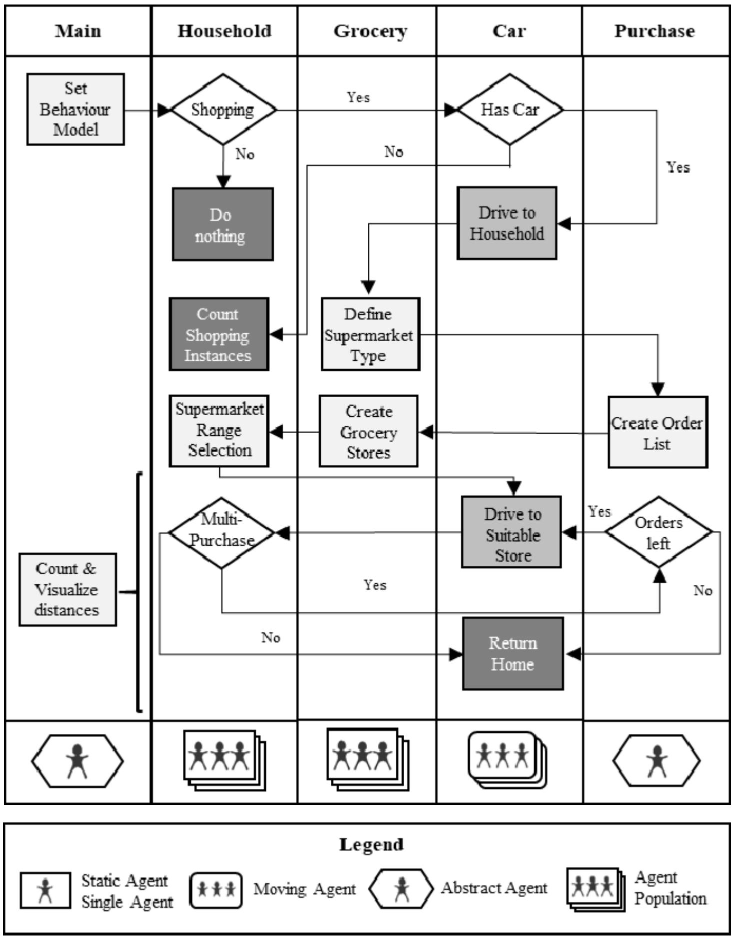

Figure 5: Stationary grocery shopping simulation process flows.

model, which in turn is responsible for the implementation of general rules according to the parameters described above. In the case of e-grocery operations (Figure 4), "Household" agents evaluate their shopping options individually and eventually create e-grocery orders. These orders are collected within the "FFC" and distributed across the given vehicle fleet. Afterwards, a shipment list is collected and the delivery process is initiated by the "Vehicle" agents. Based on a random distribution, a minor likelihood is given for order recipients not being present when a delivery attempt is made. If this condition evaluates to be true, the delivery "Vehicle" parks at the designated location for a specified time and subsequently continues with delivering the remaining orders. In contrast, if the condition returns false, the parking time is extended in order to reflect the actual delivery activity. After each delivery attempt, the "Vehicle" agent reviews the shipment list and checks the "Shipment" agent for remaining orders.

If the remaining order condition returns true, the "Vehicle" agent assesses its remaining order capacities required to complete outstanding orders from the shipment list. If that expression also evaluates true, the "Vehicle" drives to the next customer determined by the kNN routing algorithm and restarts the delivery process. In case the expression returns false, the Vehicle drives to the "FCC" to refill missing order capacities before continuing to fulfil remaining orders.

Households engaging in stationary grocery retail evaluate their individual shopping activities based on a probability distribution, taking into account average shopping frequencies as well as shopping type shares (bulk or small purchases) of German consumers [3]. If the shopping activity expression returns true, the modal split for the shopping trip is determined by the model, randomly assigning cars to the respective households based on structural data for as well as statistical information on car admissions and distribution in the investigated area [42].

For "Households" that have been assigned a car, a "Car" agent is created. Moreover, "Grocery" agents are classified into supermarkets suitable for small or bulk purchases and an order list for the given "Household" agent is created. Finally, "Households" select suitable supermarkets depending on their shopping trip type and drive to the designated destination, following a routing algorithm based on a distance-based cost function. In case several supermarkets are required to complete a bulk purchasing activity (multi-purchase), "Households" head for several supermarkets until all purchases from the order list have been made.

Ultimately, distances are tracked for both agent networks and transferred into a statistical diagram as well as a joint database. Both, stationary retail activities as well as e-grocery deliveries complement each other within a given agent network, providing a complete overview of total distances resulting from different e-grocery utilization rates and shopping behaviours. To account for chained trips (i.e., trips carried out for a different primary purpose than grocery shopping: 74 %) as well as the fraction of individuals employing public transport for their grocery shopping activities (25 %), the respective share of households engaging in these concepts is distributed randomly across all "Household" agents for each simulation run. This was based upon a comprehensive mobility survey in various cities [3].

3.1 Encountered challenges

In the course of the outlined model development and the adjacent test and validation iterations, several challenges regarding the quality and availability of data as well as the computational performance of the simulation were encountered. Due to the complexity of the system and a lack of publicly available data sources, the acquisition and choice of model input parameters was a major challenge within the modelling phase. To address this issue and select appropriate input values as well as behavior scenarios, we cooperated with a major German retail chain and acquired missing information by means of expert feedback. Furthermore, the use of a modified kNN algorithm resulted in major computational requirements, which we addressed by defining population samples for each simulation run as well as parallelization of the simulation. Nevertheless, we aim to refine the routing algorithm in future research in terms of its computational efficiency and, therefore, enable larger sample sizes as well as shorter simulation cycles.

4 Emission Model

While the simulation model has been designed to simulate and export driving distances in terms of kilometers, we have developed a separate emission model to transfer mileages into specific emissions. Traffic emissions (E_{ij}) are derived based on the number of vehicles in a nation's fleet of category j and technology k ($N_{j,k}$), the average annual distance covered per vehicle of category j and technology k in kilometers ($M_{j,k}$) as well as the technology-specific emission factor of pollutant i for each vehicle category j ($EF_{i,j,k}$). The respective emission calculation equation is denoted as:

$$EP_{i,j} = \sum (N_{j,k} \; x \; M_{j,k} \; x \; EF_{i,j,k}) \qquad (1)$$

Vehicle categories include passenger cars (private traffic) as well as light-duty vehicles (commercial traffic), required for delivery operations on the last mile, while vehicle technologies range from Euro 1 to Euro 6. The fleet composition of passenger cars in terms of technologies, combustion engine, and cubic capacity has been determined in accordance with structural data of the city of Hanover [42]. The referenced light-duty vehicle employed for e-grocery delivery operations is a Renault Master L2H1 with Kiesling Flat Runner Box Body and features an ENERGY dCi 145 engine with an output of 107 kW (145 hp) as well as a tare weight of 2.29 tons. Moreover, the given light-duty vehicle combusts diesel fuel and is classified as Euro 6b.

Concerning specific emission output values, ammoniac (NH_3), nitrous oxides (N_2O), and nitrogen oxides (NO_x) are calculated by emission factors proposed in [41], whereas carbon dioxide (CO_2) emissions of vehicles k, combusting fuel m, are determined by:

$$E^{CALC}_{CO_2,k,m} = 44.011 \; x \; \frac{FC^{CALC}_{k,m}}{12.011 + 1.088 r_{H:C,m} + 16.000 r_{O:C,m}} \qquad (2)$$

Here, FC_{CALC} describes the fuel consumption of vehicles for a given period, while $r_{H:C}$ as well as $r_{O:C}$ account for the ratios of hydrogen to carbon (H/C) and oxygen to carbon (O/C) in the fuel. Overall, the emission model employs emission-, pollutant-, and vehicle-technology-related data inputs from the European Environment Agency [41] and has been designed to assess the relative effects of mobility and logistics concepts based on the driven mileages.

The method can be used to evaluate emission outputs resulting from driving activities to a good approximation and to combine various influencing factors such as driving speeds in different environments (motorway, inner-city), acceleration and deceleration, or ambient temperature. However, the model is primarily based on average values for many influencing factors. Thus, it is more suitable for comparing the relative effects of individual scenarios rather than determining absolute figures with high accuracy.

5 Results

Employing the proposed simulation and emission model, we have conducted a sophisticated simulation study on the environmental impacts of e-grocery as well as stationary shopping in the urban area of investigation. With each simulation run representing one particular day, a total of 1,000 simulation runs employing the parameter values referenced in Table 2 have been conducted and analyzed. We assessed three potential behavioral scenarios as well as one benchmarking scenario within the study to reflect current as well as probable future realities concerning the utilization of e-grocery:

1. **0 %-Case:** Sole stationary grocery shopping without any e-grocery activities as benchmarking scenario.
2. **5 %-Case:** 5 % e-grocery utilization rate as present in other European countries such as France or the United Kingdom [58].
3. **20 %-Case:** 20 % e-grocery utilization rate as present in the United States of America [35].
4. **Bulk-Shopping-Case:** E-grocery utilization adjusted to the daily bulk shopping frequency of consumers.

To reproduce reliable outputs, the total results for the entire simulation period have been averaged for each scenario. To enable a holistic assessment and evaluation approach, each e-grocery scenario (1-3) is complemented with stationary shopping activities of the remaining population share. The results of the simulation study in terms of vehicle mileages and the resulting emission outputs per scenario as well as standard deviations (SD) with a 95 % confidence interval for the 1,000 simulation iterations are outlined in Table 3 and Table 4.

Our results indicate that e-grocery can, indeed, contribute to a more sustainable environment in central urban areas as present in the investigated case. Nevertheless, the potential to reduce traffic and emissions in the investigated operational set-up highly depends on behavioural patterns in particular and e-grocery utilization in general.

With low utilization rates as given in Scenario 1, the overall share of traffic-related mileages and emissions exceeds the benchmarking case without any e-grocery operations, proving the e-fulfilment concept to be less efficient from a sustainable point of view than the absence of grocery deliveries. With low e-grocery utilization rates, the delivery fleet features a very low degree of capacity utilization (50 % – 70 %), ultimately resulting in additional mileages and emissions. Moreover, shopping-related behaviour mechanisms such as trip chaining as well as the modal split in the research area reduce the positive effects of order bundling and operational efficiency provided by the proposed home delivery concept.

Scn.	Distance		SD	
	Car	Truck	Car	Truck
0	2428	/	105	/
1	2321	122	102	7
2	1983	359	97	16
3	1354	542	74	28

Table 3: Distances (in km) and standard deviations per scenario.

Scn.	Emissions				
	CO	CO_2	N_2O	NH_3	NO_x
0	1.488	469.9	0.007	0.047	0.519
1	1.432	480.1	0.008	0.046	0.614
2	1.243	474.8	0.007	0.040	0.769
3	0.871	399.4	0.006	0.028	0.810
	Standard Deviations				
0	0.091	20.818	0.0003	0.002	0.023
1	0.098	24.424	0.0004	0.002	0.032
2	0.076	22.184	0.0003	0.002	0.039
3	0.057	21.289	0.0004	0.001	0.048

Table 4: Total emission outputs (in kg) and standard deviations per scenario.

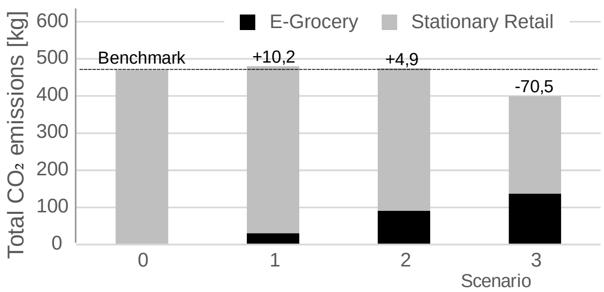

Figure 6: Total CO_2 emissions resulting from e-grocery and stationary retail per scenario.

Accordingly, also the simulation results of Scenario 2 do not outline a significant mileage or emission saving potential, with some emissions (e.g., CO_2) still exceeding emission outputs accruing without any e-grocery activities (Figure 6). Concerning high e-grocery usage rates as given in Scenario 3 (42 %), the e-grocery concept can significantly contribute towards reducing CO, CO_2 and NH_3 emissions by up to 41.5 % (CO), 15 % (CO_2), and 40.4 % (NH_3) compared to stationary retail in the baseline scenario. In line with the high production of N_2O and NO_x emissions by delivery vehicles compared to private vehicles, the former barely change across all scenarios, while the latter even develop contrariwise to CO, CO_2 and NH_3 emissions and increase by up to 56.1 % from Scenario 0 to 3.

As shown in Figures 7 and 8, emissions develop in accordance with the share of mileages among private and commercial vehicles in the given scenarios. Per order, each delivery truck covers about 1.0 kilometers in Scenario 1, 0.4 kilometers in Scenario 2, and 0.3 kilometers in Scenario 3, while every passenger vehicle covers a distance of 5.3 kilometers in Scenario 0, 4.8 kilometers in Scenario 1, 3.5 kilometers in Scenario 2, and 1.7 kilometers in Scenario 3, respectively.

The strong decrease in mileage per order for passenger cars in Scenario 3 can be described through the scenario peculiarities, as bulk shopping activities, which often require consumers to select supermarkets in a broader range, are entirely outsourced to e-grocery carriers. Similarly, the kilometers covered per order and delivery vehicle decrease with an increasing e-grocery usage rate, as more-efficient processes in terms of vehicle utilization degree can be achieved.

6 Discussion and Conclusion

In this contribution, we presented a simulation approach and model, capable of reproducing shopping activities within the context of grocery retail. Model design and procedure were aligned and delineated to investigate the potential impact of e-grocery on sustainability metrics such as mileage and emissions within an urban context.

The proposed simulation approach and model can be effectively employed to assess the environmental influences of offline and online grocery shopping concepts in urban areas.

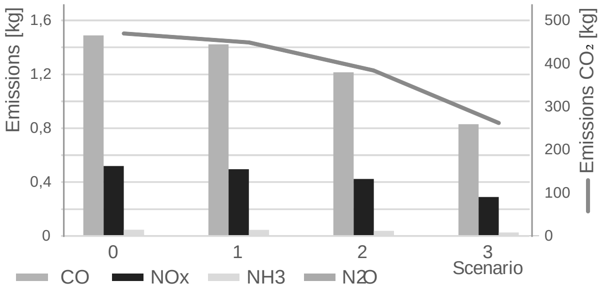

Figure 7: Emission outputs per scenario resulting from private traffic

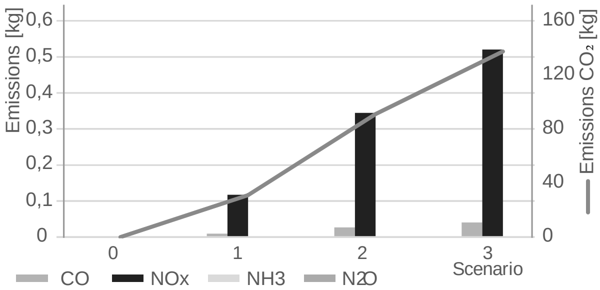

Figure 8: Emission outputs per scenario resulting from commercial traffic

The modelling framework and simulation methodology can be adapted and transferred to other cities as well as contexts and model the impacts of different grocery shopping scenarios based on a prevailing operational delivery model in a dynamic, integrated way. Ultimately, it can be used to quantify both, holistic conceptual interdependencies and system states as well as influences of specific parameters and characteristics.

Applied to the City of Hanover, Germany, we proved that e-grocery can holistically outperform stationary grocery shopping in terms of traffic and emission outputs in the investigated set-up. However, an environmentally beneficial application of e-grocery within central urban areas requires high e-grocery utilization rates to leverage delivery vehicle utilization degrees and overcome influences of behavioral traits such as chained trips. Especially in the latter case, where e-grocery is employed for all bulk purchases across the entire area of investigation, e-grocery yields a very high potential to decrease traffic (by up to 21.9 %) as well as emissions (e.g., CO by up to 41.5 %) compared to a scenario exclusively featuring stationary grocery shopping. Nevertheless, despite its given sustainability potential, currently, e-grocery utilization rates are far below 20 % in many countries, which may result in the fact that the e-grocery operations result in additional traffic and emission outputs [59].

Hence, to tap on the potential benefits of e-grocery within an urban context, the utilization of the concept needs to be fostered and promoted in the near future, especially when considering the high share of mileages and emissions in a scenario with low utilization rates.

While the proposed simulation model and study offer comprehensive insights into grocery shopping impacts, additional constraints and influence factors need to be added and investigated in future research to ensure an integral analysis and evaluation. It can be expected that the location of the respective fulfilment center has a major impact on delivery vehicle mileages in various e-grocery scenarios, which should be examined through simulated sensitivity analyzes. In addition, the simulation approach can be used to analyze the role of different time windows in the operational performance of e-grocery deliveries as well as various national and international fulfilment concepts, as highlighted in [10] (e.g., Click and Collect, grocery deliveries by parcel service providers). Moreover, in line with current and future mobility trends, the role and impact of private and commercial vehicle electrification as well as shared mobility concepts in terms of sustainable operations and emission outputs should be assessed. Future research should employ the basic concepts of our simulation approach and mode, to conduct further analyzes, verify our results in different contexts, and identify the impact of different fulfilment peculiarities in various countries. Ultimately, different cases with other supermarket outlets, geographical structures (e.g., rural delivery areas), or even purchase behavior influences such as the impact of seasonal demands could be investigated.

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Simulation and Optimization of a Sequenced Mixed-Model Line – Case Study of an Assembly of Gantry Car Washes

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Abstract. In car wash machine manufacturing, the assembly line is characterized by product diversity and workforce flexibility. The main challenge of operational control is to schedule assembly tasks to workstations by taking workforce availability and qualification into consideration. In order to help planners to better analyse, plan, and evaluate the assembly line, in this paper, we develop a framework in which simulation and optimization are applied. Particularly, a simulation-based optimization approach is used to reduce excessive overload peaks for workstations. At last, an example of a solution for our industrial partner is given to show the feasibility and the applicability of our framework.

Introduction

Every company must face the challenge of offering top performance at globally competitive prices. In addition to technology and quality, customer service is playing an increasing role in all industries in order to differentiate their own range of services from those of their competitors. In order to successfully meet the requirements economically, it requires, on the one hand, a high level of innovation and strong technical competence. On the other hand, the long-term maintenance in global competition can only succeed, if the highly developed production skills are planned and controlled as flexible as possible, and, at the same time, at optimal cost.

Due to the labor-intensive production structure and the low level of automation, the employees in assembly lines of car wash manufacturers are still the main production resources. In order to keep the high German labor costs under control, a high degree of workforce flexibility is necessary.

1 Workforce Planning in Sequenced Assembly Lines

The aim of workforce planning is to manufacture the constantly changing production program with as few employees as possible [4]. Workforce flexibility is expressed, for example, by drifting across cycle times or switching workers from one station to another station within one cycle in order to avoid bottleneck situations (floaters). Drifting means that employees go to subsequent orders or follow the workpiece to the next station.

Floaters can be divided into internal and external floaters. External floaters are not planned in the line and support the employees of a station in the case of overloads in order to carry out the tasks involved within the specified cycle [1]. The employee balances the changing process time requirements over the cycle times. In the practice of deploying personnel in assembly, it also happens that employees perform activities at more than one station in one cycle. This always happens when there is enough free capacity at the main station to allow one of the assigned employees for working at another (floater) station. In this case, an internal floater balances the different process time requirements at the same cycle across two different stations. After performing the workload, the employee returns to his or her base station.

Another factor influencing the balancing of the lines is the qualification of the employees. The planner is, therefore, faced with the daily task of carrying out the sequence of orders depending on the number of employees, the qualifications, and the process time requirements, to balance the process time requirements per cycle and station and to avoid both underutilization and overload cases.

In fact, due to the high process time spread of the products, it can be observed that there are often overload cases that could have been avoided by efficient sequence planning. The prerequisite for efficient planning is the exact predictability of the effects of employee behavior, taking into account the possibilities for work flexibility (drifting, jumping between stations, assigning employees to stations, etc.).

The simulation has established itself as state of the art to support the planning of assembly lines in recent years [5]. Simulation is used to make reliable predictions of the dynamic behavior of employees over the period of a delivery week. In order to predict the behavior of each employee, each individual process step is assigned to the employees and the process duration is calculated based on the qualification. The qualification considers the experience of the employee. This gives the planner a clear overview of the workflow depending on the order sequence.

However, the simulation only evaluates a planning scenario and does not determine an improvement in the planning solution. In this respect, the simulation is a very efficient tool for evaluating the effects of sequences on the workload of employees and the need for external floaters. The sequencing of a complex assembly line is a combinatorial optimization problem, which is unfortunately an NP-hard problem. To solve the real-world planning tasks under consideration of dynamic effects, classic solution algorithms or heuristics such as dispatching rules are insufficient. A promising approach to solve this task is simulation-based optimization [3].

The basic idea of simulation-based optimization is to simulate, evaluate, and compare different scenarios in order to create new scenarios using rule-based configuration. The basic idea of these iterations is the generation of feasible solutions. For example, the meta-heuristic method of genetic algorithms (GA) in combination with simulation or dispatch rules in combination with simulation have been successfully used several times in various industries to solve sequence problems [2, 6].

In addition to personnel planning and sequence optimization, the application presented in this article also serves to synchronize the line (Figure 1).

These three fields of application can be differentiated depending on planning horizon and objective: the workforce planning is based on a given sequence, and – in the case of a divergent personnel availability – it examines the effects and evaluates possible alternative personnel assignments. The sequence optimization runs in advance and determines minimum needs for employees and floaters. The balancing falls within the scope of workforce planning and distributes the processes to stations and employees in such a way that, despite the variety of variants, the workload of the employees is as uniform as possible.

This article focuses on sequence optimization. For this purpose, the scope of the illustration and the simulation of personnel deployment are first presented in Section 2. Section 3 explains the methodology for sequence optimization. Section 4 presents the results. The article closes with an outlook.

Workforce planning • Impact of deviations of personnel availability • Realization of variations of production programme • Realization of variant peaks in one shift to assign floaters	► Dynamic capacity analysis to ensure short-term productivity
Sequence optimization • Minimizing overload cases per cycle and station • Adjustment of order sequence on the basis of given criteria • Determination of order volume	► Simulation-based optimization of sequence to improve productivity
Line Balancing • Relocating of workload from one station to another station • Changing number of staff • Adjustment of cycle time or process times	► Dynamic capacity analysis to increase long-term productivity

Figure 1: Application areas of simulation-based line optimization.

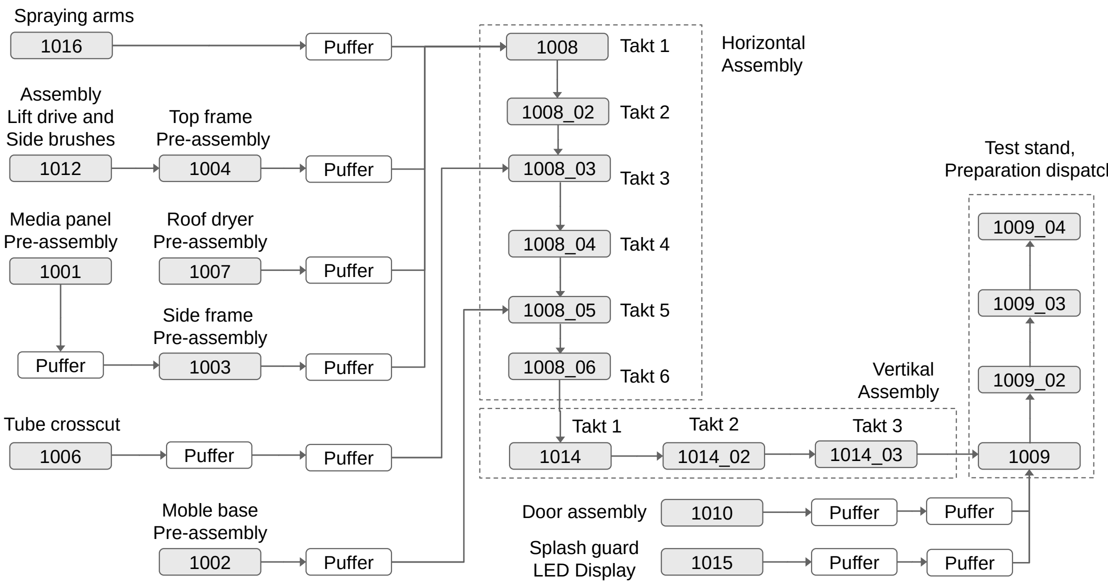

Figure 2: Scope of the sequenced assembly area.

2 Assembly Structure and Personnel Deployment

The sequenced production line at WashTec includes pre-assembly and final assembly stations. In total, the portal systems are assembled at a high rate of product diversity at 23 stations. The structure of the assembly is shown in Figure 2. The stations are run through in 17 clock cycles, which means that the pre-assembly of an order sometimes runs parallel to the main assembly work. The cycle time varies between 45 and 55 minutes depending on the order situation.

The employees are assigned to the stations and have station-dependent qualifications. A qualification of 100 % means that the employee can fulfill the processes in the time specified in the work plan. If the employee has a qualification of 50 %, then he needs twice the time for the same job. The qualification levels of each employee for each station are stored in the employee qualification matrix.

The employees can drift. Drifting means that in the event of an overload of the subsequent order, the employees can go ahead (preparatory work) or rework in the next cycle. The drift capacity can be stored in the simulation model depending on the cycle time per station. For example, a drift capacity of +0.5 cycle times means that the employees assigned to this station can rework for a total of 25 minutes at a given cycle time of 50 minutes, for example.

Employees can also act as floaters. In the practice of deploying personnel in assembly, it happens that employees perform activities at more than one station in one cycle. This happens whenever there is enough free capacity at the home station to allow one of the assigned employees for working at another (floater) station. The potential floater employee must be identified as such in the personnel deployment table in advance of planning.

There are also floaters who are not assigned to the stations and who step in whenever the core workforce can no longer meet the process time requirements within their time frame.

Figure 3 shows an example of the process time requirements for each cycle as the left bar per group. To its right, the bars represent the workload of the employees per cycle, with the number of bars showing the number of employees. The 100 %-line marks the capacity of the employees considering their qualifications.

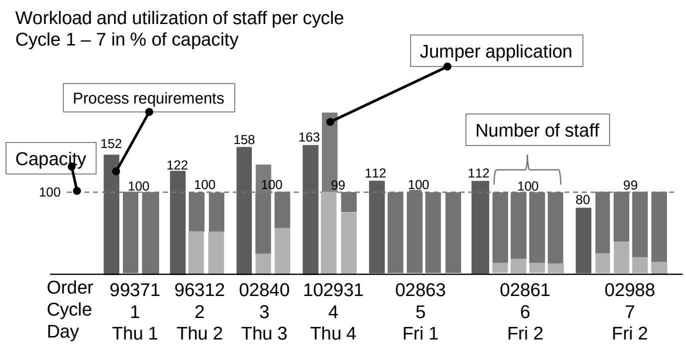

Figure 3: Process time requirements and personnel deployment.

This shows to what extent the pending orders exceed the capacity of the assigned employees per cycle. The light sections of the bars show which process time portions of the previous cycle had to be processed in the subsequent cycle (rework). The bars above the capacity line of 100 % show that an (external) floater was necessary in this cycle. It is important to avoid these cases. By continuous improvements of the data quality and of line balancing, the number of external floaters could be minimized to a few events per shift.

3 Architecture and Methodology of Sequence Optimization

The architecture of the application is structured based on the functions that are specified by the planning process. After reading the order and process time data from SAP, the initial sequence is first simulated. The assignment of work content to the stations is based on the work plan data from SAP, in which the individual process times are assigned to the stations. This first sequence is based on an upstream, rough division of orders into shifts under consideration of main features. This prevents predictable overload cases from occurring too often in one shift due to optional equipment options. This first sequence proposal serves as a reference for assessing the subsequent sequence optimizations. The sequence optimization considers a production period of two weeks, which means a total number of about 100 products. Each product is an individual configuration based on a product platform (lotsize 1).

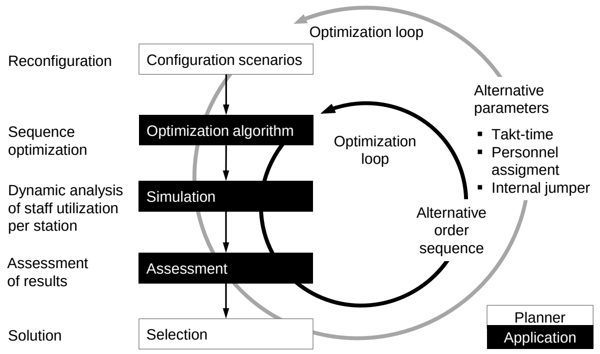

Figure 4: Optimization process.

The evaluation takes place based on the floater operating times. For this purpose, all floater operating times are summed up across all stations and all cycles.

Figure 4 shows the iterative run of the sequence optimization integrated in the higher-level process for optimal configuration.

The operation is as follows: After simulation and evaluation of the initial sequence, alternative sequences are determined and simulated again. The selected optimization algorithm determines the selection of new order sequences. The results of the modified orders are evaluated and compared. After a given number of iterations, which depends on an abort criterion, it is clear which floater operations are necessary. If the result is not satisfactory, the dispatcher can make alternative configurations. A few parameters are available to him, for example:

- Increase or decrease the cycle time
- Changed personnel assignment to stations, e.g., by assigning less qualified employees to stations with underload
- Classification of employees as internal floaters

Afterwards, the system-supported sequence optimization can run again. In the case of changes on very short term, which, e.g., may occur before start of work if the planned personnel availability is not given, the dispatcher can solve critical bottleneck situations by changing personnel assignments. Prior to a shift, sequence optimization can help to find an optimal sequence in combination with the other configuration options.

The objective function of the optimization tries to minimize the usage times of floaters. After each simulation run, the number of employments and the total floater operating times per station are determined. The shorter the employment time, the better the result. Table 1 shows the results of the simulation with the floater operations per station.

The optimization was initially tackled by using rule-based algorithms. After selecting a time period of, e.g., a calendar week, the algorithm goes through the following steps:

1. Sort the stations in descending order according to their floater operating times
2. Take the station with the highest floater deployment time
3. Sort the orders pending at this station in the period under review by process time totals
4. Sort the orders alternately according to the highest and lowest value of the total accumulated process times, i.e., first take the order with the highest process time requirements, then the order with the lowest process time requirements, then the order with the second-highest ones, etc.

5. Continue in this scheme until all orders have been placed in the sequence
6. Simulate the sequence and save the result
7. Take the next station from the sorted list from Step 1
8. Continue until all stations with a floater assignment greater than zero have been rated
9. Compare the results and choose the scenario with the lowest floater operating times

Station	Floater Rate [%]	Floater Rate [Minutes]	Quantity	Factor	Weighted Quantity
1001	22	875.5	16	1	16
1012	22	311.6	13	1	13
1007	12	350	9	1	9
1016	6	101	2	1	2
1003	5	243	7	1	7
1004	0	0	0	1	0
1006	20	261.2	10	1	10
1008	0	0	0	1	0
1008_02	0	0	0	1	0
1002	1	41	1	1	1
1008_03	16	232	9	1	9
1008_04	0	0	0	2	0
1008_05	0	0	0	2	0
1008_06	0	0	0	2	0
1010	24	1,022.5	11	2	22

Table 1: Evaluation of the floater deployments per simulation run.

The number of floater employments can also be used as an evaluation instead of the floaters' duty times. A weighting factor (Figure 5) that takes this into account has been introduced, because the floater operations are more difficult in the final assembly stations.

4 Sequence Optimization Results

Overall, with the rule-based sequence optimization improvements in the use of floaters, based on the total number of employees in the line, between 3 % and 5 % could be achieved.

Table 2 shows the results of a total of six randomly selected weeks, which were sorted in ascending order depending on the employment times of the floater.

The floater operating times of the initial sequence are compared with the results of the rule-based optimization.

Floater time [min]	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
Initial seq.	3,102	6,272	6,891	9,660	9,781	12,996
Optimization	2,804	3,845	4,336	5,853	6,333	10,076
Improvement [%]	9.6	38.7	37.1	39.4	35.3	22.5

Table 2: Sequence optimization results.

The results show that the maximum improvement can be achieved if the sum of the floater operating times is in a certain range.

The employment of floaters is the result of the product mix. In the ideal range, improvements of up to 40 % less deployment times of floaters could be shown! However, due to smaller sequence periods (e.g., 2–3 days or shifts) and improved line balancing, smaller improvement potentials can also be expected.

The simulation was carried out in the self-developed, high-performance simulation and optimization platform STREMLER REALTIME TECHNOLOGIES. The simulation takes less than a second to simulate the assembly of a shift, making the results of an optimization run available within 70 seconds – including data import and export – via an interface to the database.

In a further step, heuristic methods are now to be used in parallel in order to determine further optimization solutions depending on the available planning time.

5 Outlook

With the introduction of the application for simulation-based personnel planning and sequence optimization in the assembly area, WashTec Cleaning Technology GmbH is treading the path towards a supply chain in real time.

The application for simulation-based optimization of the sequenced assembly line, which has been running for over a year, is based on a modular planning architecture that enables the successive introduction of functionalities to plan and optimize the value chain.

The full benefit of this modular principle can be generated with the implementation of a consistent mapping of the value chain in the planning modules and a customer-specific defined supply chain platform.

These are mainly based on the following relationships:

- Continuous adjustment of production to the market development by pull from shipping date and a prompt reaction of the value chain (production close to the market)
- Higher planning security and harmony in production through simulation-based dynamic capacity analyzes and optimization, considering all relevant influencing factors in production
- Takt-based synchronisation of planning and control of the value chain steps
- Continuous tracking of the weighted targets of productivity, service, and profitability
- Higher productivity through optimal sequencing and better lot sizes in all stages

Optimized planning and scheduling of assembly represents a complex planning case at WashTec. This new step enables significant improvements in productivity and service as well as drastic savings in planning effort.

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On the Usage of Deep Learning for Modelling Energy Consumption in Simulation Models

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Abstract. With the increasing availability of data, the desire to interpret that data and use it for behavioral predictions arises. Traditionally, simulation has used data about the real system for input data analysis or within data-driven model generation. Automatically extracting behavioral descriptions from the data and representing it in a simulation model is a challenge for these approaches. Machine learning on the other hand has proven successful in extracting knowledge from large data sets and transforming it into more useful representations. Combining simulation approaches with methods from machine learning seems, therefore, promising. Representing some aspects of a real system by a traditional simulation model and others by a model generated from machine learning, a hybrid system model (HSM) is generated. This paper discusses such HSMs and suggests a specific HSM incorporating a deep learning method for predicting the power consumption of machining jobs.

Introduction

For a computer simulation of a real system it is indispensable to create a model of this system. System models are generally abstractions of the real-world system under observation and will focus on the most relevant parts, or attributes thereof that are of interest to the model designer. In traditional modelling approaches, the modeler is bound and potentially limited by the chosen modelling paradigm.

Machine learning (ML), in contrast to simulation, is a set of algorithms that provide an efficient way to aggregate rather big data sets and to find patterns within that data [1]. Those patterns can then further be used to describe the mechanism of the system of interest that emitted the initial data points. Applications of ML are not limited to sets of static data, as the most prominent picture-classification tasks, but can also be applied to dynamic data sets such as time series data. This duality results in ML methods being a promising match for hybrid systems modelling since a chosen simulation methodology can be complemented by an ML method with a different methodology and vice versa.

While ML methods are no simulation technique by definition, they can be used to design a data-driven model as a constituent part of a hybrid systems model (HSM) [2]. In this paper, we propose such an HSM that combines discrete event simulation (DES) with Sequence2Sequence (Seq2Seq) neural networks. This newly proposed HSM focuses on the realistic depiction of electrical power consumption of a job in a manufacturing cell that contains a waiting room and a machine tool.

The investigation of energy efficiency issues within simulation has become a widespread research approach. Existing studies are often based on the consideration of the power consumption of resources (machines, furnaces, etc.) by means of metrologically recorded operating conditions, which are regarded as constant over a defined period of time [3].

The power consumption of resources averaged over a period is then assigned to a resource state and can be mapped and analysed status-based with discrete event simulation approaches. It is questionable, for which application cases these quasi-static operating states provide enough closeness to reality! For the determination and smoothing of load peaks of many resources such an approach does not offer sufficient proximity to reality.

A solution for this is presented in [4]. It is based on the basic idea of combined simulation, which is also proposed, for example, in [5]. While the production and logistics part of the model is represented classically with discrete event simulation, the system dynamics approach is applied for electricity usage in [4]. This enables the time series of the measured power consumption to be reproduced in high resolution in the simulation, offering the advantage of a high-resolution overall picture of a production line's power consumption.

However, the disadvantage of this approach is that only the power consumption of measured jobs can be reproduced. Power consumption of upcoming differing job types cannot be predicted. Furthermore, the approach described in [4] does not depict cause-effect relationships between control parameters (e.g. half feed, slower heating phase, etc.) and the anticipated power usage.

Within the scope of this paper, we will therefore examine whether there are alternative possibilities for high-resolution forecasting of electricity usage that can overcome the disadvantages mentioned above. The focus of the investigation is on the field of ML learning. Particularly, a promising method is proposed based on deep learning.

The aim of the proposed method is to be able to predict time series for the power usage of differing jobs by means of appropriately trained artificial neural networks (ANN). The basic idea is to train an ANN with relevant control information (here: numerical control codes of the production jobs of a machine tool and machine states) and the high-resolution time series of power consumption measured for these jobs.

Then, in perspective, the ANN can forecast a time series of the expected power consumption for any job, possibly even a job with deviating numerical control codes. Then, these time series could be used in hybrid simulation models of the entire production system.

This paper presents a concept for the outlined procedure as well as a prototypical implementation and validation. The paper is structured as follows: Section 1 discusses related work concerning the combination of simulation and ML and introduces the specific ML approach used. In particular, the necessity and basic idea of a deep learning method, which can map asynchronous sequences of different lengths to each other, are presented. This approach was first mentioned in [6], but led to non-conclusive results.

Building on this, Section 2 proposes a concept and prototypical implementation for the overall architecture with its input and output sequences. Section 3 discusses the makeup and necessary preprocessing steps of the data that are required to lead to conclusive results of the model. A brief description of the application case is given in Section 4. A prototypical application of the concept is demonstrated in Section 5. A critical review of the results and a discussion of future work is given in Section 6.

1 Related Work

1.1 Combining Machine Learning and Simulation

The need for data-driven decision making in a dynamic environment results in a need for methods that allow simulation models to adapt over time by learning [7]. Classical simulation approaches, such as discrete event simulation, have traditionally used data about the real system. This was either done manually within the modelling process, e.g., in the context of input data analysis for modelling stochastic influences by fitting theoretical distributions to the real observations, or semi-automatically within data-driven model generation approaches for depicting structural aspects of the model [8]. Automatically extracting behavioral descriptions from the data and representing it in a simulation model can be considered a weak point of automatic simulation modelling approaches [9].

Previous work focused, therefore, on combining ML with traditional simulation modelling for mitigating this weakness.

The papers by Bergmann et al. [10, 11] present an approach for using trained artificial neural networks. These networks can be called from material flow simulation models to obtain a decision on which control strategy to apply within the simulation, depending on certain input parameters modelled in the simulation project.

Another example is given by Rabe et al. [12], where Reinforcement Learning was used alongside a simulation-based Decision Support System for logistics networks. Here, the actions of an agent were modelled through ML, to identify and select principles on which decision-making policies should be carried out by the agent.

In [13] a set of machine learning classification techniques is proposed as a method to generate metamodels for the simulation of sawmilling processes. Here, data-driven models of the sawing process are generated and used to determine what sets of lumber are derived from breaking down the logs in a sawing mill.

Within patients care pathway design for hip fracture, ML was used to identify clusters of patients, and their underlying characteristics to use that insight in the development stage of a simulation model [14]. Unsupervised machine learning was used to cluster a set of patients into subgroups that relate in common characteristics. Once groups of patients at risk being treated for fractured hips were discovered, that information was considered in the simulation model to increase the efficiency of the overall healthcare process through optimized coordination of care resources.

Finally, ML is a key constituent in the modelling of a digital twin, as it is stipulated for symbiotic simulation approaches, and further be referred to as the result of HSM in [15]. Here, ML enables a digital twin that is a virtual representation of a physical system, as it allows the systems simulation model under observation to adapt primarily according to the behaviour of variables controlled by the physical system in question, and not the intentions of the shareholder of the model. Further such hybrid simulation-ML environments can be used to predict the changes in state variables of a system, as ML methods can be trained on past changes in the same system.

These examples have in common that they allow the representation of certain isolated decisions by an ML model and to include that decision within the simulation.

A different – widely uninvestigated – area is the inclusion of entire time-series data delivered from an ML model into a simulation model. This new approach contrasts with classical time series data analytics and prediction in simulation modelling, which have been discussed extensively (e.g., in [16], where time series data were used to generate wait time predictions).

To motivate the potential necessity for machine-learning-based time series predictions, let us consider one of the basic characteristics of discrete event simulation approaches: State changes can only occur at specific event time stamps. Anything that would happen in the real system between two events cannot be depicted. However, for some activities, i.e., the time span between two events, it may be necessary or desirable to describe a progression of a state variable belonging to the activity (e.g., the progression of power consumption during processing). To depict this, a modelling paradigm outside DES would need to be used in combination with DES. If the time series can be described analytically, some form of combined (i.e., continuous and discrete) simulation could be used. Often large amounts of data cannot be used to derive an analytical model, giving rise to the use of ML.

However, large quantities of data are not seen as a liability, but a prerequisite in a machine learning methodology. ML methods, as shown above, represent an effective way to aggregate data at particular steps of a modelling and simulation study, and their further use within a generative aspect will be discussed here.

1.2 Recurrent Neural Nets and Encoder-Decoder Architectures

Artificial neural nets (ANN) are used to identify patterns in complex data structures. For this purpose, embedding layers of a neural network embed the data under observation and guide them through the hidden layers of an ANN. Hidden layers consist of hidden units, the actual neurons. These neurons are self-parameterizing units. The more hidden layers an ANN contains, the higher the degree of abstraction of the recorded information can be. If an ANN has more than one hidden layer, it can link abstractions gained in one layer to another layer, thus creating a more complex abstraction with each added layer. This deep staggering of neural layers is commonly referred to as Deep Learning [1].

If patterns change over time, this temporal sequence of patterns is understood as a sequence. For an ANN to be able to process temporal patterns, recurrent connections must be present in the network topology that enable feedback of abstract knowledge [17, 18]. Such feedback or recurrent neural networks (RNN) are particularly suitable for data that are presented in sequential form [1]. Accordingly, a neural cell must be provided, which on one hand retains its own state and can pass it on, and on the other hand has access to successor states and can classify them. The requirements for such a neural cell with memory are fulfilled by neural Long Short Term Memory (LSTM) cells [19], and their simplification Gated Recurrent Units (GRU) [20].

If the inputs and outputs of a deep learning method are sequences, one speaks of Sequence to Sequence (Seq2Seq) architectures. Here, one embedding layer of an RNN encodes the input sequence. If the input sequence is encoded into a specific neural layer, one speaks of an encoder. If a sequence is generated from of a neural layer, this part of a network topology is called a decoder [1].

The recurrent Encoder-Decoder model (RNN-ED) as described in Figure 1 encodes a sequence X_T of T values into a summary vector C that is then decoded into a sequence $Y_{T'}$ of T' values. The encoder and decoder are conjoined by the fixed sized vector C [20].

If the task of a Seq2Seq model is to map asynchronous sequences, i.e., such of different lengths, to one another, such structures are generally referred to as Encoder-Decoder networks [1]. If sequences of different lengths and different attributes are to be mapped to each other, they must be extended by an additional description, a *context* (cf. context C Figure 1). The context is an intermediate hidden layer between the hidden layers of the encoder and decoder [20].

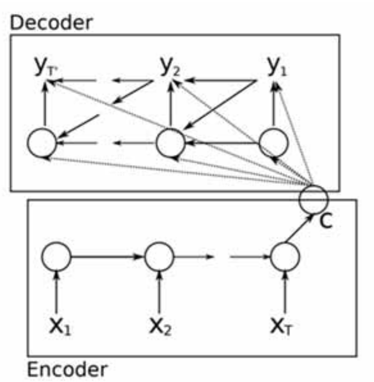

Figure 1: The Encoder-Decoder model as proposed by [20]. Note that $\boldsymbol{T}' \neq \boldsymbol{T}$.

Once all the values of X_i have been processed, the last hidden state is encoded into the summary vector C. The decoder now has two inputs C and $Y_{T'} = (y_1, \ldots, y_{T'})$ and learns the conditional distribution between them by updating its hidden state whilst reading in the values of $Y_{T'}$ and C, accordingly.

Here, the hidden state is linked to a *Softmax*-layer holding the unique tokens found in the training set $\mathbb{Y}$. Once training is finished the decoder can be initialized by any sequence X_i that can mapped to C, and generates a sequence $\widehat{Y_{T'}}$ therefrom [20, 21].

As the model learns to generate the next token y_{t+1} according to the previous token y_t and C, a stop condition needs to be added to keep the decoder from infinitely generating new tokens.

This is commonly done by placing a unique *end-of-sequence* (EOS) token at the end of the sequences Y_i in the training set $\mathbb{Y}$. Then ,once the trained decoder generates an EOS token, the sampling of new tokens is terminated [20, 21].

Further explanations of the encoder decoder used here can be found in [1, 20, 21].

2 Concept and Prototypical Implementation

For conceptual verification it is proposed to use such input and output sequences that are belonging to the same temporal-spatial entity. As a characteristic of a temporal-spatial entity, an activity is assumed that takes place at the same place and at the same time. For this purpose, the technological process of machining a job on a machine tool was identified.

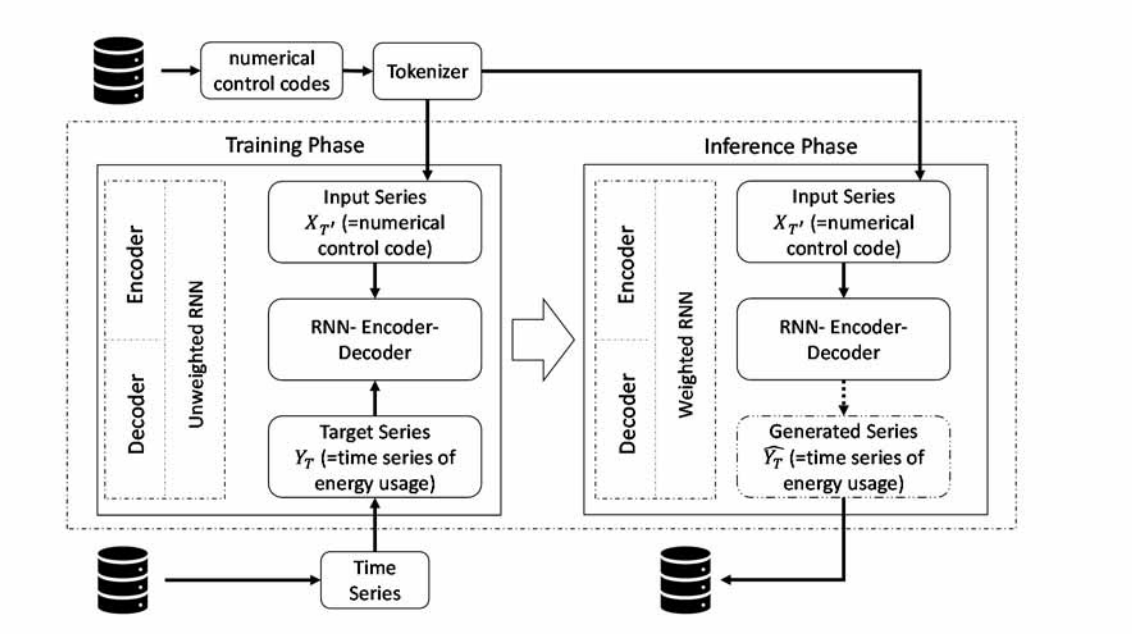

Figure 2: Implementation and components of an RNN Encoder-Decoder-Architecture for asynchronous and asymbolic series.

2.1 Predicting Energy Consumption through Seq2Seq

Figure 2 shows the overall concept of the proposed method. In the training phase, an unweighted RNN, the Seq2Seq-model, is parameterized using the input and target sequences $\{X_i, Y_i\}$.

For the training data, 51 in-field measurements of the active power usage of a machine tool and their corresponding numerical control codes, along with machine states, i.e., *modes*, were taken.

In the training phase, an unweighted RNN, consisting of an RNN-ED, is parameterized using the input and target sequences $\{X_i, Y_i\}$. The task of the inference phase is to provide a meaningful power consumption profile $\widehat{Y_{T'}}$ explicitly quasi-continuously over time (see Figure 2).

2.2 Seq2Seq in Hybrid System Models

Furthermore, the RNN-ED is called within a discrete-event-oriented simulation in accordance with a hybrid simulation methodology (cf. Hybrid Systems Model in [22]). Here, the power consumption for each job within the machining room of a machine tool (see the jobs trajectory in Figure 3) is characterized by the described RNN-ED method.

For this purpose, the weighted RNN-ED is called as a constituent of the timeout function within the simulation model once the machine tool is seized by a job (see Figure 3). Here, the prediction of the time for which a job seizes the machine tool is solely achieved by the assignment of an input sequence X_T to the timeout function of a job's trajectory. A specific time series is subsequently generated for each job that passes through the machining room, as it consequently activates the timeout function.

This happens once the job has blocked the resource of the machine tool it is machined on. The resource remains blocked until the seize time according to the timeout function has been reached. Then, the job is released from the resource's trajectory and it can be seized by the next job.

In a simulation run with this hybrid simulation method, the same time series is generated as it is done with a standalone inference of the RNN-ED (see $\widehat{Y_{T'}}$ in Figure 2).

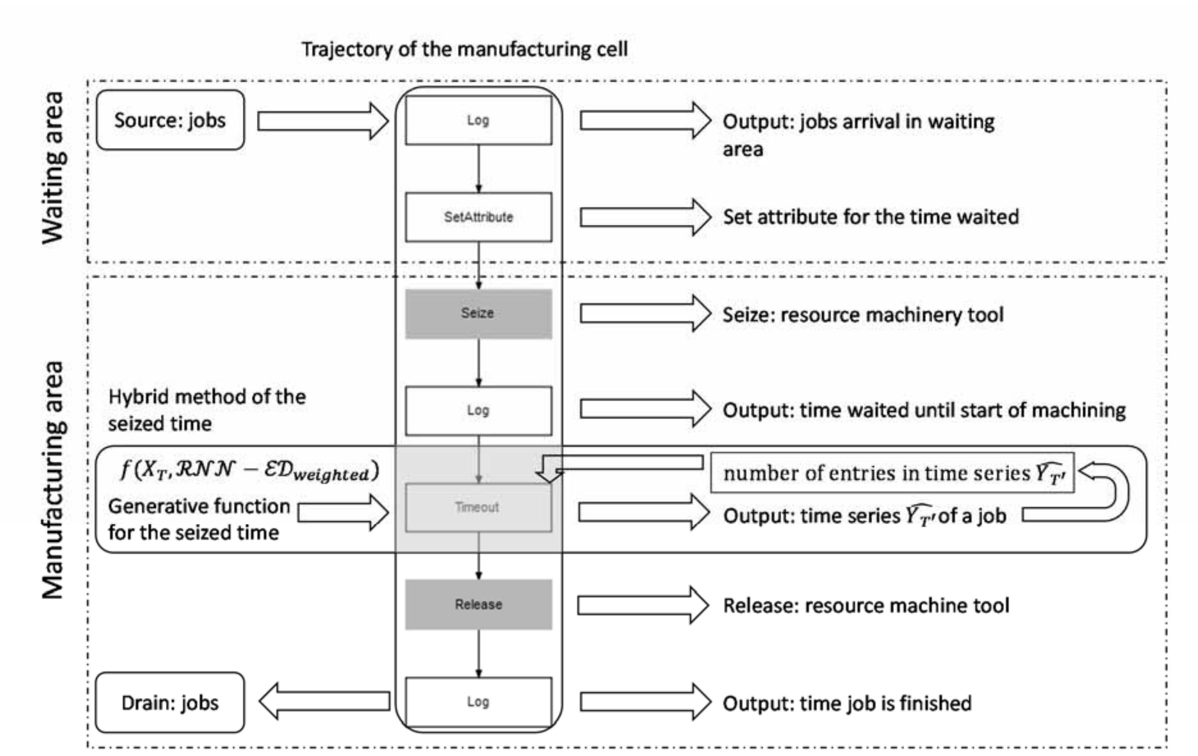

Figure 3: Visualization of a job's trajectory through a manufacturing cell. The constituents of the cell are modeled in a discrete-event-oriented fashion, while the manufacturing area's submodel contains a hybrid method adjacent to the trajectory's timeout function.

3 Preprocessing of Input Data

The machine tool's consumption of energy, and inherently the time it takes to process a job, was initially monitored every time a job is processed on it and then saved as time series data. The numerical control code that controls the machine's action for a job is monitored and saved as well.

In accordance with the findings in [6], both types of sequences need to be preprocessed for the RNN-ED to learn a meaningful context and the connection between them.

3.1 Setup of Input Sequences $\mathbb{X}$

A set of numerical control code and machine states for jobs is used as the input sequence X_T of an RNN-ED (see Figure 1). A numerical control code describes a sequence of necessary technological processes up to the completion of a job and can be understood as a direct description of a sequence of states underlying the process of machining jobs. The numerical control code decisively determines the behavior within the machining room of a machine tool. Furthermore, a job is only considered to be completed once the numerical control code has been completely processed.

The numerical code must first be translated into a sequence of numerical values that retains the structure of the targeted input sequence. This is realized by a so-called *tokenizer* (1). A tokenizer assigns a numeric value to each symbol or set of symbols present in the numerical code, e.g., based on the frequency of the symbol concerned.

$$[\ldots G\ 00, X0\ Y0\ Z0, \ldots] \xRightarrow{Tokenizer} [\ldots 1\ 2\ 3\ 4\ 5\ \ \ldots] \quad (1)$$

The tokenizer also removes symbols or sets of symbols that are assumed to have a low information content, such as commas, upper or lower case letters, etc. One way to limit the dimensions of the vector space is to dictate the tokenizer a maximum number of symbol sets (i.e., words) that can be mapped to a numerical vector. In our case, a word to vector (Word2Vec) tokenizer was used, which translates all symbols into a vector.

The input sequences are further extended with different modes $\{x_{11}, x_{12}\}$ in which the machine tool can be operated on. Those modes reflect a common work routine in machining a job. The numerical control code runs for the first time $\{roughing = x_{11}\}$ to chip a larger amount of excess material off and give the material its shape.

Afterwards the same numerical control code is run for several times $\{smoothing = x_{12}\}$ to smooth the surface of the now shaped material. Those two modes are reflected in time series of power consumption that are comparable in length but show very different characteristics in their features. The input sequence X_i is described accordingly as:

$$X_i = \{\{x_{11}, x_{12}\}, x_2\}$$

with x_2 being the numerical control code. The sequences of $\mathbb{X}$ are further tokenized to a list of integer values, where any unique word is represented by exactly one integer. This allows for modelling recurring patterns within the numerical control code.

3.2 Setup of a Set of Time Series $\mathbb{Y}$

The basis of values for the quasi-continuous time output series Y_T, is the current power consumption of a job when the numerical control code was processed (see Figure 2). The temporal power consumption gives concrete information about when and how much consumption must be expected before a decision has to be made about the machining of a job.

In contrast to [6], the set of time series $\mathbb{Y}$ has further been discretized. Discretization is the process of portioning continuous values into new discrete groups of values or *bins* that resemble the original values of the data.

This was necessary as the empirical results presented in [6] led to the conclusion that a uniform or long tail distribution, i.e., where the tail tends towards a discrete uniform distribution, P^f of value frequencies prevents the Seq2Seq model from learning a meaningful joint distribution.

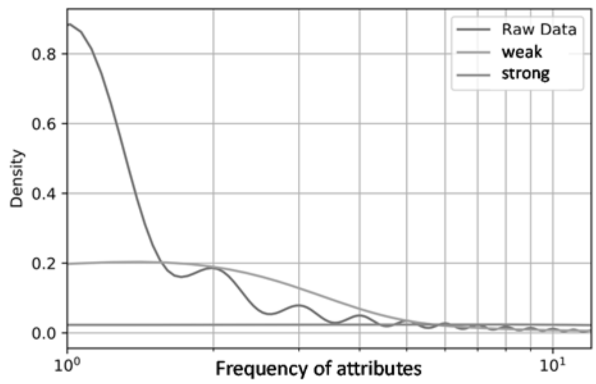

Figure 4: The KDE-plot shows that the raw data contained mostly unique values, while a strong discretization results in a uniform distribution, where the probability of a value belonging to any frequency is the same as for any other frequency. A weak discretization results in a heavy tail distribution of frequencies.

To find the right parameter, as to which degree needs to be discretized, several runs of training with alternative discretization parameters were conducted. The different discretization parameters were applied on the whole data set of time series and, then, classified according to the frequency f of the discretized values (Figure 4). For this purpose, the distribution of frequencies P^f was analyzed using a Gaussian kernel density estimator (KDE).

The proposed concept has been tried for all three frequency distributions and results only for the weak discretization in satisfying results.

4 Case Study

Tensorflow was used to call the tokenizer function and to implement the RNN-ED architecture. For the ease of use of *Tensorflow*, the API *Keras* was used. The *Keras* API was used as the interface to *Tensorflow*, because it provides a high level of clarity when presenting network architectures with a higher level of abstraction. The package *rSimmer* [23] was used for the discrete event modelling part.

The time series data $Y_{T'}$ was recorded under field conditions and has the same clocking of Δt – 500 ms – representing quasi-continuous recordings of the active power usage. The input sequences X_i represent the numerical control codes of the same jobs along with the machine states. A tokenizer was used to generate the vectorized input sequence from the input data.

The RNN-ED sequentially embeds the vectorized input sequence X_i and the time series $Y_{T'}$ of power consumption associated with the initial jobs. The trained net and its weightings are then saved. To use the weighted RNN-ED in the inference phase (see Figure 2), the vectorized input sequences X_i of a job are entered into the encoder. This results in the generation of a time series $\widehat{Y_{T'}}$ of the power consumption from a trained RNN-ED for a job.

As this paper focuses on the generation of the values for the time series $\widehat{Y_{T'}}$, instead of its integration, the simulation at runtime will no further be discussed here.

5 Results and Evaluation of the Seq2Seq Method

Metrics to compare the generated time series $\widehat{Y_\iota}$ and Y_i are the median length $len(\overline{Y}_i)$ and average $sum(\overline{Y}_i)$ of time series as found in the training set. Further, the time series have been visualized and features of characteristic patterns or labels have been added to those visualizations (see Figure 6).

Adding features helps to compare the time series $\widehat{Y_\iota}$ and Y_i more intuitively on a visual level. The result for the raw data, which have not been discretized, aligns with the non-conclusiveness of [6]. The sequences created showed no meaningful course of values and further failed to produce an EOS-token, i.e., the method did not terminate the creation of new numeric values.

The results for the *strong* discretization as shown in Figure 5 are disappointing. An EOS token was created, as well as most other features, yet the generated series can clearly be distinguished from the training data (samples shown in Figure 6) and results in low scores in the metrics, accordingly.

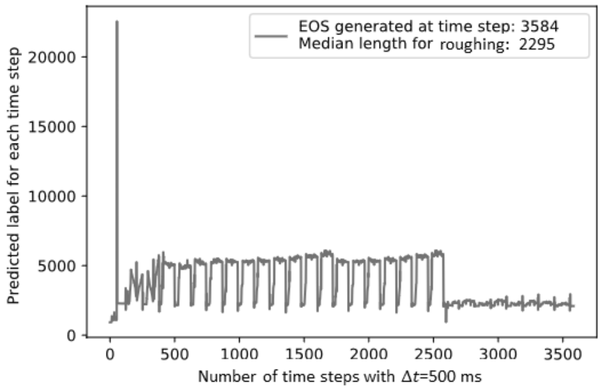

Figure 5: Result for a strong discretization and parameter setting $\{x_{11}, x_2\}$.

On the other hand, the *weakly* discretized time series shows high values in comparison to $len(\overline{Y}_i)$ and $sum(\overline{Y}_i)$:

$$\{x_{11}, x_2\}: \frac{len(\hat{y}=2258)}{len(\bar{y}_\iota=2295)} = 98.4\,\%; \frac{sum(\hat{y}=6847.7)}{sum(\bar{y}_\iota=6927.9)} = 98.8\,\%$$

$$\{x_{12}, x_2\}: \frac{len(\hat{y}=2204)}{len(\bar{y}_\iota=2256)} = 97.7\,\%; \frac{sum(\hat{y}=4843.3)}{sum(\bar{y}_\iota=4871.8)} = 99.4\,\%$$

On closer inspection of the time series $\widehat{Y_\iota}$ and Y_i for $\{x_{11}, x_2\}$, as displayed in Figure 6, a striking resemblance can be seen. The sequences displayed from the two sets clearly show the same patterns over the course of labels.

The time series generated accomplishes to mimic the course of labels as shown in the training set with a remarkable precision. It does not only achieve to reproduce an EOS token that matches the length of the time series found in the training set (green dot), a distinct peak-feature (red dot), as well as a string of subsequences (the dots of changing shades of blue), but also to generate them in the right order and dimension.

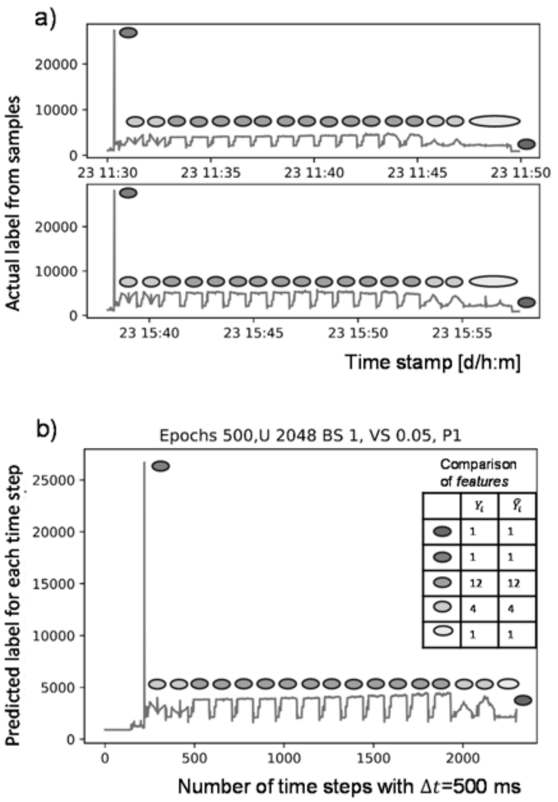

Figure 6: Comparison of (a) samples Y_i drawn from the training set $\mathbb{Y}$ and (b) the generated time series $\widehat{Y_i}$ for the weak discretization parameter and the sequence combination $\{x_{11}, x_2\}$.
The table shown on the lower-right side compares the count of features against each other.

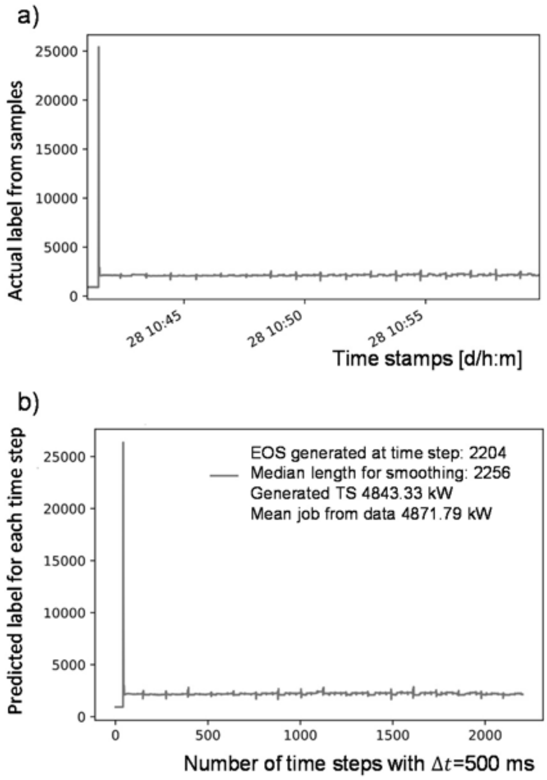

Figure 7: Comparison of (a) samples Y_i drawn from the training set $\mathbb{Y}$ and (b) the generated time series $\widehat{Y_i}$ for the weak discretization and the sequence combination $\{x_{12}, x_2\}$. No features were added as the time series holds few characteristics.

The time series $\widehat{Y_i}$ and Y_i for $\{x_{12}, x_2\}$, displayed in Figure 7, also clearly show that the Seq2Seq-model succeeded in catching the course of labels within the training set, even though the time series from the training set contained few features that could be learned in the first place.

6 Conclusion and Future Work

The functionality of the described approach was confirmed in the use case by chosen metrics. However, the generated time series still must be critically questioned and validated in further research work.

On the one hand, there is still a lack of evaluation methods for generative models of ML to check the generated time series entries for the meaningfulness of their entries. This is done at the moment by the observation and comparison of the generated time series through an application expert by optical inspection [1] as shown in Figure 6.

For a final evaluation of the methods used, it is advisable to increase the qualitative and quantitative data basis of the Seq2Seq-model. The data set used here is of a small size. Yet the set size is exemplary for real world settings that might change rapidly and in short periods of time.

On the other hand, machine learning algorithms tend to work better given that there is a lot of data to learn from. A framework in which the training set is extended by time series that have been altered to represent a ground truth of the training set of time series could solve that problem. *Dynamic Time Warping* could be used to generate such ground truth time series [24], which could then iteratively be added to the training set until an advantageous learning behavior could be displayed.

Additional end-of-sequence tokens could be used to describe events like machine failures. The *EOS* token used here simply marked the end of a finished job. Yet some jobs are prone to break due to system changes like wear and tear experienced by the tool.

Adding an alternative *EOS*, indicating machine failure, to the training set, along with data for the state of tools etc., might also answer the question whether a job can be executed given the current settings.

The method further allows for generating time series according to factorial combinations not found in the training data. As the decoder is not parametrized directly on the input sequences found in the training set, but on a summary thereof in form of the context vector, factorial combinations of input parameters can be used that are not represented in the initial training set. If the respective input parameters and their distinctive effect on the time series has been modeled, any combination thereof could be used. This would result in factor combinations of high interest to a simulation expert that could not be modeled in a generic simulation setting.

Hence, a suitable evaluation method must be added to the proposed solution, since validation cannot be guided by a (non-existent) ideal time series.

The further development of the ML method described here and its use for hybrid simulation models is currently the subject of ongoing research. Also, if the method is successfully established and validated, a solution could be developed that produces plausible power consumption forecasts for unknown jobs, e.g., based on their numerical control codes. This would have a high practical potential and would also be a breakthrough from a scientific point of view.

The transfer of the basic idea to other forms of control code and time series of other values is also conceivable and a possible subject for further investigations.

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Agent-Based Simulation Approach for Occupational Safety and Health Planning: A Case of Electroplating Facilities

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Abstract. The current and future occupational safety and health (OSH) regulations from various national and international regulations such as REACH ask for an increasing process transparency in the electroplating industry to monitor the OSH situation. Currently, the COVID-19-related situation of shopfloor workers also requires an increased transparency in contact tracking. Manufacturing system simulation is a promising approach in this context. To date, simulation models mainly focus on the process-specific technical, economic, or environmental aspects. Modelling the OSH of workers in plating industry is rarely the focus of these approaches. This paper shows an integrated simulation framework to model industrial automated electroplating lines and the interaction with involved shopfloor workers as part of a cyber-physical production system. Line-integrated pre- and post-treatment processes as cleaning and degreasing are considered as well as their effects on shopfloor workers. In a case study, different applications with regard to OSH are shown to demonstrate the applicability of the developed framework and the high adaptability to new challenges as social distancing during pandemics.

Introduction

Industrial electroplating processes are characterised by a high variety of process parameters. Due to dynamic interdependencies between and within the process steps, the relationship between process parameters, surface structure, and surface properties including energy and resource demand are not fully understood. Especially highly automated barrel plating lines are complex dynamic systems, consisting of subsystems that influence each other. Improvement measures in one subsystem often influence other subsystems, for example, the drag out from plating baths influences the following post-treatment baths.

Recently, in the EU, stringent requirements under the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation require increased process transparency and measures to increase the occupational safety and health (OSH) of the workers in electroplating facilities [1]. Today, in most countries OSH authorities restrict the use of widely used electroplating substances if no sufficient data regarding the OSH situation are available. Further, recent challenges such as the COVID-19 pandemic require a fast adaption for production processes and OSH planning as plating lines require shopfloor workers.

Currently, these OSH aspects are rarely considered in simulation models for planning and operation of electroplating facilities. The high complexity makes it difficult to rate the effects of a single measure on the overall OSH situation. Especially for OSH measures, the interdependencies to process parameter are often not considered in the planning phase nor during operations.

To support higher process transparency, an integrated multiscale and multilevel simulation approach has been developed. The simulation is used as part of the cyber system and embedded in the cyber-physical production system (CPPS) that is the basis for a comprehensive decision support system. This approach significantly increases the process transparency allowing for evaluating the OSH situation a priori in the planning phase of an electroplating line as well as during operation. OSH planning benefits significantly from a simulation approach, as changes during operation are often very costly or even not realisable in a productive manufacturing environment. Further, specific exposure measurements only consider static production situations during the measurement. These measurements do not consider the dynamic character of electroplating process lines such as changing process parameters.

1 Background

1.1 Automated Electroplating Process Chains

Automated rack and barrel plating lines enable plating high volumes of small-to-medium-sized parts at high quality and reproducibility. Figure 1 provides a schematic overview of an automated industrial rack electroplating line. Parts are loaded and unloaded manually at the beginning and at the end of the plating line. In the plating facility, a set of tanks, filled with pre-treatment, plating, and post-treatment fluids, is aligned in one or multiple lines. A rail-mounted hoist (RMH) system transports the barrels, or more generally the carriers, between the single tanks starting from pre-treatment processes as cleaning and degreasing, through the electroplating process to post-treatment processes as rinsing or passivation [2]. Peripheral systems as exhaust air systems support the process baths and ensure that workplace concentrations are not exceeded [3; 4].

Although electroplating lines are highly automated processes, shopfloor workers are required for loading and unloading parts for the maintenance and cleaning of tanks, fluids, and periphal devices. Electroplating lines for small lots of big parts that require high quality coating are often less automated and also require workers for shifting the parts between the tanks. In this case, also groups of workers can be necessary to manoeuvre the parts with a crane through the electroplating line.

Typically, the carriers follow the direction of the plating line. However, backwards and lateral movements to parallel tank lines are required due to space restrictions and in order to enhance the flexibility. Further, storage spaces can be included to store carriers between processing steps to enhance the productivity of the plating system.

1.2 Occupational Safety and Health for Electroplating Processes

Especially the use of hazardous chemicals in the electroplating industry catched the interest of OSH authorities and organisations in nearly all countries over the world, starting from international organisations such as the International Labour Organisation (ILO), which published International Hazard Datasheets on Occupation for electroplater [5], to more specific European Regulations from the European Chemicals Agency (ECHA), which restrict the use of specific plating chemicals by placing them on the authorisation list [1].

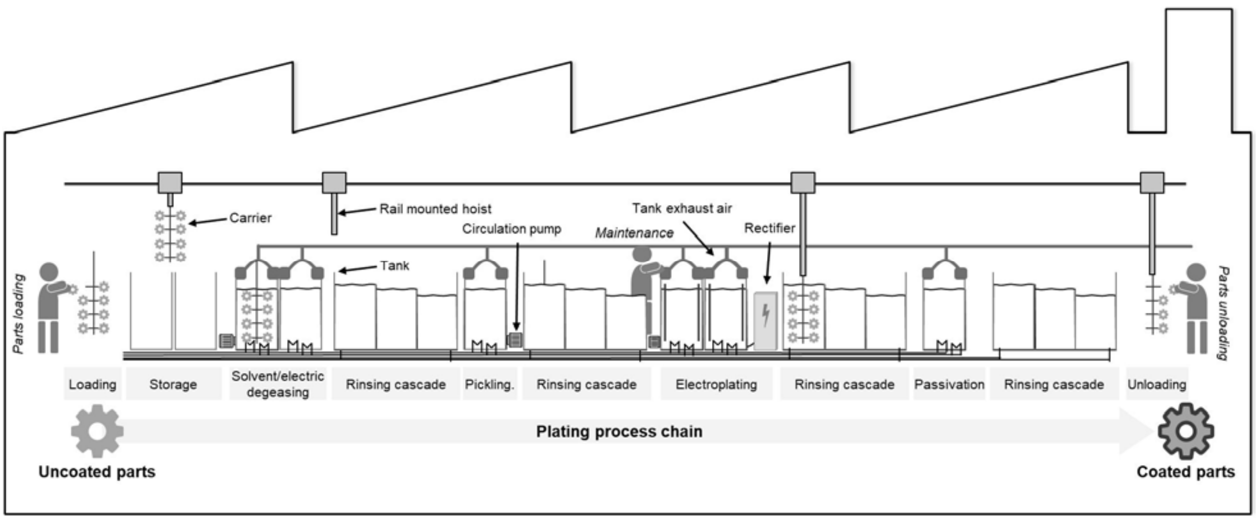

Figure 1: Overview of elements of an electroplating line.

Also in the United States [6] and in China the ministry of environmental protection put relevant plating chemicals such as hexavalent chromium (CrVI) on the first batch of the priority control chemicals list [7]. A commonality of all these regulations is the requirement for a higher transparency to rate to the risks for the workers on the shop floor in the electroplating facility.

Aside the risks from chemicals, in pandemic also social distancing measures become necessary to keep the number of cases low [8]. A flexible manufacturing systems simulation with focus on the shop floor workers allows for rating the effects of measures minimizing the infection risks of shop floor workers.

1.3 Simulation of Manufacturing Systems

Electroplating combines discrete and continuous processes. The workpieces are typically stored in barrels or racks and go through the cleaning, rinsing, and plating processes, which have a discrete character, in batch mode. Fluids for cleaning, rinsing, plating, and post-treatment flow continuously through the system. [9] Therefore, a combined discrete and continuous simulation approach within an agent-based simulation environment is proposed as simulation paradigm.

Today, most available simulation tools for manufacturing systems are capable to model discrete manufacturing systems focussing on material and product flows. Within the last decade the simulation of energy flows has been included [10]. Hesselbach et al. [11] introduce a model-coupling approach to consider the production and technical building system within one environment. The approach by Thiede [12] is generic and supports simulating many different production systems, but mainly focuses on the energy demand. Bleicher et al. [13] developed a simulation with a focus on the energy demand simulation for machining processes and also included the energy and building system into their simulation.

The approach by Eisele [14] focuses on the energy demand of machine tools. Schönemann [15] developed an approach allowing co-simulation applied to battery production systems. Kurle [16] partially included electroplating processes into his approach, but mainly focusses on the heat flows in the production system. Xu et al. [17] model the resource flows in electroplating and rinsing systems in detail, but neglect the energy demand and further systems of the plating line. This detailed approach also allows for simulating only one specific product.

Modelling workers in production engineering simulation environment is already described in the German VDI guidelines 3633, part 6 [18] and 4499, part 5 [19]. The guideline 4499 part 5 is focussing on ergonomic representation of humans in the digital factory, while guideline 3633 part 6 also describes the use of simulation models for planning purposes.

In difference to existing approaches, the developed simulation focusses on automated plating lines addressing the specific characteristics. Dedicated models for electroplating lines and shop floor workers are developed. New innovative visualisations are integrated to analyse the OSH situation.

2 Framework for Manufacturing Systems Simulation of Electroplating Lines

CPPS contain a physical and a cyber system that are interlinked with data acquisition, feedback, and control systems [20].

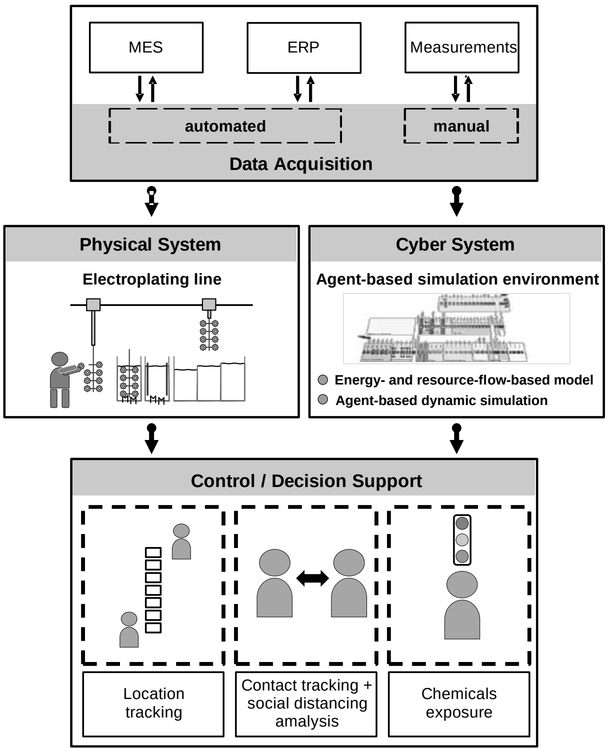

Figure 2: Integration of simulation as cyber system into a CPPS.

For this study, an automated barrel electroplating line is used as physical system and the simulation as cyber system (Figure 2). Relevant data are acquired from the electroplating line and used as input for the simulation. The simulation is the basis for a comprehensive decision support system and allows for predicting the future behaviour of the plating line.

Compared to a stand-alone simulation, the integration of the simulation in the CPPS enables a comprehensive decision support for multi-criterial planning and control of the electroplating line, using live data from the electroplating line.

For a CPPS realisation, an efficient data acquisition from the physical system is decisive. Already available sensors and data are used and enhanced by additional manual measurements. From the Manufacturing Execution System (MES), the pending production batches with their characteristics and the process chains are transmitted. At the same time, product-specific data are retrieved from the Enterprise Resource Planning System (ERP). MES and ERP were connected with file-based interfaces to the simulation to enable an automated data transfer. Additionally, electrical power, chemicals, and air emissions concentration measurements were conducted to build an electricity and resource flow model for the plating line. Compared to the installation of various sensors for electricity and air emission measurements, this approach is more efficient, and no extensive additional sensor network is required.

The acquired data are the basis for the parametrisation of the agent-based simulation. Figure 3 provides an overview of the simulation model. Seven state-based multi-parameter models were developed to build up a framework for the simulation model. Each model represents an agent type and can be multiplied to build the whole plating line.

The agent type *product* represents the product to be plated and contains the product's properties as surface, volume, weight, material, or drag-out behaviour. These properties are required to calculate the energy demand and the drag-out behaviour of specific products. *Carriers* are filled with a defined number of products and are used to transport the products to different tanks. *RMHs* transport the carriers between the tanks. The operation area of RMHs is restricted and contains a state-based model, which also allows for modelling the energy demand. The RMHs can be controlled by commands from the MES system or by algorithms within the simulation environment.

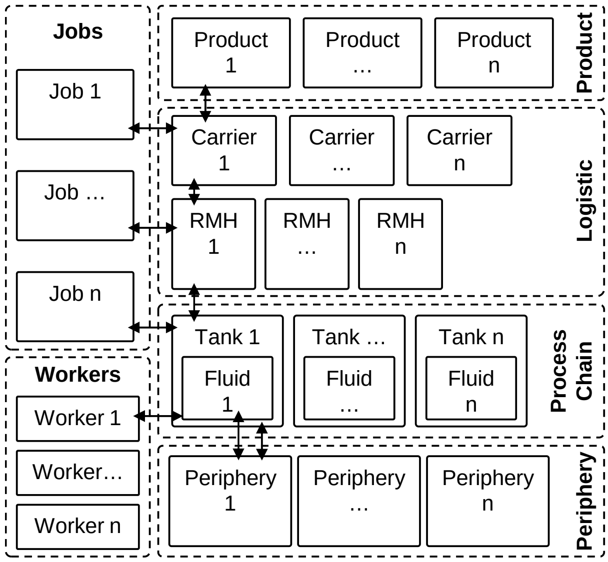

Figure 3: Structure of the simulation model [21;22].

The agent type *tank* represents the fluid tanks to build the plating process chain. Again, a state-based model represents the current situation (empty, occupied, in process, and waiting for RMH) and is the basis for the energy model of the tank. The energy demand of local energy consumers, for example the drives for rotating the carriers during plating or rectifiers for the electroplating process, are modelled within this agent. Tanks can be filled with a *fluid* or remain empty in case a tank is used as storage space. It is possible to use one fluid for multiple tanks in case the tanks are connected with a piping system. Additional *periphery* can be connected to the fluid (e.g., in case of circulation pumps for multiple baths), to multiple tanks (e.g., in case of tank-state-controlled exhaust air systems) or depending on factors outside of the process chain (e.g., in case of cooling units for control systems).

The agent type *job* contains all relevant information to proceed a product through the plating process chain, such as process steps, times and parameters. This is the basis for a simulation run, and this agent type receives job data from the MES. The agent type *worker* represents people working within the plating line. Each worker has a specific order of tasks, which are related to OSH data. In chromium plating lines, the CrVI air emissions are in the focus of the OSH authorities and should be monitored.

In Table 1, an exemplary list of task is shown that contains the duration of the tasks and the exposure during this task. The available tasks and the corresponding CrVI exposure values are stored in a database, so that each worker can be configured with its specific tasks during a shift.

Figure 3 also provides an overview on agent communication and interaction during the models runtime.

For control and decision support, three specific amending decision support modules with model-based key performance indicators and visualisations were developed. These are introduced with industrial examples in the following sections:

- Workers location modelling on shop floor
- Workers contacts and social distancing modelling
- Hazardous chemicals exposure modelling

ID	Task	Duration	CrVI exposure
1	Loading Parts	60 min	0.1
2	Taking samples	20 min	1
3	Refilling Chemicals	10 min	4
...	...	...	...

Table 1: Extract from work schedule with example emission data.

3 Industrial Case Study

The presented framework was applied to the example of a small-to-medium-sized company running an electroplating facility for small-to-medium-sized automotive parts. Six active plating baths are available as well as all the required pre- and post-treatment baths to fulfil the requirements from the automotive industry. In the following three subsections, the three developed applications for OSH planning are presented.

3.1 Workers–Locations Modelling

For effective measures towards reducing OSH risks, it is required to know the work places that are associated with OSH risk and the paths between them depending on their tasks. Also, for human factors and ergonomics planning, the lengths of walking paths and working time at specific work places on the shop floor are required. Tracking the location of workers with technical solutions, such as GPS or local radio-based systems, is associated with high effort and cost as well as privacy concerns. Tracking the workers in a model-based environment reduces the technical effort significantly and does not cause privacy concerns, as the workers can be anonymsised in case of a-priori simulation. During the application process, also the workers' union should be involved to consider the perspective of the employees for specific simulation runs.

The integrated evaluation module in the simulation with visualisation towards a decision support can be implemented at low effort.

Based on the simulation for analysing and visualising of paths in operation rooms from Koshkenar et al. [23], a visualisation based on heat maps has been developed. To visualise the employees' workplaces and paths during a shift, a heat map is projected on the shop floor layout.

Figure 4 shows the plating line layout with the heat map, which indicates the number of workers per square meter. The two red points at the upper left side indicate a high employee density in an uncritical area, where the controls of the line are located and parts are unloaded. In the critical area (dosing tanks and plating baths at the right side) employees stay for a relatively short duration. This visualisation enables an easy detection of areas with a high worker density and the effect of different task schedules for the workers.

Beside the visualisation, also a quantitative analysis of the walked paths is possible. In this specific scenario, the first worker with changing jobs walks 800 m over an 8-hour shift while the second walks only 29 m and the third worker 73 m. The reason is that the first and the second worker focus on loading and unloading parts, while the first also conducts various maintenance tasks in the plating line. However, all walked paths are uncritical from an OSH perspective, especially compared to other manufacturing areas such as automotive assembly lines.

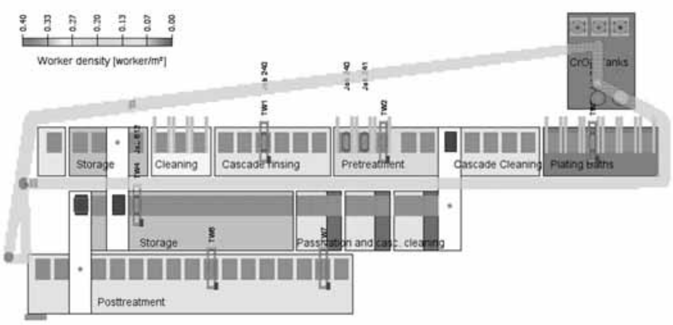

Figure 4: Shop floor heat map based on worker location

3.2 Workers Contacts Modelling

One advantage of the agent-based simulation approach is its high adaptability to new situations such as the unexpected pandemic COVID-19. With adaptations, the simulation can be used to estimate the contact durations between workers, and provide measures towards social distancing in order to tackle the COVID-19 pandemics.

To keep the number of infections low, it is required to keep the number and duration of contacts on the shop floor level as low as possible.

The worker location tracking mechanism from the previous chapter is extended by a parameteriseable social distance circle (typically 1.5 m). This circle is checked every second for other workers, respectively agents. If another worker is within this circle, a state-chart-based mechanism triggers the visualisation and statistics module.

Figure 5 shows the 3D visualisation with three workers whose social distancing circle colour depends on other workers located within this circle. In the visualization on the screen, green indicates that the worker is save with no other worker within his social distancing circle, and red indicates that another worker is within the social distancing circle.

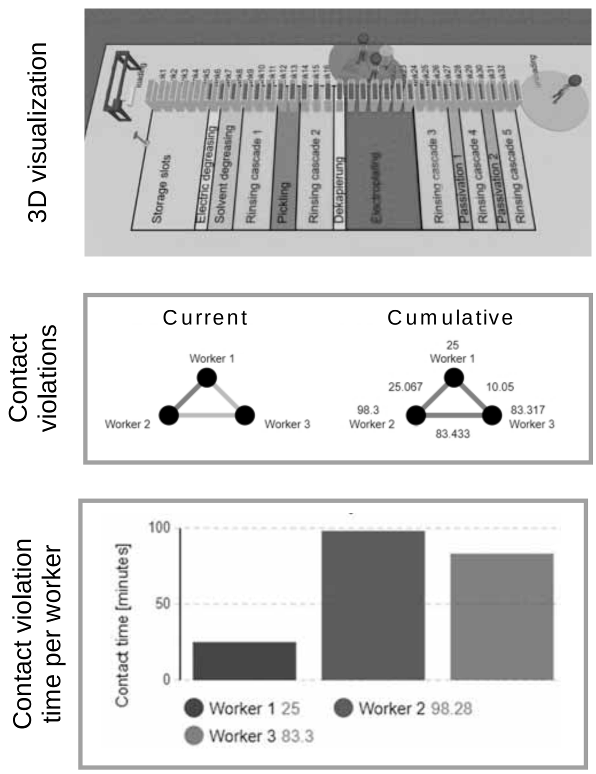

Figure 5: 3D Visualisation of social distancing in plating line.

A dashboard visualises the current and cumulative contact situation. Beside a classic bar diagram that indicates the contact length to other workers, a graph-based visualisation has been developed. Workers are visualised as vertices and the contact between them as edge. The colour of the edges depends on the contact intensity between two workers.

Table 2 summarises the contact times between three workers during an 8-hour shift from two scenarios. In the first scenario, Worker 1 and 3 work in parallel for 75 minutes during a shift.

By adopting their task schedules, their contacts could be prevented. Worker 1 and 2 meet for 2 seconds while walking to their next workplace. It has been assumed that this short duration is uncritical. Thus, no changes are required.

	Scenario 1		Scenario 2	
	Worker 1	**Worker 2**	**Worker 1**	**Worker 2**
Worker 1	-	-	-	-
Worker 2	75 minutes	-	no contact	-
Worker 3	2 seconds	No contact	2 seconds	no contact

Table 2: Evaluation of social distancing violations.

3.3 Hazardous Chemicals Exposure Modelling

Recent updates of the REACH regulation ask for a higher process transparency for the use of critical substances, in particular chromium trioxide in the electroplating industry. The developed simulation approach is used to calculate the workers' OSH situation based on their job profile and the current process parameters in the plating line. This allows for calculating the workplace exposure to a worker during single tasks based on surrogate models from the advanced reach tool [24]. The simulation tool can be used for comparing different scenarios a priori without further measurements.

In Table 3, the average and current emission loads for specific work schedules of three workers are shown. The average CrVI emissions are below the limit of 5 µg/m³ during an 8-hour shift. For Worker 2 and 3, the limits are exceeded for short durations, so that measures to lower the peak loads are required. In this specific case, the use of respirators for adding hexavalent chromium to the plating bath is advised.

	Average	Max.
Worker 1	0.756	5.0
Worker 2	3.689	16.1
Worker 3	0.075	16.0

Table 3: CrVI emission load in μg/m³.

Different measures can be applied to improve the workers' OSH situation. Beside personal protective equipment, operations close to the plating baths and dosing tanks should be avoided. In addition, job rotation can be a measure to improve the situation. The simulation approach can be used for the validation of these improvement measures.

To increase the awareness of decision makers in production planning, innovative ways to visualise the workers' OSH situation were developed. For the 3D simulation visualisation, the current situation of a worker is indicated by coloured balls above their head (Figure 6).

On the original screen, green indicates no critical exposure, yellow an exposure close to the critical value (4 to 5 μg/m³), and red a critical exposure (> 5μg/m³) that requires immediate measures.

As the air emissions exposure highly depends on the location of a worker during a shift, a visualisation to map their location during a shift (as shown in Figure 4) will help to prioritise measures.

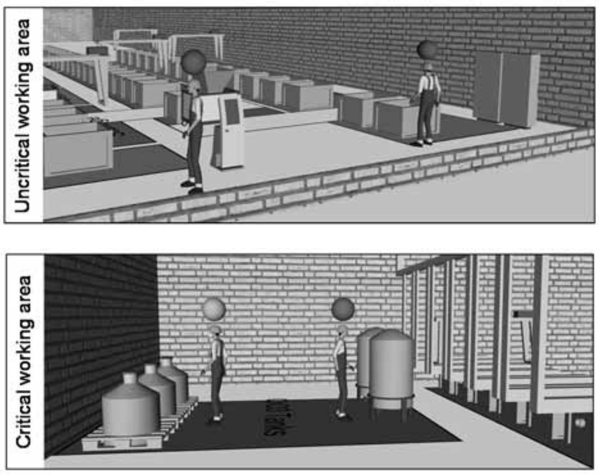

Figure 6: Visualisation of occupational workplace OSH situation.

4 Conclusion, Discussion, and Outlook

A framework to use an agent-based simulation with focus on OSH applications as part of a CPPS for automated industrial electroplating lines has been introduced. The case study showed the applicability and the benefits from using a simulation approach for studying the OSH situation. Three specific decision support modules increase the transparency regarding the OSH situation significantly and provide the basis for further development of the simulation framework.

For future steps, especially the results from the hazardous chemicals exposure modelling should be verified with temporal measurements. As a further step, detailed indoor air emission models could be integrated to model the spread of aerosols containing hazardous chemicals or viruses.

The CPPS approach can be the basis for further surface treatment processes such as chemical or electrophoretic coating. From a production engineering simulation perspective, the general plating layout is similar and mainly the model's details need to be adjusted. In addition, the generic character of the models is transferable to production processes from other industry sectors.

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Simulative Study of Aluminium Die Casting Operations Using Models with Varying Degrees of Detail

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Abstract. Aluminium die casting plants offer great potential for optimisation in terms of production and energy efficiency, which can be demonstrated by simulation. However, real companies often have a poor data basis for complex simulation. Based on a complex model, simplified simulation models are designed that are compatible with a low amount of data acquisition. These are described in this paper and tested on different scenarios. One scenario is the variation of downtimes of production machines. Considerable savings in computing time can be reached with still plausible results in terms of material and energy consumption.

Introduction

Simulation-supported methods are increasingly used in production and logistics companies to demonstrate operational optimisation measures [1]. The simulation models often aim to accurately represent the real operating processes. This usually requires a high level of detail, but is also associated with a high modelling effort, a need for detailed operational and production data, and a long computing time. For models with little need for measurement data and computing time, new areas of application arise, such as model predictive control (MPC). In addition, the use in companies with a low data acquisition rate is possible. Especially in the non-ferrous industry, the data basis is often insufficient for the application of a complex simulation model.

Energy-intensive companies are particularly suitable for simulation of optimisation measures or predictions of material and energy consumption. Within the scope of a preliminary study, simulation models with varying degrees of detail of an aluminium die casting plant were set up and compared under certain scenarios [2]. The highly detailed simulation model was validated by the data of two real facilities and can, thus, serve as a reference for the simplified models. As the results reveal a lower level of detail, a massive saving of computing time and data acquisition effort can be achieved. However, there are deviations in the results, such as the output of processed mass and the specific energy consumption.

A weakness of the models with a low level of detail lies in the exclusive consideration of the liquid aluminium storage tanks. By adding the melting shaft with the solid-liquid phase transition, the quality of the models is improved without significantly increasing the calculation effort and the scope of the required operating data. In the present work, the considered melting die casting operation as well as the simulation models of different levels of detail are described. Based on the models, different operating scenarios are examined and the models are compared.

1 Aluminium Die Casting Company

The present study is based on a large aluminium die casting facility. The typical structure of such a plant is shown in Figure 1. The operating sequence includes both continuous (e.g., melting) and discrete (e.g., forklift transport) process steps.

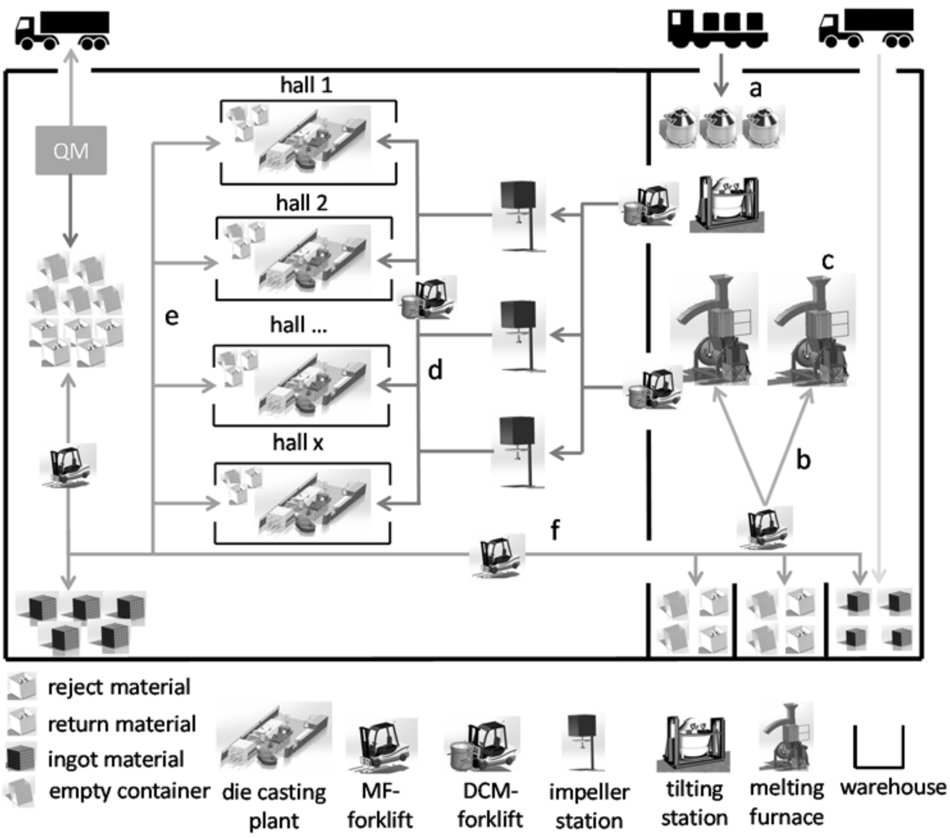

Figure 1: Scheme of an aluminium die casting plant with its process steps [3].

The underlying processes are (Figure 1):

1. delivery of molten aluminium
2. feeding the gas-operated shaft melting furnaces via forklift trucks with metal ingots, return, or reject material
3. heating, melting and overheating, or keeping the metal warm
4. distribution of the liquid aluminium with forklift trucks to the dosing furnaces of the die casting machines
5. production of cast parts in the die casting machines and quality control
6. transport of material containers from the die casting machines or ingot packages from the warehouse to the melting division

The plant can be supplied with liquid aluminium in two ways. On the one hand, the melting furnaces are supplied with solid aluminium in the form of ingots, return, or reject material by forklift trucks. In the furnaces the aluminium is melted and kept warm in the holding area until it is removed.

Alternatively, the liquid aluminium can be delivered directly from external smelters and stored in a tilting station until removal. Once per shift the furnaces must be melted free and cleaned. The melting and holding processes in the furnaces are particularly energy-intensive processes and are, therefore, decisive for the energy efficiency of the facility. The melting division requires about 50 % of the total energy consumption of the company.

For this reason, the melting and holding process is in the main focus in terms of calculating energy consumption. This process is displayed in an energy flow model.

For the material flow, all process steps are relevant. For example, after the melting process, the liquid aluminium is removed from the trough of the melting furnace and transported to the die casting machines by forklift trucks. The forklift trucks operate according to predefined rules: Die casting machines that have a little liquid aluminium available for production are supplied with priority. In the die casting machines, the actual production of the parts takes place. Depending on the machine, different components are casted, which leads to a machine-specific consumption of liquid aluminium.

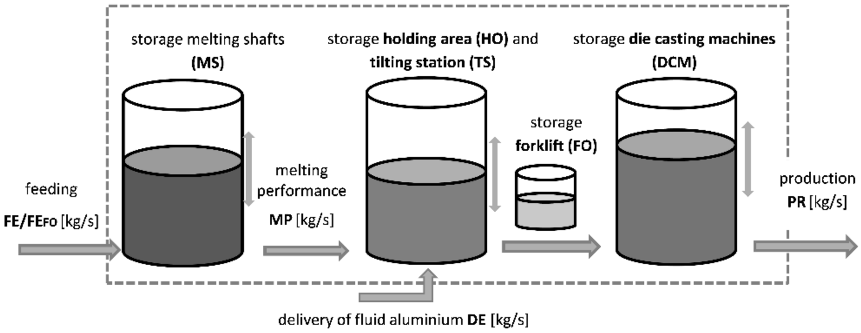

Figure 2: Scheme of the simplified model.

2 Simulation Models

In a previous study, different simulation models were developed depending on the level of detail, which simulate the aluminium die casting operation shown in Figure 1 [2]. The highly detailed model is used as a reference model to evaluate the models of lower levels of detail. In the further development of the simplified and detailed model, importance is attached to ensure that the models remain mathematically describable using hybrid automata that take into account both continuous and discrete event elements [4]. The models are constructed and simulated with the software tools Matlab, Simulink, and Stateflow.

2.1 Simplified Model

In the simplified model (Figure 2), entire machine groups are considered as liquid aluminium storages. The machine groups – such as melting shafts, furnace tanks with tilting station, and die casting machines – are combined to form a material storage. The material flow between the reservoirs is described by continuous and discrete event elements. The energy flow is determined by the continuous variable melting performance.

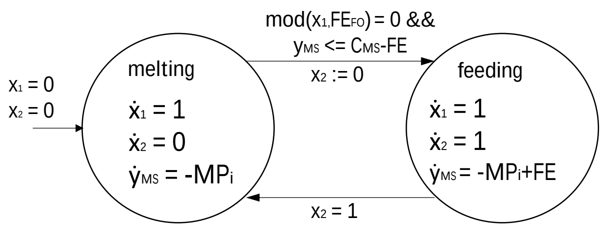

Figure 3: Hybrid automat for the melting shafts in the simplified model (x_1 time for determining the feeding, x_2 time for determining the feeding duration, y_{MS} total filling level of the melting shafts, C_{MS} total capacity of the melting shafts, MP melting performance of the melting shafts, FE feeding quantity, FE_{FO} duration for the renewed feeding process).

The individual storages are described as hybrid automata and as such are implemented in Stateflow. Figure 3 shows an example of the hybrid automaton, which describes the melting shafts. The machine has two states to switch in between and in which continuous processes are included. The change from melting to feeding takes place after a certain time if the melting shaft still has the necessary capacity.

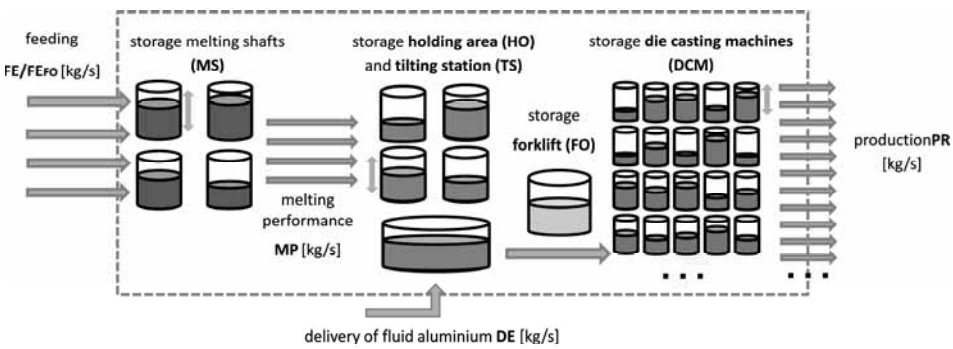

Figure 4: Scheme of the detailed model.

In addition to the previous investigations [2], the model was extended by the charging process, the observation of the melting shaft and an own energy model. The model is characterised by low computing time and low complexity. Due to the combination of the storages, no intelligent forklift control is required. Also, it was not possible to model individual machine failures due to a lack of aluminium.

2.2 Detailed Model

In the detailed model (Figure 4), the machines are each considered as separate material storages, which allows for depicting the aluminium shortage of individual machines.

An individual energy model is implemented for each melting furnace. As there are several material sources and sinks in the detailed model, a forklift control is required to determine which material source to take and which sink to supply. This control of the forklifts is steered by the filling levels of the machines. The control logic specifies that the tilting station is used as a material source with priority. If the tilting station has no aluminium in stock, the furnace with the maximum level of aluminium is chosen.

The die casting machine with the lowest relative filling level is supplied. For the feeding of the melting shafts, a control is also implemented that prioritises the melting shaft with the lowest relative filling level. The storages in Figure 4 are modelled as hybrid machines, too. Figure 5 shows an example of the hybrid automaton of a melting shaft including the states free melting, melting, and feeding. The states melting and feeding correspond to the states of the same name in the simplified model. In the state of free melting, the furnace cannot be charged during the time of the cleaning period.

Besides, a control system is implemented in the automatic machine, which determines whether a certain melting shaft is to be charged. The logic is outsourced in an external control module. Considering the feeding processes and the individual melting shafts, the detailed model offers the advantage that machine- and filling-level-dependent melting capacities and energy consumptions can be implemented for the melting shafts.

2.3 Highly-detailed Model

In the highly detailed model (Figure 6), all process steps from Figure 1 are represented except for warehousing. The highly detailed model, which is validated by the data of two facilities, serves as a reference model for the following study. The simulation model focuses especially on the melting shaft, the melting process, and the associated energy model.

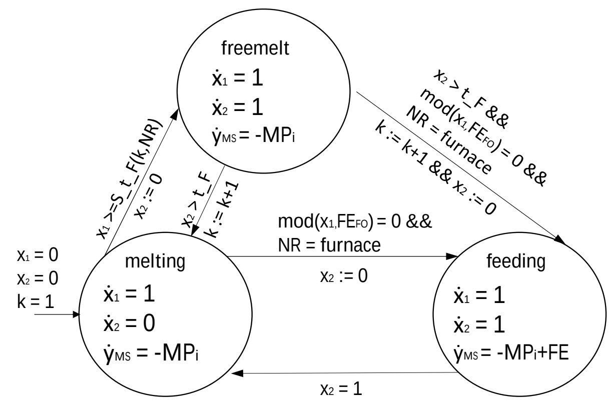

Figure 5: Hybrid automat of a melting shaft in the detailed model (S_t_F array with free melting times, k position in array S_t_F, NR number of the melting furnace, t_F duration of the free melting and cleaning process, furnace furnace to be charged; determined by control).

The material flow model includes the complete material flow within the plant, while the energy flow model captures the thermodynamic processes within the melting furnaces. The synchronisation is done in each time step using an interface object, which realises data exchange between both models. To control operating sequences, orders for the forklifts and the melting furnaces are generated in a control module based on plant and process parameters as well as the defined control strategies.

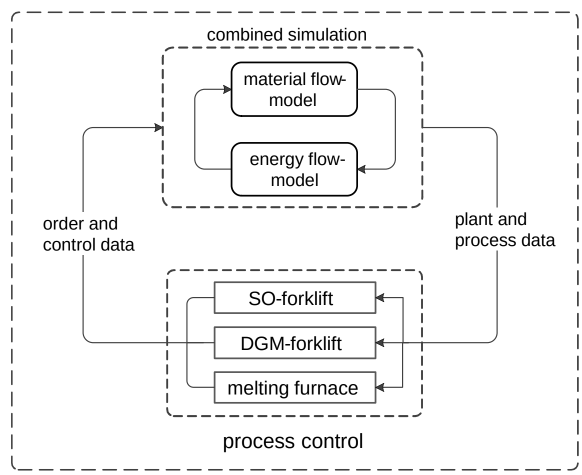

Figure 6: Components of the highly detailed operational simulation [5].

The highly detailed simulation model includes further functionalities such as the consideration of different alloys and the mapping of the impeller stations. Buswell et al. describe the model in detail [5, 6].

3 Results

The quality of the simplified models is analysed by using the highly detailed model. In particular, factors such as the output of the die casting machines, the molten mass, and the energy consumption of the melting furnaces are considered. Various applications for the models of varying levels of detail are analysed. For the simulation, a large plant with four melting furnaces, 31 die casting machines, and additional delivery of liquid aluminium is displayed.

3.1 Calculation Time and Data Volume of the Models

The primary goal of the model simplification is to save computing time and the amount of necessary data acquisition. The evaluation is shown in Table 1.

	Simplified model	Detailed model	Highly detailed model
Simulation duration in minutes	1	4	132
Required operating parameters	30	157	275

Table 1: Calculation time and data scope of the models.

A considerable reduction of the simulation time is gained by minimizing the level of details. When using the detailed or simplified model, the calculation time is reduced by a factor of 33 in the detailed model and 132 in the simplified model. The amount of data decreases with the reduction of the level of detail, too.

The number of required operating parameters using the detailed model is lowered by 43 % compared to the highly detailed model. Only 11 % of the operating parameters are required for the simplified model.

3.2 Scenario A: Operation Procedure Under Real Conditions

To compare the models, the first step is to simulate the operation based on the operating data of a working week. The comparison is based on the determined material consumption of the die casting machines, the molten mass, and the specific energy consumption of the melting furnaces.

The specific energy consumption is determined by the molten mass and gas consumption. The results are shown in Table 2.

	Simplified model	Detailed model	Highly detailed model
Molten mass [t]	937	912	920
Cast mass [t]	1198	1198	1200
Specific energy consumption [kWh/t]	851	968	972

Table 2: Comparison of the models.

In terms of material consumption, the simplified models were able to reproduce accurately the mass melted by the furnaces and the mass cast by the die casting machines. Only the molten mass shows significant differences of 1.9 % in the simplified model and 0.9 % in the detailed model. These differences result from the different feeding strategies of the models.

The simplified model shows considerable weaknesses in specific energy consumption. While the detailed model mirrors the energy situation well with a deviation of 0.4 %, the simplified model deviates by 12.5 %.

The deviations can be explained by the fact that different furnace types are used in operation under real conditions, whereas the simplified model considers the furnaces in an aluminium storage tank as one all together.

3.3 Scenario B: Variation of Downtimes at Die Casting Machines

In Scenario B, the downtimes of die casting machines vary. In the highly detailed model a reduction in downtimes increases the efficiency of the melting furnaces, as they are consequently utilised to a higher degree.

The study investigates whether this effect can also be displayed in the simplified models. The downtimes were reduced by 50 % and 75 % in the course of the study. The results are shown in Figure 7.

The simplified as well as the detailed model illustrates the effect. Especially the detailed model and the highly detailed model are very close together in their behavior. The deviation of the simplified model results in the combination of the different furnace types to one aluminium storage tank, as described in Section 3.2.

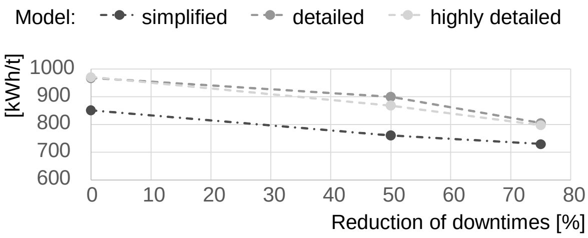

Figure 7: Specific energy consumption in the models with a variation of downtimes at die casting machines.

4 Summary and Outlook

Within the scope of this study, two simplified simulation models of an already existing highly detailed simulation model have been created and described. The simplified models enable a massive reduction of computing time and required operating data. Only small deviations from the highly detailed model could be observed in the mapping of material and specific energy consumption.

However, the simplified model shows significant deviations in the energy calculations, since a single storage does not sufficiently describe the different furnace types. Therefore, the detailed model is particularly suitable for quick use to make predictions about energy and material consumption.

In order to enable a real application of the simulation models, the models should be tested and optimised on further real scenarios. A final goal is the use of the models in smart services, such as intelligent forklift truck control up to model-predictive control of the operation.

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Electrical Power Peaks in the Simulation of Material Handling Systems

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Abstract. The expansion of local power supply with renewable sources is one option for shaping the energy transition. Power supply from renewable sources has to be balanced with power demand of dynamic technical systems. Investigation of detailed electrical power demands in production and logistics systems receives increasing attention in this context. This paper describes a method for the analysis of power demand of material handling components within a material flow simulation. The simulation approach enables the examination of power peaks as well as the system throughput during system operations. The power calculation model was developed with the environment MATLAB and integrated into the AutoMod simulation environment. The simulation of a high-bay warehouse with several handling machines delivers the proof of concept. We introduce a new control approach for the reduction of power peaks and investigate its effect on the transport performance with simulation experiments. The results of experiments show that the control approach can limit power peaks without a considerable reduction of the transport performance in the warehouse system. The achieved reductions of the maximum power peaks range from 80 % up to 67 % in different settings and correspond with a transport performance decrease of no more than 3 % in maximum.

Introduction

The consideration of energy demand and energy efficiency takes place in planning, design, and control of technical systems and processes over the last two decades.

In addition to the monetary aspects of energy saving, legal requirements force increased efforts by industry to protect the environment and the climate.

Accordingly, energy and environmental aspects received greater attention in simulation of production and logistics systems, as [1] show in their publication. To include these new aspects, various approaches and methods extended discrete event simulation, which is an established tool for analysis of these systems.

Mainly aspects of long-term energy saving and energy efficiency dominate the studies. The investigation of short-term electrical power peaks is a further topic worth to consider in technical systems. The following paragraphs motivate this.

Renewable energy sources, such as wind and sun, provide a volatile energy supply due to technological reasons. The compensation of asynchronous fluctuations of energy supply and energy demand is complex. Energy storage systems may compensate short-term peaks. The planning and control of suitable storage systems requires knowledge about power peaks that occur in the technical system.

A further motivation results from the dimensioning of electrical supply systems (e.g., transformers, circuit breakers) that depends on the estimated maximum power in the electrical subnetwork. In today’s practice, the lack of methods for predicting power peaks leads to an oversized design of supply systems [2]. A limitation of the peaks enables a reduction in size and cost of the electrical supply components.

This article considers the analysis of the electrical power demand of material handling systems by means of discrete event simulation. We discuss representations of energy-related aspects in calculation models and ways of integrating power calculation into material flow simulation. We explain our selected implementation. Simulation experiments evaluate a control intervention for reducing the power peaks in a high-bay warehouse system.

1 Related Work

The consideration of energy aspects in the simulation of production and logistics systems relates to two topics:

1. The representation of energy-related aspects in calculation models.
2. The integration of energy calculation models into simulation.

In advance to a simulation study, the energy-related aspects of real technical systems must be mapped into calculation models. For this topic, the following introduction of related work focuses on energy models of storage and retrieval machines (SRMs) in high-bay warehouses. The second part of this chapter discusses different ways of integrating energy calculation models into discrete event simulation (DES).

1.1 SRM Energy Models

Automatic SRMs used in high-bay warehouses receive special attention in the energy analysis of material handling systems. Due to their construction and mode of operation, these devices have a high energy demand per transport as well as significant power peaks when starting up. SRM serve horizontally- and vertically-arranged storage locations in a warehouse storage aisle. The machines are equipped with a drive for horizontal movement and another drive for vertical movement. Industrial storage systems typically consist of multiple parallel aisles.

Several studies, such as [3], [4], and [5], investigated the factors influencing the energy demand of SRMs. The focus of these studies lies on the development and validation of calculation models for energy demand. The aim is to determine the energy requirement of SRM with different configurations or to select the most energy-efficient travel trajectory for a transport in advance. The energy demand calculations in these studies are based on the same motion transformation model approach and differ only in details. In addition, models of this type enable in principle the identification of power peaks.

The model equations used for this paper are based on the author's previous work and explained in detail in [3] and [14]. The approach in general is briefly described later in Section 2.1.

Hahn-Woernle considers in [2] the overlap of power demand and its reduction by delaying the start of SRM transport orders. The warehouse system is represented as a simulation model in MATLAB/Simulink.

The strengths of the model lie in the detailed mapping of the power demand. The approach is limited to the singular consideration of storage systems and is not suitable for the simulation of interactions within a material flow system.

Shifting the starting times of the drives can minimise the maximum power demand at simultaneous start of SRMs [6]. The authors use an optimization with a genetic algorithm to determine the best shifting. The approach focuses on the single situation that all SRMs start at the same time. The authors do not explain the application in case of constantly new transport orders.

1.2 Energy-related Simulation

The representation of energetic interrelationships of plants and processes in DES can be differentiated in terms of their complexity in a modelling by

a) constant power values in discrete time periods, assigned to plant states or process phases, or
b) continuous variable power values derived from physical models or measurement series.

Roemer and Strassburger stated in their overview that the majority of publications use a discrete event system model with state-based energy representation [7]. Only a few publications describe an approach with representation (b), among them [10] and [11].

The modelling with phase-wise constant power values enables direct integration into discrete event simulation, if the phase changes can be represented by events. The power value is fixed from event to event. This implementation offers sufficient accuracy for a calculation of the energy demand in a simulation study, but not for an analysis of power curve and power peaks [8].

Modelling variable power values offers higher accuracy in the mapping of real electrical power demand curves, but also causes higher efforts for data acquisition, model generation, and validation.

The application of option (b) in material flow simulation requires a combination of the event-based model of the material handling system with a time-continuous model of the power demand. There are three basic approaches to this (cf. [9]):

1. Simulation with a downstream energy analysis with external software.
2. Dynamic coupling of the simulation with a parallel energy consideration in an external tool (cf. [10]).
3. Integration of energy analysis and simulation in one application (cf. [11] and [12]).

The downstream approach is sufficient for a static system analysis, but does not allow for any dynamic influence on the simulated process and, therefore, it is not suitable for analysis of strategies to reduce power peaks.

The combination of different tools offers an advantage by using problem-specific modelling domains. The dynamic coupling enables model interaction. The main disadvantage of this option is the additional effort for the model coupling and synchronization.

The integration of the energy calculation and the operations simulation in a uniform application avoids the disadvantages of the previous options, whereby [13] emphasize in their evaluation that the linkage represents a considerable challenge.

This paper describes an approach that uses two different tools for modelling. A discrete event model describes the transport operations of the material handling system. A continuous value model calculates the power demand curve of material handling components. The continuous value model is integrated in the DES environment.

2 Simulation Model

We base our investigation of electrical power peaks on a typical pallet high-bay warehouse. The use case was modelled using the simulation environment AutoMod, which supports the mapping of various material handling subsystems by means of ready-made modules and predefined simulation routines.

The geometric representation of the high-bay warehouse in the simulation depends on the number of aisles, vertical levels, and storage bays per level. The SRM gets the target position in the shelf front at random or specified by program code. The transport time results from parameterisable kinematic parameters like speed and acceleration as well as from additional times like load pick-up time and load set-down time.

2.1 SRM Power Model

This paper describes an approach that corresponds with option (b) from Section 1.2 using continuous power values. This option enables a fine calculation of the power demand in time and thus of the power peaks of the SRM.

The physical energy-related model for determining the power demand is already described in detail in [14]. Basis is a kinematic motion model for the chassis and for the lifting system. A 7-phase motion model arises by the use of a constant jerk in the motion equations (Figure 1).

The other movement variables (acceleration, velocity, and distance) result accordingly from its integration. The combination of motion variables and moving masses determines the mechanical power demand.

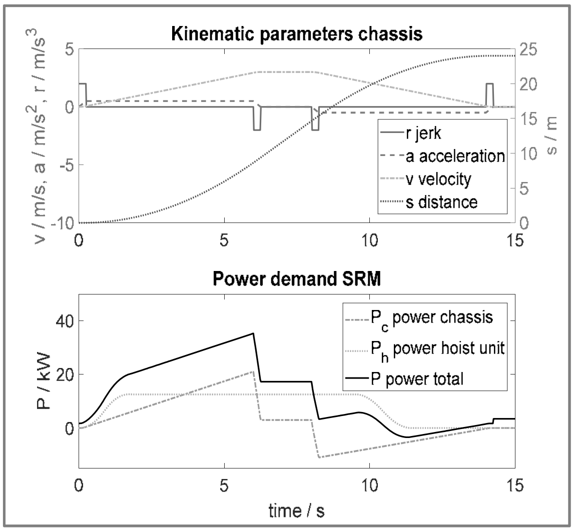

Figure 1: SRM power demand model.

Mechanical losses (e.g., the driving resistance of the wheel-rail combination) and electrical losses (e.g., in the frequency converter) of the power transmission are included in the calculation as well as the efficiency of the drives.

The power demand for the complete motion sequence of an SRM results from the superposition of horizontal and vertical motion (cf. Figure 1). The power demand of the load handling device is considerably lower and can, therefore, be simplified by using constant values.

The used energy-related model was developed in a former research project and calibrated by power measurement data of a real SRM, described in [3].

Table 1 gives an overview of power key values of the SRM drives in the later experiments.

	Max. power in kW
Horizontal drive start up	20.0
Horizontal drive continues	4.0
Lifting drive	16.0
Load handling device	2.0

Table 1: Power values of the modelled SRM.

2.2 Power Model Implementation

There are different ways to connect software systems. The coupling options include the use of DDE (Dynamic Data Exchange), OPC (Open Platform Communications), TCP/IP (Transmission Control Protocol/Internet Protocol), and DLL (Dynamic Link Library). A DLL can integrate an encapsulated software code into another program. This solution supports our hybrid modelling approach. It works without additional tool communication interfaces and offers a high data transmission rate. For these reasons we selected the DLL technology.

The MATLAB environment offers the possibility to compile developed functions to a DLL using the MATLAB Coder. The restriction that not all built-in functions of MATLAB are supported is not limiting the selected model context. The calculation equations of the energy-motion model were developed in MATLAB and then transferred to a DLL. The DLL is supplemented by functions for setting parameters of the calculation model and for communicating with external software. The C-interface of the AutoMod simulation system supports the integration of DLL into simulation models. It requires additional header files and the declaration of the utilized DLL functions within the specific model.

At the beginning of an experiment, the simulation model initializes the DLL with the technical parameters of the SRMs. During simulation, the model sends start time, start location, and destination of each SRM trip to the DLL and receives the calculation results for further control decisions. The DLL calculates the movement trajectory of the SRM and the corresponding power demand for the complete trip in advance. Based on the saved data of previous trips, it calculates the total power of the warehouse including the new trip. The identification of power peaks is inclusive.

As a side effect, the DLL can calculate the travel time more precisely than the built-in function in the simulation system that uses a 3-phase motion model only. An additional wait for synchronization option in the simulation model supports the use of this returned travel time value.

3 Power Peak Limitation

The next steps after identification are reduction and limitation of power peaks. The consideration that the system power peaks are primarily caused by the superimposition of start-up processes of SRMs supports the selected approach. The significantly highest power demand is in the short phase of accelerating the SRM drives.

Following the approach in [2], slight shifts in the start-up processes can avoid their temporal overlap and reduce system power peaks.

A control procedure for reducing and limiting the power peaks in a high-bay warehouse system complements the previously presented implementation. It was developed as part of a funded research project.

Control approach. A central control for start shifting was implemented in the simulation model with two different sets of restrictions:

a) Start-up restriction: The number of simultaneous start processes is limited by the control.
b) Power restriction: A given limit of the maximum power demand is monitored by the control.

By the start-up restriction, the control monitors acceleration and velocity of the SRMs. As they are responsible for high power peaks, we exclusively consider trips where starting and lifting take place simultaneously. A new trip is delayed as long as the SRM start-up limit is reached. The limitation of simultaneous starting processes offers a limitation of the maximum power requirement.

In power restriction, the control monitors the total power demand of the system. Before starting the SRM, each new trip adds virtually its predicted power demand to the current system demand to test the power limit. If the specified power maximum is exceeded, the start time of the new trip will be shifted with step size one second and the new maximum power is calculated again. The control executes shifting until the system power maximum stays below the limit or the maximum possible delay is reached. The maximum possible delay is a selectable starting parameter for experiments.

Finally, the DLL returns the calculated start delay of the next trip to the simulation model. The effect of this control measure on the reduction of power peaks and simultaneously on the transport performance in the system was focussed in the following experiments.

4 Experiments and Results

The high-bay warehouse used as model case for the experiments in this paper consists of eight aisles with ten levels and one SRM per aisle. This configuration corresponds to a real-system pallet warehouse in terms of size. The AutoMod simulation subsystem AS/RS enables a detailed representation of real-system properties.

The model includes the following assumptions: Storage and retrieval of the pallets are independent processes. The throughput target value is the number of pallets per aisle per hour. A random selection sets the storage position in an aisle regardless of the fill status. A dedicated storage bin management is not taken into account.

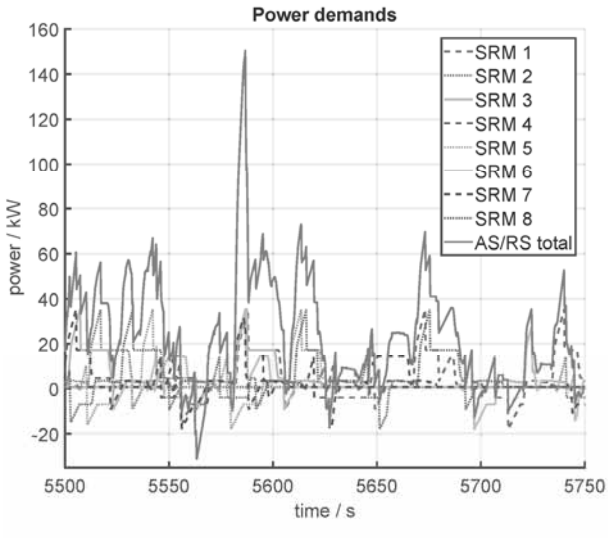

Figure 2: Example of total power demand for eight SRMs.

Table 2 defines the kinematic parameters of the SRM. Load pickup time and load set-down time are twelve seconds each. Each experiment lasted ten hours of simulation time. The evaluation of the control approach is based on two different transport scenarios:

1) Unidirectional transports: Maximum throughput with only storage trips
2) Bidirectional transports: Maximum throughput with storage and retrieval trips.

	Horizontal	Lift
Velocity [m/s]	2.0	1.0
Acceleration [m/s²]	0.5	1.0
Jerk [m/s³]	2.0	1.2

Table 2: Kinematic parameters of SRM.

In Scenario 1, each SRM achieves about 55 storage operations per hour in case of no peak limitations. The SRM transports a load from the transfer point to a randomly selected storage location. After completion of the transport operation, the SRM returns empty to the transfer point and collects the next load immediately. This procedure results in 110 trips per hour.

In Scenario 2, each SRM fulfils about 34 storage and 34 retrieval operations. First, the SRM transports a load from the transfer point into the shelf. Then it travels empty to the start location for the retrieval transport from the shelf. Finally, it returns the retrieval load to the transfer point in front of the shelf. This creates a double cycle with three movements. In case of maximum utilization only double cycles occur. This results in a total of about 100 trips per SRM and hour in the experiment.

Both scenarios were simulated with both control options. The system power limits in the second approach were 120 kW and 140 kW. The maximum allowed shift limit is twelve seconds in all experiments.

Control limit	Shift in s per SRM per hour	Peak power in kW	Through-put per hour	Through-put in %
1 SRM	106	121	53.3	97
2 SRM	10	146	54.9	99
3 SRM	1	165	55.1	100
No limit	--	178	55.1	100
120 kW	3	119	55.0	100
140 kW	1	139	55.1	100

Table 3: Results for Scenario 1.

Limiting the number of devices starting simultaneously does not support a precise limit of power peaks. It only avoids the unfavourable superposition of single peaks of the SRMs' start-up processes. The remaining motion processes continue to contribute to the power demand of the system. Furthermore, start delays can also occur in situations where they are not necessary to reduce peak loads. Not every start-up superposition leads to a relevant power peak.

On the basis of a theoretical maximum of eight parallel start-up processes in the example system, a limitation to two start-up processes leads to a significant reduction in the power peaks by 80 % compared to the unlimited approach. The throughput of the system drops by only 1 %. It should be noted that superposition of eight unfavourable start-up processes is an extremely rare event.

The approach with a fixed limit as in the power restriction control enables a much better adapted response to the current demand situation. The extent of the start postponements is considerably smaller with an equivalent reduction of the power peaks. The throughput of the system remains almost unchanged even with the limit of 120 kW.

Control limit	Shift in s per SRM per hour	Peak power in kW	Through-put per hour	Through-put in %
1 SRM	96	108	66.2	97
2 SRM	6	128	67.9	99
3 SRM	1	155	68.1	100
No limit	--	160	68.2	100
120 kW	2	119	68.1	100
140 kW	0	139	68.2	100

Table 4: Results for Scenario 2.

Both control options have the need for a higher-level coordination between the driving controls of the SRMs in common.

The control with start-up restriction focusses on the SRM start processes in the warehouse system. This implementation does not require a detailed model or measurement of the SRM power demand. It is based on the assumption that the start-up process produces the highest power peaks.

The control with power restriction permanently monitors power demand of the system. It needs a power forecast model. On the one hand, this implementation requires more effort for this reason. On the other hand, it can guarantee considerably lower maximum power peaks accompanied by better system throughput.

To summarize for a practical implementation, limiting the number of devices that start simultaneously is technically a more realistic option than monitoring the power demand of the system. However, even this option requires changes in the current system control structure. The individual SRM controls need to communicate with an additional central coordination instance.

The experiments were carried out with the technical maximum throughput of the SRMs. In these cases start delays always lead to a reduction in throughput. In the vast majority of practical applications, the logistic system's throughput is lower. There are idle phases between transport orders. Therefore, short start delays will have a significantly lower impact on the throughput of the system than in the presented scenarios. We suppose that power peak limitation in real systems can be reached without a reduction in throughput.

5 Summary and Outlook

This publication presents an enhancement of material flow simulation by a calculation of electrical power demand in order to evaluate systems power peaks.

First, we motivated the aim of knowing and limiting power peaks in material handling systems. Second, we set the chosen integration approach in relation to previous work in the field. Then, we explained the way of modelling and the implementation. Finally, we used the simulation of a high-bay warehouse with several SRMs to investigate the extent of power peak limitation in relation to the transport performance.

We applied a hybrid modelling approach to create the simulation model. The discrete event material flow model of a high-bay warehouse system was implemented in the AutoMod simulation environment without power calculation. In parallel, the power calculation model was developed with the MATLAB environment. Subsequently, the calculation model was compiled into a DLL and in this form integrated into the simulation model. Based on the parameters of the SRM, the calculation model evaluates the transport order data given from simulation and predicts the power demand for the warehouse system.

Furthermore, we presented a control approach that uses a device start delay for the reduction of system power peaks. In simulation experiments we investigated two different power restrictions and their effect on the transport performance. The results show that both approaches can effectively limit power peaks in combination with a small reduction in the transport performance of the warehouse system. The implementation and test of the control in a real-world system are the next logical steps. The modelling approach and the way of implementation are not limited to warehouse systems.

The idea of using electrical energy storages in material handling systems motivates further work in the field. In a volatile electrical demand situation, energy storage systems can cut the unwanted peaks and lower the load on the power network. Energy storage systems act as a buffer between supply and demand, enabling the integration of local renewable energy sources in the power supply. The extension of the material flow simulation by models and control algorithms of energy storage systems supports the research in this development.

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Development and Status of Personnel Deployment Simulation and its Inclusion into the Digital Factory

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Abstract. The development of personnel deployment simulation started just before 1980. To the first, more production-logistics-oriented simulation procedures, macro-ergonomic features have been added, i.e., mainly solving capacity- and utilization-related problems. The current status is characterized by the integration into tools of the Digital Factory, which increasingly includes micro-ergonomic considerations. Above all, anthropometric and physiological questions of human operations predominate. In addition to these aspects aiming at the human work task itself, the focus is currently also placed on the work environment that the working person is exposed to. This is currently still the focus of research and development related to ergonomics and occupational health and safety. With regard to further steps, there is a particular need to better link discrete event simulation procedures with Digital Factory tools. Thereby, also strong demands on ergonomic research are made. This is shown, e.g., in the still unsolved problem that types of stress acting together on the working human cannot be assessed in common.

Introduction to Considering the Staff in the Digital Factory

The inclusion of personnel deployment simulation in tools of the Digital Factory is an essential part of plant planning today, or at least it should be. It makes it possible to plan the future workforce in the factory in advance, not only in terms of numbers, but also with regard to the necessary qualifications of the employees.

In this way, the productivity of the individual work systems can be forecast, analyzed for weak points and secured before the factory goes operational.

However, this rather production-logistical view of future personnel deployment is no longer sufficient today. Questions are also asked about the expected stress and strain on the staff as a result of the assigned work tasks. Related tools already exist, the focus being on the stresses and less on the effects on the working person, the strains. Therefore, the focus of development is increasingly placed on aspects of occupational health and safety.

The endeavors to analyze the effects of the spatial environment on the working person as early as in the planning stage of a factory are relatively new. These effects can not only lead to a reduction in productivity, but above all to impair the health of employees. But, in this regard, primarily isolated software tools are available and only very few of them are already integrated into the Digital Factory procedures.

The mentioned aspects of the personnel-related expansion of the Digital Factory are discussed in more detail below. This is done on the basis of guidelines from the Association of German Engineers, some of which are still being worked on. Current developments and trends are discussed and illustrated by some selected application examples.

1 Basic Requirements for Personnel Deployment Simulation

In principle, personnel deployment simulation encompasses all areas of work system planning: It extends from the flow of materials and information, with the involvement of people, to the production-logistic analysis of work systems.

Furthermore, the question of the division of labour under qualification aspects and the human cooperation in parts manufacturing and assembly systems as well as the design of working methods at individual workplaces are regarded. From its early developments on, the presentation of result scenarios in tools of the Digital Factory plays an essential role.

A fundamental requirement for personnel deployment simulation is the modelling of personnel qualifications. What is essential here, is the separation into machine and personnel simulation objects that are related to one another in the simulation process via functions (in particular work activities). This largely corresponds to the requirements of time management according to the REFA methodology ([1]; see also [2]). With the help of these simulation objects, the responsibility of workforce for machines or workplaces, the requirements and abilities needed, and the feasibility of functions and, thus, the qualification of a person or type of personnel can be modelled (Figure 1). The personnel deployment simulation differs significantly from the purely production-logistics one, which generally treats people and machines as an integrated resource.

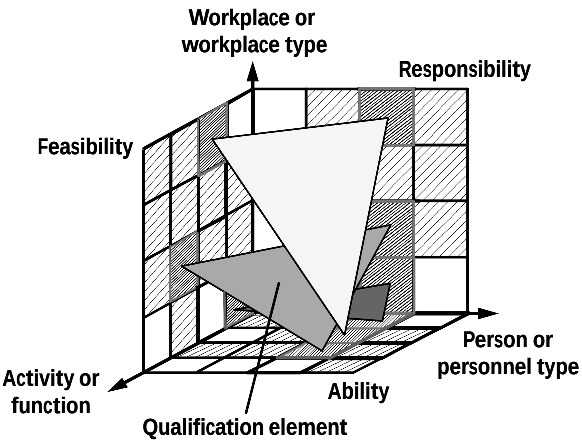

Figure 1: Modelling the qualification as part of the personnel deployment simulation (according to [3], p. 53).

At the international level, personnel deployment simulation receives relatively little attention. Static methods of calculating personnel requirements dominate here, especially through using spreadsheets. Dynamic analyses with the help of simulation with its necessary separation of human operators and technical equipment are largely ignored.

A typical example for the consideration of personnel in the production area is provided by Mounsey et al. [4]. The authors take into account the costs of different shift systems and staff assignment, but do not consider the qualifications of the individual employees.

When it comes to personnel deployment problems, the focus is mainly on service areas, e.g., on hospital operations [5] or call centres [6], whereby optimization and simulation methods are occasionally combined (e.g., [7]). In contrast to the modelling of production operations, simplifications are often possible in the service sector, so that a part of the equipment and its operator can be viewed as one resource. Furthermore, as a rule, only uniform qualifications of all employees are very often assumed.

2 Production-Logistics-oriented Personnel Deployment Simulation and the VDI Guideline 3633 Part 6

The application field of personnel deployment simulation were initially parts production and assembly systems (see the overview at [8]). The first dissertations on this subject appeared in Germany in 1980 almost simultaneously at the RWTH Aachen University and the University of Stuttgart. Since these first publications, personnel deployment simulation in Germany has a history of forty years. This effort was reflected by the German Association of Engineers in their Guideline VDI 3633 Part 6 from 2001 [9], which is currently being revised.

In this context, a new possibility of modelling will also be discussed: While it is well-known that the precedence graph can be used to describe work processes, this graph itself can be mapped onto a capacity graph of the stations in the work system and, in the case of multi-station operation, the latter in turn can be mapped onto a staff assignment graph of the employees providing the basis for simulation (Figure 2).

An actual example from production logistics is the investigation of what influence demographic development may have on the productivity of a work system. The basis for such an investigation is the well-founded assumption that the performance decreases with the age of an employee (see already [10], pp. 518). A study for an assembly line showed a decrease in the output of the work system of around 13 % over a period of 14 years [11].

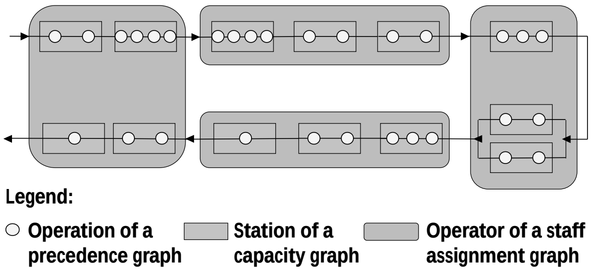

Figure 2: Precedence, capacity and staff assignment graph of a U-shaped assembly system.

Müller et al. [12] pursue an approach using their WorkDesigner software which combines personnel planning in the production area with macro-ergonomic aspects. The aim is to take into account not only the use of resources, but also the individual ability to work and the age of the simulated employees.

Subsequently, the application field of personnel deployment simulation was extended to service areas. In line with the social discussion, in addition to questions of production performance, the focus was also on the organization of working time with regard to the work-life balance of the employees. Thus, productivity-related evaluation was connected to social-psychological effects.

An example of this was provided by a study in a self-service department store ([13], p. 166). To investigate the effect of different working time systems on the work-life balance, the potential working time conflicts of the employees were first recorded and then anonymized using a cluster analysis. Seven full-time and seven part-time staffing models were combined with the working time systems. These were finally combined with eight scenarios with 80 % to 150 % customer traffic and ten employee scenarios with different working time preferences.

Taking into account ten test replications, in total 3,920 scenarios were created, which were then statistically evaluated with regard to various target criteria. For this purpose, the concept of the degree of goal achievement was used, which normalizes the original values in a range of 0 % for the theoretically worst and 100 % for the optimal result.

As expected, the degree of goal achievement shows contrary trends with regard to the throughput time of the customers and the utilization of the employees (Figure 3).The potential for temporal conflicts, on the other hand, hardly varies: However, this is due to the fact that with one conflict per hour a very strict measure for worst values was defined, so that optimal values of 100 % could be reached relatively easily. Working time systems with a higher proportion of flexitime proved to be favourable (see an example from the logistics area at [13], p. 201).

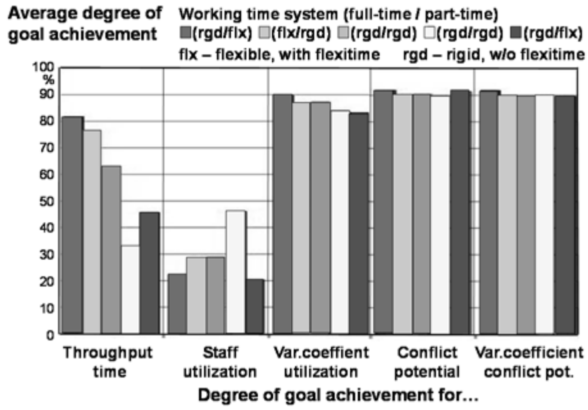

Figure 3: Average degree of goal achievement for selected working time systems in a self-service department store (according to [13], p. 192).

3 Stress Originating from the Work Task and the VDI Guideline 4499 Part 4

The main focus of the development is the connection of human models with tools of the Digital Factory, which already dates back to the 1960s. Regarding human models and the associated analysis and visualization of ergonomic effects originating from the work task, a number of methods and software tools from the American and English area (see the overview at [14], p. 44) are available.

In this regard, the VDI guideline 4499 part 4 from 2015 [15] deals with the micro-ergonomic effects of the work task, preferably at an individual workplace. Present methods primarily aim at the analysis of anthropometric and work physiological stress. This has already been discussed in more detail earlier [16].

Such analyses already found their way into tools of the Digital Factory at an early stage, as the example of the redesign of one of the Adam Opel AG plants in Germany from 2001 demonstrates [17]. Figure 4 shows the NIOSH assessment of a lifting task [18] using the eM-Engineer software [19] as another early example. The Gantt chart illustrates the possibility of connecting to a discrete event simulation; it shows the actual work situation for which the ergonomic assessment is carried out.

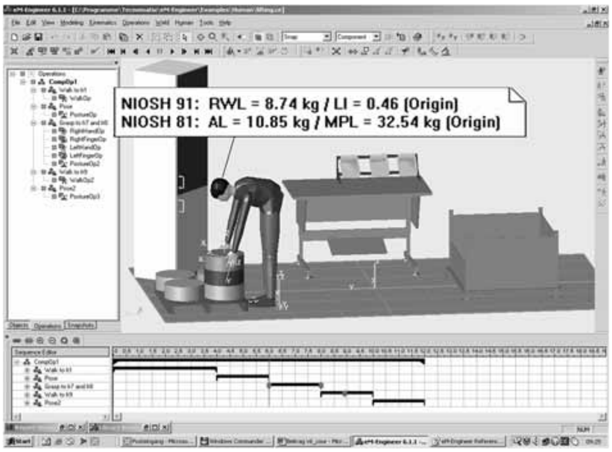

Figure 4: Ergonomic evaluation of a lifting task using the software eM-Engineer [19].

4 Influences from the Working Environment and the Draft Guideline VDI 4499 Part 5

The principles of ergonomics, especially its stress-and-strain concept [20], require consideration of external exposures or stresses as well as internal (physiological or mental) strains of the individual employee who is exposed to these stresses. The ambition is to determine the various physical (e.g., cardiovascular problems) and sometimes chemical effects (e.g., through skin-receptive hazardous substances) in Digital Factory tools on the basis of a uniform data model of the work space. The need to forecast environmental influences on working people was already pointed out at an early stage [21]. A guideline committee is currently working in a project devoted to prepare the corresponding guideline VDI 4499 Part 5 ([22]; see also [23]).

Internationally, there is almost no evidence for the virtual prediction of stresses and strains from the working environment. But, also in the German-speaking area, which the named draft guideline project is focusing on, the majority of the relevant procedures remain with isolated solutions for evaluating individual environmental factors without including them into tools of the Digital Factory. Above all, it is about the visualization and assessment of exposures or stresses, while strains of working people are only considered in very few software procedures.

In addition to the scientifically unsolved problem of integrally merging combined environmental influences on working people in a uniform key figure, there are still gaps in the time-related and personal-oriented assessment, even for individual factors. In this regard, there are primarily point-in-time evaluation methods for stresses and their assessment in terms of occupational health and safety.

An existing example of personal exposure is that caused by gamma rays in a work area ([24]; Figure 5). The procedure is based on the *ALARA* principle (*A*s *L*ow *A*s *R*easonably *A*chievable), which requires such a low radiation exposure of the working person, "as it seems feasible when considering practical reason and weighing up advantages and disadvantages" (translated from [25]). It enables not only a point-in-time evaluation of the radiation exposure, but also a period-related one, which is represented by means of a virtual dosimeter through incorporating discrete event simulation. In addition, the form of work organization can be assessed when deploying several people in the same work area.

Figure 5: Visualization of the work situation in a radiation-exposed work area and its Gantt-chart representation [24].

5 Further Development of Integrating Personnel Deployment Planning into the Digital Factory

The coupling of discrete event simulation and its visualization in the Digital Factory is by no means trivial, since the modelling approaches of both types of software are very different: While the former may follow the depiction of workflows for months and focusses primarily on the presentation in the form of business graphics, the latter follows a realistic graphic animation at most in the minute range.

As an interim result of the personnel deployment simulation and its inclusion into the Digital Factory, it can be stated that this desirable coupling has already reached a certain level, which has led to the publication of several VDI guidelines. However, some essential aspects remain unaffected: The inclusion of occupational psychological and sociological aspects is particularly noteworthy, as there is a lack of evaluation and assessment methods that can be used in discrete event simulation. There is also a lack of options for integrally evaluating multi-factor stress. The use of a lexicographical preference ordering can only provide a substitute solution ([26], p. 42).

One obstacle is that many ergonomic evaluation procedures are only available as isolated software solutions, which are not yet integrated into Digital Factory tools. This is all the more true for the assessment of determined values: limit values for a number of stresses are available for the assessment. However, since these are only available as text, they can only be inserted manually into the respective procedures. An additional key point will, therefore, be the problem that the normative values that are necessary for assessing the work situation are not yet made available in an adequate information technology manner ([21], p. 221).

Related to time-based analysis, the question also needs to be clarified as to whether a REFA-based modelling is better suited for an integration than one derived from resources. Since practice is interested in suitably considering both views at least in parts, new research questions arise. In addition, it must also be clarified which modelling method is more suitable for an ergonomic evaluation and assessment.

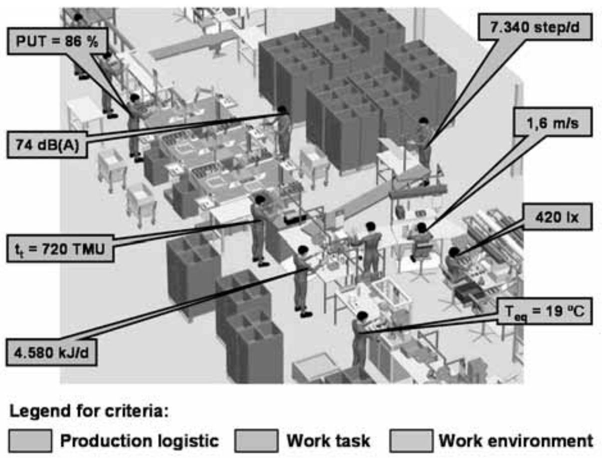

Figure 6: Vision of stress forecasts in the Digital Factory (Layout software: Ergomas; see [27], p. 215).

The existing obstacles for considering ergonomic aspects in the Digital Factory give rise to the further development of the related tools. The vision of the forecast is to provide not only production-logistics criteria, but also ergonomic ones for the evaluation and assessment of stresses caused by the work task and the work environment (Figure 6). However, a comprehensive forecast of strain on working people will probably still be a long way off.

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Simulation of Construction Disturbances with Agent-Based Petri Nets and Employing a BIM in Expert Building Time Analyses

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Abstract. This paper is based on a research project focused on updating a disturbance-modified schedule for the evaluation of building claims. In this context, the quantification of time effects in expert analyses is discussed. This novel approach is based on a time-discrete simulation method using an agent-based simulation with Petri nets and building information models. Here, the focus is on the reconfiguration of the composition structure of the Petri net, which is triggered by events in the sequence structure. In addition, this paper presents a conceptual proposal how to chronologically integrate documents into the Petri net structure. Thus, the simulation model and the building claims can be verified and validated. Specialized transitions are also used to implement document integration into the Petri net model.

Introduction

Forensic expert reports on claims due to disruptions in the construction process are often not recognized by German courts. The reasons for this can usually be traced back to an impracticable presentation of the facts in expert reports [1]. Tiesler [1] has shown that experts often fail to conclusively identify and explain the necessary causal relationships in the disrupted construction process.

In this context, there is no general approach to solve such issues in German expert practice. Rather, individual case-related approaches are used to explain the disrupted construction process in the expert reports.

Within this setting, the expert analysis must be adapted to the respective problem case. Therefore, the choice of a suitable methodology for carrying out the analysis always depends on the individual case studies.

One challenge in the forensic analysis of construction time is that disrupted construction processes can be extremely complex systems. Complexity analyses are, therefore, essential to meaningfully separating and understanding the effects of disturbances during the construction time under consideration.

German expert practice currently mainly uses project management software, which is usually based on the critical path method (CPM), to perform complex analyses of disturbed construction processes [1–3]. However, such trivial calculation methods can lead to inconclusive results [2–5].

1 Literature Review

Experts rarely ask whether CPM is suitable for the conclusive analysis of complex construction time disturbances. Instead, they scrutinize the methods of detection for target–actual comparisons used rather than the calculation methods of valid process durations [1].

Modern approaches solve this challenge with building information models (BIMs) linked to CPM networks. [6]. Such procedures create so-called four-dimensional (4D) models or 4D BIMs (i.e., 3D geometry + 1D time). For 4D BIMs, it is claimed that the validity of the construction time analysis is stronger [7].

To obtain knowledge using the 4D model, the 3D components of the BIM must be played back as a 4D visualization using time information. The modelled dependencies of the production processes in particular are then clearly illustrated.

Overall, a 4D model can present more information than a bar chart and is more comprehensible for third parties. Similarly, a 4D model provides a greater understanding during the modelling phase.

This approach seems to have many advantages compared to conventional presentation methods. Thus, in the past, researchers discussed these advantages for forensic construction time analyses [8–10].

1.1 Research Gap

4D visualizations are helpful in clarifying human perceptions [11]. Moreover, it has been shown that manually performed construction time analyses can produce more-realistic results if calculations are based on BIMs [18].

However, the logic and practicability of the calculated processes in such methods are still based on the subjective, transcendent perception of the modeler. In addition, forensic analyses of construction time disturbances often require the objective consideration of the many complex environmental influences on a building project [3]. Here, it is possible that the circumstances substantiating the claim were not thought through holistically. For example, the dependencies of complex design processes cannot be recognized or misunderstood [3]. It follows that in many cases no practicable system behavior can be assumed due to the limitations of human perception [3, 4].

For this reason, despite 4D support, invalid expert opinions can still emerge. This can be especially true if the time sequences are modeled using CPM [3]. Regarding justiciable claims relating to disruptions to construction processes, gaps may arise in the argumentation line [1, 3]. Inconsistent calculation results can be challenged in court easily. In such cases there is a risk that a court will declare the expert report to be unsuitable and entitled claims are lost.

The challenges discussed above are well-known simulation topics. This raises the question of whether simulation techniques in combination with BIMs can be used to prove claims due to construction process disturbances.

Construction process simulations have the advantage that they can execute large-scale calculations. This usually enables more intensive and realistic analyses of complex processes [21–23]. For example, complex spacetime conflicts can be considered due to the realistic building geometry [24, 25]. In addition, virtual production processes can be interrupted, delayed, inhibited, or accelerated with specific parameter inputs [21, 23].

These properties of computer-aided simulations are suitable for disturbance-modified schedule updates and the evaluation of entitled claims [3, 13, 14, 23], which can lead to unexpected analysis results. The anticipation that unexpected results will be simulated can lead to a greater objectivity in the analysis process, because the simulation user will inevitably examine the simulation results before they can be understood [3].

Indeed, only a few researchers consider using BIM-based simulation methods to solve these challenges [12–19]. However, there are almost no concrete proposals for solutions regarding a suitable calculation methodology (some exceptions are [3, 20]).

1.2 Further Procedure

This paper proposes an approach using a simulation method for practicable production processes to provide expert reports about construction time claims. In this context, Gnerlich's approach [3] is summarized. For this purpose, this paper first discusses the related simulation methods in the BIM context. Subsequently, the simulation design follows. Finally, the paper concludes with an outlook.

Overall, the conceptual design and less technical details are dealt with. Mathematical descriptions are also omitted from this article. The agent logic is explained in more detail by Gnerlich [3].

2 Related Simulation Methods

Gnerlich's simulation approach comprises an agent-based Petri net using a BIM to simulate disturbance-modifying effects for an objective schedule update. The method also includes a mechanism for chronological management of external documents. This linkage is suitable for model verification and validation as well as for the legal presentation of entitled claims. All aspects are realized by using a Petri net as a simulator.

2.1 Benefits of Petri Net Simulation

Token-based semantics are regularly used for executable BPMNs, EPKs, and UML displays [26] or for executing software and hardware [27, 28] due to their causal computational logic. Accordingly, Samkari [29] showed that extremely fast and extensive background calculations of BIM-based construction process simulations can be realized with Petri nets.

He also demonstrated that the simulation modelling can be done directly in the BIM viewer. In this case, the calculation of the sequence structure of the Petri net is realized by an algorithm in the application's background. For this purpose, subject-specific user interfaces can be designed for intuitive input [3]. Users who are not simulation experts can, thus, contribute their technical knowledge more easily and quickly [29, 30]. This can be particularly helpful for updating a disturbance-modified petri net model, because a manual modelling can become extremely complicated and error-prone due to the increased complexity [29].

Petri nets are suitable for simulating complex and causal relationships of user-defined model processes [3, 27, 31]. In addition, Petri nets can represent a composition structure in ordered detail [3, 27, 31]; thus, it is possible to define modular subnets in several hierarchical levels [27, 31, 32]. For example, these properties allow for dividing the system "construction project" into its components [3, 31, 32]. Based on this procedure, the simulation results can later be structured meaningfully. In addition, such a composition structure usually contributes to a certain clarity and readability of the simulation results [32].

Beyond that, the Petri net markings represent reproducible intermediate states of the simulation runs [3]. Using these markings, the various calculation steps can later be traced back in detail [3, 29], which enables previously executed simulation runs to be rewound, the model design revised, and the simulation run restarted, as necessary.

2.2 Benefits of BIM- and Agent-based Simulation

Some simulation researchers have demonstrated that users gain a better understanding of production processes when agent-based simulation models use BIMs as spatial model environment [22, 30]. Agent-based simulation can reproduce an emergent model behavior corresponding to more-realistic system behaviors [22, 30]. An example of emergence results from changes in the construction process as a result of disturbances. Emergence often stems from a changed behavior of the ancillary trades. Those effects are core questions that often must be clarified in expert reports [14, 33].

In addition, BIMs enable a component-related and chronological integration of external documents about the construction project [3, 16, 34, 35].

This is particularly suitable for the analysis of disrupted construction processes. Thus, the accuracy of the simulation model can be checked and a claim can also be verified [3].

2.3 Useful Petri Net Concepts

Damrianant and Wakefield [36] present switch functions for delays and interruptions to be able to simulate disturbances with (cyclic) Petri nets. For this purpose, they combined a Petri net with additional modelling elements for switching delay factors on and off. They also simulated interruptions by temporarily ignoring the tokenized resources in the process calculations.

Further approaches can be found in so-called "time Petri nets", which hold the tokens in the transitions or places and, thus, delay the switching (e.g., [37]). In contrast, Samkari [29] presents a simulation approach with agent-based Petri nets.

In this case, the agents are an additional constraint for switching the transitions. Here, the process calculation of the transitions uses a guard function, which checks the availability of the necessary resources before switching. An activated transition only switches completely if all required agents are available [29]. The Petri net is also constructed as a predicate transition net. Each place has only one input and one output edge, like a marked graph. Each newly created token represents an elementary model state. According to this, Samkari [29] dispensed with any cyclical structures.

In contrast to time Petri nets, the simulation time is not stopped at so-called "timed Petri nets" [38]. Instead, the tokens transmit time information from the preset transitions to the activated transitions. If a transition is switched, all time information is compared and calculated. This method enables very fast simulation runs of complex construction process scenarios [29].

To a large extent, the simulation approach used in this paper was oriented towards Samkari's [29] agent-based Petri net method. In addition, similar switch functions from Damrianant and Wakefield [36] were used to model date discrete changes as construction process disturbances.

3 Simulation Design

The basis for agent movements is a path network in the BIM, which consists of path edges and nodes. Figure 1 shows a virtual BIM with such a path network.

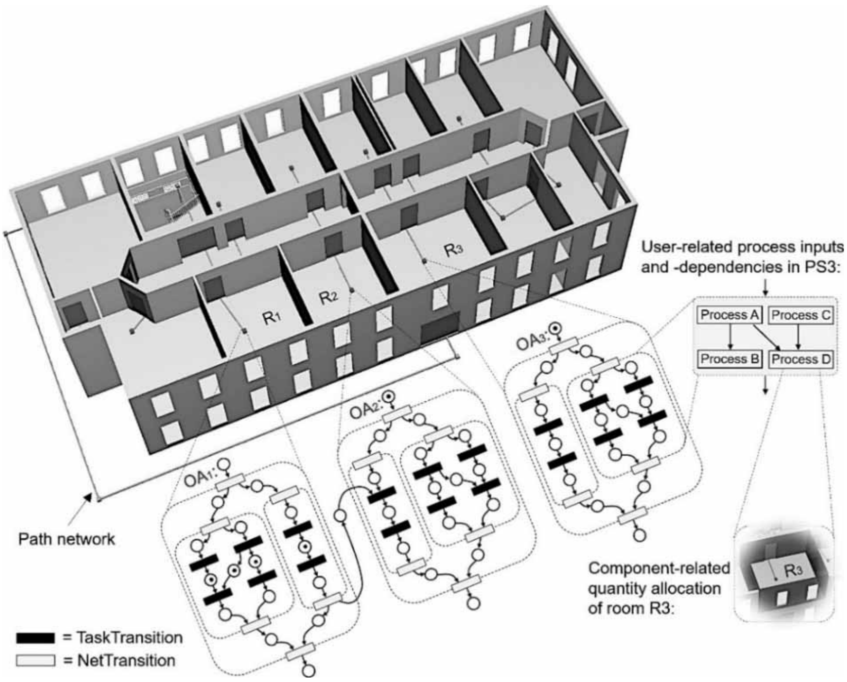


Figure 1: Definition of the local operational areas: OA_i are subnetworks.

A dark color indicates the path nodes that are used for the user-related definition of local operational areas (OAs), which can refer to user-defined rooms, floors, or sections, etc., in the BIM.

Figure 1 indicates that the Petri net is derived from the process inputs and quantity assignments of the BIM. Thus, the user does not need to model a Petri net structure. According to Figure 1, all local OAs can be converted into executable Petri net structures. The Petri net is, therefore, the interface between the BIM and the Petri net. The Petri net itself is in the background of the simulation application as the “calculation tool” in the sequence structure and is invisible to the user. However, it is possible for the user to access the local OAs to carry out the simulation modelling there.

The right side of Figure 1 shows an example section that illustrates the user-specific process definitions and process dependency entries using the local OAs. In these, it is possible to model individual composition structures, e.g., to delimit the (sub)processes of individual construction trades from each other. The process structures are defined by entering simple arrows. They specify the necessary dependencies of sequential processes. Overall, dependencies between the local OAs can also be defined.

For the calculation of the construction process durations, the entered processes must be offset against the respective quantities of components in the BIM.

To do this, the user can get the properties of the topologically arranged building objects of the BIM. There are no conditions for when the user chooses the component objects. With this method, the local OAs can include processes that apply to several floors or sections of any size.

However, the user should consider the spatial proximity of the local OAs inserted in the BIM, which can be important later to better understand the simulated production processes.

To finally simulate the construction production processes, it may be necessary to assign resources to the processes, such as worker groups, equipment, dates and deadlines, materials, or standing areas of the local OAs. However, no resource allocation is necessary for curing or drying processes. All inputs necessary for the calculation of the process duration have now been described.

During simulation execution, the workers (agents) must get to the local OAs using the path network and fulfill the defined work tasks. To ensure that a production sequence is followed as far as possible, the user can define one or more production direction(s) for the worker groups using the local OAs. The production directions can be prioritized, so that the workers (agents) in a group can give preference to specific production processes in case of alternative measures.

3.1 Petri Net Components

Subnetworks are derived from the composition structure of the local OAs of hierarchically combined processes. These are limited within the Petri net structure by two *NetTransitions*. One *NetTransition* forms the input and the other *NetTransition* forms the output of each subnet. In between are the elementary *TaskTransitions*, which are derived from the entered processes and execute the task calculations (according to Figure 1).

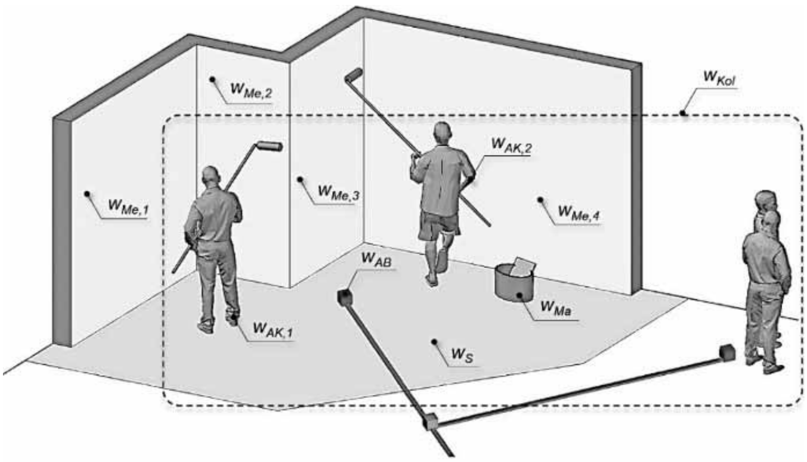
As soon as a *TaskTransition* switches, all associated building-component-related quantities and associated trade-specific process definitions are offset against each other. A *TaskTransition* can only be switched if its pre-set is activated and the resources required for the process are available [3]. For example, enough material must be available for switching resource-dependent *TaskTransitions*. In addition, a permitted number of agents must be able to reach the local OAs using the path network.

For the calculation of the process duration, a time effort value for labor productivity must be specified in the process definition. The time effort value can be weighted by various parametric effort factors.

Depending on the value, these expense factors offer several possibilities. The simulated production processes can be inhibited, accelerated, or interrupted. In the expert analyses of construction time, statements on necessary productivity as a result of experimental weighting combinations can, thus, be obtained. From the weighted time expenditure value, findings of the simulated working speeds can be derived. Figure 2 provides an overview of the possible weightings and the formula for the process duration calculation. This is processed by default when switching a *TaskTransition*.

For the simulation of discrete time construction process disturbances, the Petri net is divided into two subnetworks. In terms of Figure 3, these are the *Process-Branchnet* and the *Date-Time-Branchnet*. The subnetworks switch alternately during a simulation run and mutually renew their previous Petri net structure.

Based on Figure 1, the *Process-Branchnet* includes all subnetworks of the local OAs. Figure 3 illustrates how the subnetworks can be organized into a hierarchical composition structure. In this way, e.g., different companies can be separated from each other with their trade and service descriptions down to the elementary work tasks.



Process duration of a work group $= \dfrac{A_m \cdot (A_w \cdot w_{Kol} \cdot w_{Me,i} \cdot w_S \cdot w_{AB} \cdot w_{AK,i} \cdot w_{Kol} \cdot w_{pKol})}{|M_{AK,i}|}$

Basic variables for calculating the process durations:

- A_m = Production quantity of all BIM components per production plant
- A_w = Time effort value per worker group
- $|M_{AK}|$ = Number of workers involved in the work process

Parametric effort factors:

- w_{AK} = Factorial weighting(s) of the used worker group
- w_{Kol} = Factorial weighting(s) of the complete worker group
- w_{Me} = Factorial weighting(s) of the BIM component set(s)
- w_S = Factorial weighting(s) of individual bottom area(s) as standing spaces
- w_{Ma} = Factorial weighting(s) of the material used
- w_{pKol} = Factorial weighting(s) of parallel performing worker groups
- w_{AB} = Factor weighting of the local operational area

(The daily working hours are taken into account by discrete process sequence conditions)

Figure 2: Calculation content of a *TaskTransition* [3].

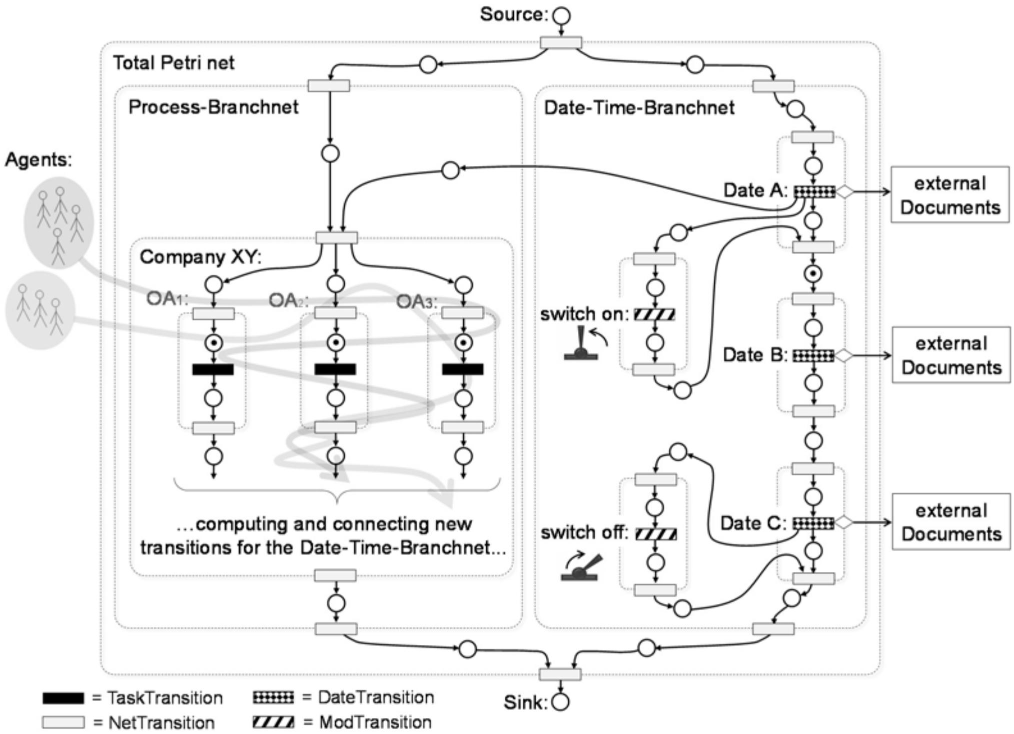


Figure 3: Overview of the entire Petri net structure.

Work tasks are represented by *TaskTransitions*, which calculate the process times for start, intermediate, and end dates when they are switching tasks. During a simulation run, all dates calculated by the *Process-Branchnet* are successively transferred to the *Date-Time-Branchnet* as date-bound *DateTransitions*. Afterwards, they are linked in a chronological order.

DateTransitions are time discrete starting conditions for any number of *TaskTransitions*. The user can also integrate *DateTransitions* into the Petri net as time-critical process conditions if dates are entered and linked to the processes. External attached documents can also be assigned to these dates or the resulting *DateTransitions*. This enables the validation and verification of the simulated process sequences by means of comparison values that are fixed for specific dates.

Figure 3 shows that *DateTransitions* and *ModTransitions* are in the *Date-Time-Branchnet*. *ModTransitions* perform switching functions for time-discrete disturbances in the *Process-Branchnet*. Therefore, they must be arranged within the Petri net directly behind a *DateTransition* and change their discrete values during switching. For example, when switching *ModTransitions*, any number of agents can be added or removed from the simulation model.

In this way, the working hours or absences due to illness of the employees can be represented. With this principle, any component objects of the BIM can also be blocked so that further work in certain local OAs is no longer permitted. Furthermore, it is possible to renew discrete model values during a simulation run with isolated *ModTransitions*. For example, changes of the displayed effort factors are achieved according to Figure 2. Figure 3 illustrates the principle of extraction and addition using “switch on/off” symbols. For clear differentiations in the *Date-Time-Branchnet*, the *DateTransitions* and the *ModTransitions* are enclosed by their own subnets.

3.2 Structural Petri Net Update

Figure 4 shows six steps of mutual switching for the update of a disturbance-modified schedule of the Petri net. Mutual switching means that one subnetwork must always wait while the other subnetwork switches.

Overall, the six steps illustrate the markings of the Petri net states that are reached during model execution. Furthermore, the waiting states of the subnets are also shown.

For example, the right side of Figure 4 shows the maximum state descriptions that the *Process-Branchnet* can assume until the *Date-Time-Branchnet* is switched.

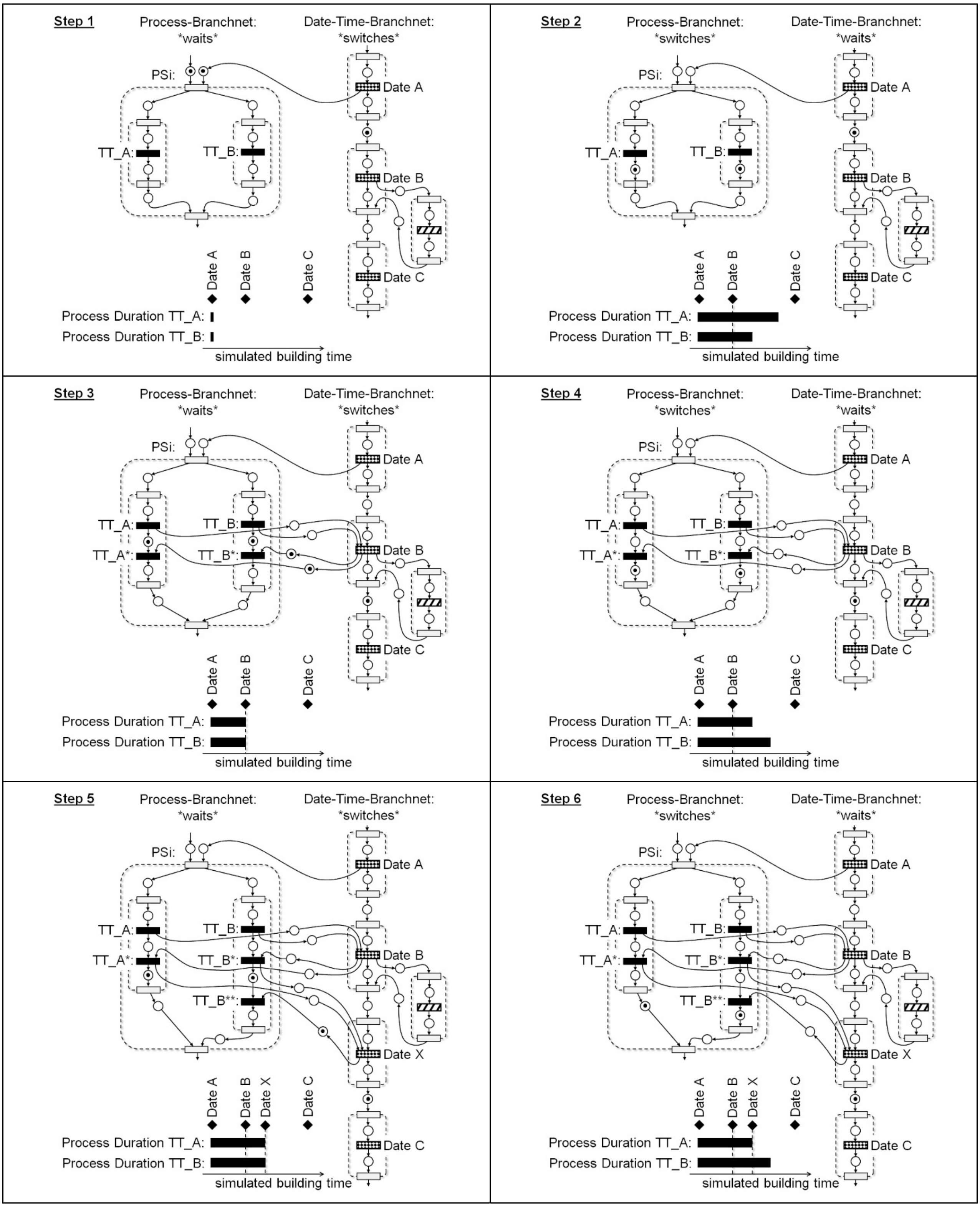


Figure 4: Mutual switching principle in six steps.

In contrast, the left side shows the switched *Date-Time-Branchnet*. A bar chart is displayed for each step. There, the black bars show the calculated process durations. Black diamonds represent dates in the *Date-Time-Branchnet*.

In Step 1 all transitions of the *Date-TimeBranchnet* are switched until a token is between the two subnets of *Date A* and *Date B*. Afterwards the switching of the two *TaskTransitions TT_A* and *TT_B* in the *Process-Branchnet* follows in Step 2. The resulting tokens remain in the direct downstream area of the two *TaskTransitions*. Here, the lower bar chart shows that both *TaskDurations* have overlapped the *Date B* of the *DateTransition*.

For this reason, *Date B* remains the next earliest date. All overlapping process durations are cut and removed. Therefore, the simulator copies and links the two *TaskTransitions* according to Step 3.

In this case, the *TaskTransition TT_A** is a copy of *TT_A*. All copied *TaskTransitions* share the process definitions of their original *TaskTransitions*. However, they differ in the calculated performance states. Thus, from the original *TaskTransition TT_A*, the previously calculated process state up to the time of the intersecting date remains as the final state. On the other hand, the copied *TaskTransition TT_A** receives the last reached process state as an initial state. In addition, all affected *TaskTransitions* are linked to the *DateTransition* of *Date B* according to Step 3. For that, it is necessary to create new tokens, which pass the calculated performance states to the following transitions.

In Step 4, the *ModTransition* also switches, which means that the process duration of TT_B* is longer than of *TT_A**. The transitions in the *Date-Time-Branchnet* switch until a token is between the subnets of *Date B* and *Date C*. Step 5 shows the situation that the calculated date (*Date X*) is the next earliest compared to Step 3. Analogous to Step 3, the simulator copies and links all *TaskTransitions* whose process durations overlap *Date X*. For this purpose, a new subnetwork is automatically created by the simulator for *Date X* in the *Date-Time-Branchnet*. For the sake of completeness, Step 6 shows the switching process that determines the final process durations.

During the structural Petri net update, the construction production processes are shifted forward or backward in time. The documents that are stored in the Petri net remain unchanged at the specified dates of the *DateTransitions*.

Their contents describe those model states that must be reproduced by simulation experiments as a result of the structural Petri net update.

On the one hand, a sufficiently justified verification is present if the state descriptions of the documents correlate with the simulation results in time. On the other hand, the simulation results can be validated with the simulated process sequence behavior. In such cases, experts must estimate whether the construction processes were practicable and under which parameter settings the step-by-step verifications were possible. The effort factors can be combined to determine deviations or to make other statements about the building time analysis, e.g., regarding missing information. Further details can be found in [3].

With the automated update rules presented here, a Petri net can be used as a background simulator. Despite reconfigurations, an executable process sequence structure can be realized. For example, the user can already be informed during his or her input whether the process sequence structures can be executed or not. In summary, the presented simulation principle can generate a very complicated process sequence structure with extremely complex construction processes.

4 Summary and Perspectives

This paper presented an approach to simulate construction process disturbances with agent-based Petri nets using a BIM for expert construction time analyses.

In contrast to the CPM technique, which is predominantly used in current consultant practice, the benefit of the approach presented here is the availability of chronological and process-related input options, in order to achieve disturbance-modifying effects for an objective schedule update

With the reconfigurable properties of the designed Petri net, complex simulation experiments are possible, which can well reproduce an emergent system behavior. The integration of external documents provides clues for validation and verification of the model behavior. Expert opinion argumentation lines can also benefit from this Petri net, because the simulated performance progress can be compared with the attached documents.

Experiments have already been carried out to simulate complex construction sequences of disturbed production processes. Gnerlich's [3] research project presents several simulation runs that illustrate the functionality of the approach presented in this paper.

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Virtual Simulation Presentations, from June 2020 on www.eurosim2023.eu

SIMS EUROSIM Conference 2021
Sept. 22-24, 2021, Oulu, Finland www.scansims.org

MATHMOD Vienna 2022
Feb. 16-18, 2022, Vienna, Austria www.mathmod.at

EUROSIM CONGRESS 2023
Spring/Autumn 2023, Amsterdam, The Netherlands www.eurosim2023.eu

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General Information. **EUROSIM**, the Federation of European Simulation Societies, was set up in 1989. The purpose of **EUROSIM** is to provide a European forum for simulation societies and groups to promote modelling and simulation in industry, research, and development – by publication and conferences. → *www.eurosim.info*

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CSSS	Czech and Slovak Simulation Society *Czech Republic, Slovak Republic*
DBSS	Dutch Benelux Simulation Society *Belgium, Netherlands*
KA-SIM	Kosovo Simulation Society, *Kosovo*
LIOPHANT	LIOPHANT Simulation Club; *Italy & International*
LSS	Latvian Simulation Society; *Latvia*
PSCS	Polish Society for Computer Simulation; *Poland*
MIMOS	Italian Modelling and Simulation Ass.; *Italy*
NSSM	Russian National Simulation Society *Russian Federation*
SIMS	Simulation Society of Scandinavia *Denmark, Finland, Norway, Sweden*
SLOSIM	Slovenian Simulation Society; *Slovenia*
UKSIM	United Kingdom Simulation Society *UK, Ireland*
ALBSIM	Albanian Simulation Society*; *Albania*
ROMSIM	Romanian Society for Modelling and Simulation*; *Romania*
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ISCS	*Italian Society for Computer Simulation, Italy*

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Each year a major **EUROSIM** event takes place, the **EUROSIM CONGRESS** organised by a member society, **SIMS EUROSIM Conference**, and **MATHMOD Vienna Conference (ASIM)**.

EUROSIM Congress 2019, the *10th EUROSIM Congress*, was organised by **CEA-SMSG**, the Spanish Simulation Society, in La Rioja, Logroño, Spain, July 1-5, 2019;

Due to Covid-19 virus in 2020 no **EUROSIM** events take place. To bridge this gap, **EUROSIM** is organising the series **VESS - Virtual EUROSIM Simulation Seminar** – seminars by simulation professionalists (2 hours via web), in preparation for upcoming **EUROSIM** events. → ***www.eurosim2023.eu***

Next main event is **SIMS EUROSIM Conference 2021**, September 21–23, 2021, Oulu, Finland. **SIMS**, the Scandinavian simulation society, extends every third year the annual **SIMS Conference** to the **SIMS EUROSIM Conference**.
→ ***www.scansims.org***

MATHMOD Vienna. This triennial **EUROSIM Conference** is mainly organized by **ASIM**, the German simulation society, and **ARGESIM,** with main co-sponsor **IFAC**.
MATHMOD 2022, the *10th MATHMOD Vienna Conference on Mathematical Modelling* will take place in Vienna, Februray 16-18, 2022. → ***www.mathmod.at***

EUROSIM Congress 2023, the *11th EUROSIM Congress*, will be organised by **DBSS**, the Dutch Benelux simulation society, in Amsterdam, Spring/Autumn 2023.
→ ***www.eurosim2023.eu***

Furthermore, **EUROSIM Societies** organize also local conferences, and **EUROSIM** co-operates with the organizers of the **I3M Conference Series.**
→ ***www.liophant.org/conferences/***

EUROSIM Member Societies

ASIM
German Simulation Society
Arbeitsgemeinschaft Simulation

ASIM (Arbeitsgemeinschaft Simulation) is the association for simulation in the German speaking area, servicing mainly Germany, Switzerland and Austria. **ASIM** was founded in 1981 and has now about 400 individual members (including associated), and 90 institutional or industrial members.

→ *www.asim-gi.org* with members' area

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ASIM is organising / co-organising the following international conferences:

- **ASIM** Int. Conference 'Simulation in Production and Logistics' – biannual
- **ASIM** 'Symposium Simulation Technique' – biannual
- **MATHMOD** Int. Vienna Conference on Mathmatical Modelling – triennial

Furthermore, **ASIM** is co-sponsor of *WSC* - Winter Simulation Conference, of SCS conferences *SpringSim* and *SummerSim*, and of *I3M* and *Simutech* conference series.

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EDU	Simulation in Education/Education in Simulation A. Körner, *andreas.koerner@tuwien.ac.at*
BIG DATA	Working Group Data-driven Simulation in Life Sciences; *niki.popper@dwh.at*
WORKING GROUPS	Simulation in Business Administration, in Traffic Systems, for Standardisation, etc.

CEA-SMSG – Spanish Modelling and Simulation Group

CEA is the Spanish Society on Automation and Control and it is the national member of IFAC (International Federation of Automatic Control) in Spain. Since 1968 **CEA-IFAC** looks after the development of the Automation in Spain, in its different issues: automatic control, robotics, *SIMULATION*, etc. The association is divided into national thematic groups, one of which is centered on Modeling, Simulation and Optimization, constituting the **CEA** Spanish Modeling and Simulation Group (**CEA-SMSG**). It looks after the development of the Modelling and Simulation (M&S) in Spain, working basically on all the issues concerning the use of M&S techniques as essential engineering tools for decision-making and optimization.

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CSSS – Czech and Slovak Simulation Society

CSSS -The *Czech and Slovak Simulation Society* has about 150 members working in Czech and Slovak national scientific and technical societies (*Czech Society for Applied Cybernetics and Informatics*, *Slovak Society for Applied Cybernetics and Informatics*). **CSSS** main objectives are: development of education and training in the field of modelling and simulation, organising professional workshops and conferences, disseminating information about modelling and simulation activities in Europe. Since 1992, **CSSS** is full member of **EUROSIM**.

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DBSS – Dutch Benelux Simulation Society

The *Dutch Benelux Simulation Society* (**DBSS**) was founded in July 1986 in order to create an organisation of simulation professionals within the Dutch language area. **DBSS** has actively promoted creation of similar organisations in other language areas. **DBSS** is a member of **EUROSIM** and works in close cooperation with its members and with affiliated societies.

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LIOPHANT Simulation

Liophant Simulation is a non-profit association born in order to be a trait-d'union among simulation developers and users; Liophant is devoted to promote and diffuse the simulation techniques and methodologies; the Association promotes exchange of students, sabbatical years, organization of International Conferences, courses and internships focused on M&S applications.

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LSS – Latvian Simulation Society

The Latvian Simulation Society (LSS) has been founded in 1990 as the first professional simulation organisation in the field of Modelling and simulation in the post-Soviet area. Its members represent the main simulation centres in Latvia, including both academic and industrial sectors.

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KA-SIM Kosovo Simulation Society

Kosova Association for Modeling and Simulation (KA-SIM, founded in 2009), is part of Kosova Association of Control, Automation and Systems Engineering (KA-CASE). KA-CASE was registered in 2006 as non Profit Organization and since 2009 is National Member of IFAC – International Federation of Automatic Control. KA-SIM joined EUROSIM as Observer Member in 2011. In 2016, KA-SIM became full member.

KA-SIM has about 50 members, and is organizing the international conference series International Conference in Business, Technology and Innovation, in November, in Durrhes, Albania, and IFAC Simulation Workshops in Pristina.

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MIMOS – Italian Modelling and Simulation Association

MIMOS (Movimento Italiano Modellazione e Simulazione – Italian Modelling and Simulation Association) is the Italian association grouping companies, professionals, universities, and research institutions working in the field of modelling, simulation, virtual reality and 3D, with the aim of enhancing the culture of 'virtuality' in Italy, in every application area.

MIMOS became **EUROSIM** Observer Member in 2016 and **EUROSIM** Full Member in September 2018.

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Last data update November 2020

NSSM – National Society for Simulation Modelling (Russia)

NSSM - The Russian National Simulation Society (Национальное Общество Имитационного Моделирования – НОИМ) was officially registered in Russian Federation on February 11, 2011. In February 2012 NSS has been accepted as an observer member of **EUROSIM**, and in 2015 NSSM has become full member.

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Last data update February 2018

PSCS – Polish Society for Computer Simulation

PSCS was founded in 1993 in Warsaw. PSCS is a scientific, non-profit association of members from universities, research institutes and industry in Poland with common interests in variety of methods of computer simulations and its applications. At present PSCS counts 257 members.

→ *www.eurosim.info*, www.ptsk.pl/

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Last data update December2013

SIMS – Scandinavian Simulation Society

SIMS is the *Scandinavian Simulation Society* with members from the five Nordic countries Denmark, Finland, Iceland, Norway and Sweden. The SIMS history goes back to 1959. SIMS practical matters are taken care of by the SIMS board consisting of two representatives from each Nordic country (Iceland one board member).

SIMS Structure. SIMS is organised as federation of regional societies. There are **FinSim** (Finnish Simulation Forum), **MoSis** (Society for Modelling and Simulation in Sweden), **DKSIM** (Dansk Simuleringsforening) and **NFA** (Norsk Forening for Automatisering).

→ *www.scansims.org*

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Last data update February 2020

SLOSIM – Slovenian Society for Simulation and Modelling

SLOSIM - Slovenian Society for Simulation and Modelling was established in 1994 and became the full member of **EUROSIM** in 1996. Currently it has 90 members from both Slovenian universities, institutes, and industry. It promotes modelling and simulation approaches to problem solving in industrial as well as in academic environments by establishing communication and cooperation among corresponding teams.

→ www.slosim.si

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Last data update December 2018

UKSIM - United Kingdom Simulation Society

The UK Simulation Society is very active in organizing conferences, meetings and workshops. UKSim holds its annual conference in the March-April period. In recent years the conference has always been held at Emmanuel College, Cambridge. The Asia Modelling and Simulation Section (AMSS) of UKSim holds 4-5 conferences per year including the EMS (European Modelling Symposium), an event mainly aimed at young researchers, organized each year by UKSim in different European cities. Membership of the UK Simulation Society is free to participants of any of our conferences and their co-authors.

→*uksim.info*

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Last data update March 2020

EUROSIM Observer Members

ROMSIM – Romanian Modelling and Simulation Society

ROMSIM has been founded in 1990 as a non-profit society, devoted to theoretical and applied aspects of modelling and simulation of systems. ROMSIM currently has about 100 members from Romania and Moldavia.

→ *www.eurosim.info/societies/romsim/*

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Last data update June 2019

ALBSIM – Albanian Simulation Society

The Albanian Simulation Society has been initiated at the Department of Statistics and Applied Informatics, Faculty of Economy at the University of Tirana, by Prof. Dr. Kozeta Sevrani.

The society is involved in different international and local simulation projects, and is engaged in the organisation of the conference series ISTI - Information Systems and Technology. In July 2019 the society was accepted as EUROSIM Observer Member.

→ *www.eurosim.info/societies/albsim/*

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Last data update July 2019

Societies in Re-Organisation

The following societies are at present inactive or under re-organisation:

- CROSSIM – *Croatian Society for Simulation Modelling*
  Contact: Tarzan Legović, *Tarzan.Legovic@irb.hr*
- FRANCOSIM – Société Francophone de Simulation
- HSS – Hungarian Simulation Society
- ISCS – Italian Society for Computer Simulation

Association Simulation News

ARGESIM is a non-profit association generally aiming for dissemination of information on system simulation – from research via development to applications of system simulation. **ARGESIM** is closely co-operating with **EUROSIM**, the Federation of European Simulation Societies, and with **ASIM**, the German Simulation Society. **ARGESIM** is an 'outsourced' activity from the *Mathematical Modelling and Simulation Group* of TU Wien, there is also close co-operation with TU Wien (organisationally and personally).

→ *www.argesim.org*

→ *office@argesim.org*

→ ARGESIM/Math. Modelling & Simulation Group,
Inst. of Analysis and Scientific Computing, TU Wien
Wiedner Hauptstrasse 8-10, 1040 Vienna, Austria
Attn. Prof. Dr. Felix Breitenecker

ARGESIM is following its aims and scope by the following activities and projects:

- Publication of the scientific journal **SNE** – *Simulation Notes Europe* (membership journal of **EUROSIM**, the *Federation of European Simulation Societies*) – *www.sne-journal.org*
- Organisation and Publication of the A**RGESIM Benchmarks** for *Modelling Approaches and Simulation Implementations*
- Publication of the series **ARGESIM Reports** for monographs in system simulation, and proceedings of simulation conferences and workshops
- Publication of the special series **FBS Simulation** – Advances in Simulation / Fortschrittsberichte Simulation - monographs in co-operation with ASIM, the German Simulation Society
- Organisation of the Conference Series **MATHMOD Vienna** (triennial, in co-operation with **EUROSIM**, **ASIM**, and **TU Wien**) – www.mathmod.at
- Organisation of Seminars and Summerschools on Simulation
- Administration of **ASIM** (German Simulation Society) and administrative support for **EUROSIM** *www.eurosim.info*
- Support of ERASMUS and CEEPUS activities in system simulation for TU Wien

ARGESIM is a registered non-profit association and a registered publisher: **ARGESIM Publisher Vienna**, root ISBN 978-3-901608-xx-y, root DOI 10.11128/z…zz.zz. Publication is open for **ASIM** and for **EUROSIM Member Societies**.

SNE – Simulation Notes Europe

The scientific journal **SNE** – *Simulation Notes Europe* provides an international, high-quality forum for presentation of new ideas and approaches in simulation – from modelling to experiment analysis, from implementation to verification, from validation to identification, from numerics to visualisation – in context of the simulation process. **SNE** puts special emphasis on the overall view in simulation, and on comparative investigations.
Furthermore, **SNE** welcomes contributions on education in/for/with simulation.

SNE is also the forum for the **ARGESIM Benchmarks** on *Modelling Approaches and Simulation Implementations* publishing benchmarks definitions, solutions, reports and studies – including model sources via web.

→ *www.sne-journal.org,*

→ *office@sne-journal.org*, *eic@sne-journal.org*

→ SNE Editorial Office
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EiC Prof. Dr. Felix Breitenecker

SNE, primarily an electronic journal, follows an open access strategy, with free download in basic layout. **SNE** is the official membership journal of **EUROSIM**, the *Federation of European Simulation Societies*. Members of **EUROSIM Societies** are entitled to download **SNE** in high-quality, and to access additional sources of benchmark publications, model sources, etc. On the other hand, **SNE** offers **EUROSIM Societies** a publication forum for post-conference publication of the society's international conferences, and the possibility to compile thematic or event-based **SNE Special Issues**.

Simulationists are invited to submit contributions of any type – *Technical Note*, *Short Note*, *Project Note*, *Educational Note*, *Benchmark Note*, etc. via **SNE**'s website:

ASIM ASIM ASIM

ASIM Books – ASIM Book Series – ASIM Buchreihen

Proceedings

Proceedings ASIM SST 2020 – 25. ASIM Symposium Simulationstechnik, Online-Tagung
14.-15.10.2020; C. Deatcu, D. Lückerath, O. Ullrich, U. Durak (Hrsg.), ARGESIM Verlag Wien, 2020;
ISBN ebook: 978-3-901608-93-3; DOI 10.11128/arep.59; ARGESIM Report 59; ASIM Mitteilung AM 174

Simulation in Production and Logistics 2019 – 18. ASIM Fachtagung Simulation in Produktion und Logistik
Chemnitz, 18.-20. 9. 2019; M. Putz, A. Schlegel (Hrsg.), Verlag Wissenschaftliche Skripten Auerbach, 2019,
ISBN print 978-3-95735-113-5, ISBN ebook 978-3-95735-114-2; ASIM Mitteilung AM172

Tagungsband ASIM SST 2018 - 24. ASIM Symposium Simulationstechnik, HCU Hamburg, Oktober 2018
C. Deatcu, T. Schramm, K. Zobel (Hrsg.), ARGESIM Verlag Wien, 2018; ISBN print: 978-3-901608-12-4;
ISBN ebook: 978-3-901608-17-9; DOI 10.11128/arep.56; ARGESIM Report 56; ASIM Mitteilung AM 168

Simulation in Production and Logistics 2017 – 17. ASIM Fachtagung Simulation in Produktion und Logistik
Kassel, 20.-22.10.2017; Sigrid Wenzel, Tim Peter (Hrsg.); ISBN Print 978-3-7376-0192-4, ISBN Online 978-3-7376-0193-1,
Kassel university press GmbH, Kassel, 2017; ASIM Mitteilung AM164

Tagungsband ASIM SST 2016 - 23. Symposium Simulationstechnik, HTW Dresden, September 2016
T. Wiedemann (Hrsg.); ARGESIM Verlag Wien, 2016; ISBN ebook 978-3-901608-49-0; DOI 10.11128/arep.52
ARGESIM Report 52; ASIM Mitteilung AM 160

Books

Kostensimulation - Grundlagen, Forschungsansätze, Anwendungsbeispiele
T. Claus, F. Herrmann, E. Teich; Springer Gabler, Wiesbaden, 2019; Print ISBN 978-3-658-25167-3;
Online ISBN 978-3-658-25168-0; DOI 10.1007/978-3-658-25168-0; ASIM Mitteilung AM 169

Simulation und Optimierung in Produktion und Logistik – Praxisorientierter Leitfaden mit Fallbeispielen.
L. März, W. Krug, O. Rose, G. Weigert (Hrsg.); ISBN 978-3-642-14535-3, Springer, 2011; AM 130

Book Series Fortschrittsberichte Simulation – Advances in Simulation

Die Bedeutung der Risikoanalyse für den Rechtsschutz bei automatisierten Verwaltungsstrafverfahren. T. Preiß, FBS 38
ISBN ebook 978-3-903347-38-0, DOI 10.11128/fbs.38, ARGESIM Publ. Vienna,2020; ISBN print 978-3-903311-14-5, TUVerlag Wien, 2020

Methods for Hybrid Modeling and Simulation-Based Optimization in Energy-Aware Production Planning. B. Heinzl, FBS 37
ISBN ebook 978-3-903347-37-3, DOI 10.11128/fbs.37, ARGESIM Publ. Vienna,2020; ISBN print 978-3-903311-11-4, TUVerlag Wien, 2020

Konforme Abbildungen zur Simulation von Modellen mit verteilten Parametern. Martin Holzinger, FBS 36
ISBN ebook 978-3-903347-36-6, DOI 10.11128/fbs.36, ARGESIM Publ. Vienna, 2020; ISBN print 978-3-903311-10-7, TUVerlag Wien, 2020

Fractional Diffusion by Random Walks on Hierarchical and Fractal Topological Structures. G. Schneckenreither, FBS 35
ISBN ebook 978-3-903347-35-9, DOI 10.11128/fbs.35, ARGESIM Publ. Vienna, 2020

A Framework Including Artificial Neural Networks in Modelling Hybrid Dynamical Systems. Stefanie Winkler, FBS 34
ISBN ebook 978-3-903347-34-2, DOI 10.11128/fbs.34, ARGESIM Publ. Vienna, 2020; ISBN print 978-3-903311-12-1, TUVerlag Wien, 2020

Modelling Synthesis of Lattice Gas Cellular Automata and Random Walk and Application to Gluing of Bulk Material. C. Rößler, FBS 33
ISBN ebook 978-3-903347-33-5, DOI 10.11128/fbs.33, ARGESIM Publ. Vienna, 2020; ISBN print 978-3-903311-08-4, TUVerlag Wien, 2020

Combined Models of Pulse Wave and ECG Analysis for Risk Prediction in End-stage Renal Desease Patients. S. Hagmair, FBS 32
ISBN ebook 978-3-903347-32-8, DOI 10.11128/fbs.32, ARGESIM Publ. Vienna, 2020

Mathematical Models for Pulse Wave Analysis Considering Ventriculo-arterial Coupling in Systolic Heart Failure. S. Parragh, FBS 31
ISBN ebook 978-3-903347-31-1, DOI 10.11128/fbs.31, ARGESIM Publ. Vienna, 2020

Variantenmanagement in der Modellbildung und Simulation unter Verwendung des SES/MB Frameworks. A. Schmidt, FBS 30;
ISBN ebook 978-3-903347-30-4, DOI 10.11128/fbs.30, ARGESIM Verlag, Wien 2019; ISBN print 978-3-903311-03-9, TUVerlag Wien, 2019

Classification of Microscopic Models with Respect to Aggregated System Behaviour. Martin Bicher, FBS 29;
ISBN ebook 978-3-903347-29-8, DOI 10.11128/fbs.29, ARGESIM Publ. Vienna, 2017; ISBN print 978-3-903311-00-8, TUVerlag Wien, 2019

Model Based Methods for Early Diagnosis of Cardiovascular Diseases. Martin Bachler, FBS 28;
ISBN ebook 978-3-903347-28-1, DOI 10.11128/fbs.28, ARGESIM Publ. Vienna, 2017; ISBN print 978-3-903024-99-1, TUVerlag Wien, 2019

A Mathematical Characterisation of State Events in Hybrid Modelling. Andreas Körner, FBS 27;
ISBN ebook 978-3-903347-27-4, DOI 10.11128/fbs.27, ARGESIM Publ. Vienna, 2016; ISBN print 978-3-903311-07-7, TUVerlag Wien, 2019

Comparative Modelling and Simulation: A Concept for Modular Modelling and Hybrid Simulation of Complex Systems. N.Popper,
FBS 26; ISBN ebook 978-3-903347-26-7, DOI 10.11128/fbs.26, ARGESIM Publ. Vienna, 2016

Rapid Control Prototyping komplexer und flexibler Robotersteuerungen auf Basis des SBE-Ansatzes. Gunnar Maletzki, FBS 25;
ISBN ebook 978-3-903347-25-0, DOI 10.11128/fbs.25, ARGESIM Publ. Vienna, 2019; ISBN Print 978-3-903311-02-2, TUVerlag Wien, 2019

A Comparative Analysis of System Dynamics and Agent-Based Modelling for Health Care Reimbursement Systems. P. Einzinger,
FBS 24; ISBN ebook 978-3-903347-24-3, DOI 10.11128/fbs.24, ARGESIM Publ. Vienna, 2016

Agentenbasierte Simulation von Personenströmen mit unterschiedlichen Charakteristiken. Martin Bruckner, FBS 23;
ISBN ebook Online 978-3-903347-23-6, DOI 10.11128/fbs.23, ARGESIM Verlag Wien, 2016

Deployment of Mathematical Simulation Models for Space Management. Stefan Emrich, FBS 22;
ISBN ebook 978-3-903347-22-9, DOI 10.11128/fbs.22, ARGESIM Publisher Vienna, 2016

Lattice Boltzmann Modeling and Simulation of Incompressible Flows in Distensible Tubes for Applications in Hemodynamics.
X. Descovich, FBS 21; ISBN ebook 978-3-903347-21-2, DOI 10.11128/fbs.21, ARGESIM, 2016; ISBN Print 978-3-903024-98-4, TUVerlag 2019

Mathematical Modeling for New Insights into Epidemics by Herd Immunity and Serotype Shift. Florian Miksch, FBS 20;
ISBN ebook 978-3-903347-20-5, DOI 10.11128/fbs.20, ARGESIM Publ. Vienna, 2016; ISBN Print 978-3-903024-21-2, TUVerlag Wien, 2016

Integration of Agent Based Modelling in DEVS for Utilisation Analysis: The MoreSpace Project at TU Vienna. S.Tauböck, FBS 19;
ISBN ebook 978-3-903347-19-9, DOI 10.11128/fbs.19, ARGESIM Publ., 2016; ISBN Print 978-3-903024-85-4, TUVerlag Wien, 2019

EUROSIM Conferences and Congress
VESS – Virtual EUROSIM Simulation Seminar

Due to Corona Virus, also **EUROSIM** changed the schedule of **EUROSIM Conferences** and the **EUROSIM Congress** – all events will take place one year later. To bridge the 2020 conference gap the **EUROSIM** societies organise virtual conferences, and the **EUROSIM Board** started in June 2020 **VESS** – the **Virtual EUROSIM Seminar**, a series of online presentations discussing trends in modelling and simulation and preparing emphasis of future **EUROSIM** events.

DBSS Dutch Benelux Simulation Society
www.eurosim2023.eu
VESS - VIRTUAL EUROSIM SIMULATION SEMINAR
free online seminar series

The **EUROSIM Board** and **DBSS** start in June 2020 **VESS** – the **Virtual EUROSIM Seminar**, a series of online presentations discussing trends in modelling and simulation. These international online simulation seminars – monthly or bi-monthly – are open to everybody, via Zoom, lasting 60 minutes (45 minutes presentations, 15 minutes Q & A).
Information and informal registration via website **www.eurosim2023.eu**

The First **SIMS EUROSIM Conference** on Modelling and Simulation, **SIMS EUROSIM 2021** takes place in Oulu, Finland, September 21-23, 2021. The 62nd International Conference of Scandinavian Simulation Society, SIMS 2021, is embedded with **SIMS EUROSIM 2021**. The **SIMS EUROSIM** conference will be organized every third year by **SIMS** and **EUROSIM**. The background of this conference series is in the 60-years history of Scandinavian Simulation Society, **SIMS**.
The program of the **SIMS EUROSIM 2021 Conference** will have a multi-conference structure with several special topics related to methodologies and application areas. The program includes invited talks, parallel, special and poster sessions, exhibition and versatile technical and social tours – info **www.scansims.org**

MATHMOD organizers continue the conference series one year later, with **10th MATHMOD 2022**, February 16-18, 2022. **MATHMOD 2022**, one of **EUROSIM**'s main events, provides a forum for professionals, researchers, and experts in the field of theoretic and applied aspects of mathematical modelling for systems of dynamic nature.
The scope of the **MATHMOD 2022** conference covers theoretic and applied aspects of various types of mathematical modelling (equations of various types, automata, Petri nets, bond graphs, qualitative and fuzzy models) for systems of dynamic nature (deterministic, stochastic, continuous, discrete or hybrid) – info and details **www.mathmod.at**

EUROSIM 2023, the **11th EUROSIM Congress**, will take place in Amsterdam, The Netherlands, Spring/Autumn 2023. It will be organized by the Dutch Benelux Simulation Society (www.dutchbss.org) supported mainly by their corporate members like TU Delft, Amsterdam University of Applied Sciences, EUROCONTROL and IGAMT (www.igamt.eu).
Due to the growth of Simulation and its relationship with other analytical techniques like Big Data, AI, Machine Learning, Large Scale Simulation and others, the event will be structured, for the first time, in dedicated tracks focused on different areas and applications of Simulation ranging from aviation to health care and humanitarian activities. We have the ambition to attract at the congress participants from Academia, industry and governmental representatives to share the latest developments in Simulation and related activities and applications.
Please follow the news and activities towards the **EUROSIM 2023** at **www.eurosim2023.eu**

www.tuverlag.at
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