SNE SIMULATION NOTES EUROPE

SNE Special Issue

Simulation in Production and Logistics: Sustainability in Production and Logistics

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ARGESIM

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SNE seeks to serve scientists, researchers, developers and users of the simulation process across a variety of theoretical and applied fields in pursuit of novel ideas in simulation. **SNE** follows the recent developments and trends of modelling and simulation in new and/or joining areas, as complex systems and big data. **SNE** puts special emphasis on the overall view in simulation, and on comparative investigations, as benchmarks and comparisons in methodology and application. For this purpose, **SNE** documents the **ARGESIM Benchmarks** on *Modelling Approaches and Simulation Implementations* with publication of definitions, solutions and discussions. **SNE** welcomes also contributions in education in/for/with simulation.

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Editorial

Dear Readers, Special Issues are a tradition of SNE: special issues on selected topics, postconference publications, promotion for simulation and conferences. We started in 2006 with a special issue on parallel and distributed simulation, followed by two special issues on object-oriented and structural-dynamic systems. Further topics of special issues were System Dynamics, control, quality aspects, health care technology, education, traffic systems, physiology, etc. (see cover snapshots below). And in 2017 we started special issues with postconference publications, some general – as with EUROSIM congress and MATHMOD conference, and some specific – as with the special issues on ASIM's conference on Modelling and Simulation in Production and Logistics. We are glad to present with SNE 34(2) the fourth special issue of this type – postconference publications from ASIM SPL 2023 in Ilmenau. Many thanks to the authors and to the special issue editors, and many thanks to the SNE Editorial Office for layout, typesetting, preparations for printing, electronic publishing, and much more. And have a look at the info in this issue on forthcoming conferences, as ASIM SST 2024 in Munich, I3M conference in Tenerife, ASIM SPL 2025 in Dresden, etc.

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

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SNE SIMULATION NOTES EUROPE

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Scope: Developments and trends in modelling and simulation in various areas and in application and theory; comparative studies and benchmarks (documentation of ARGESIM Benchmarks on modelling approaches and simulation implementations); modelling and simulation in and for education, simulation-based e-learning; society information and membership information for EUROSIM members (Federation of European Simulation Societies and Groups).

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Editorial Special Issue SPL 2023

SNE 34(2) contains a selection of outstanding papers from the 20th ASIM Dedicated Conference **Simulation in Production and** Logistics (ASIM SPL'2023), which took place in September 2023 at the Ilmenau University of Technology (TU Ilmenau), 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 thematic focus of the conference in Ilmenau was sustainability in production and logistics. The conference thus addressed an important social issue and at the same time concentrated on current research topics from the world of simulation.

In the context of sustainability, wood as a renewable, flexible and regional resource makes an important contribution to sustainable development. To ensure the most efficient use of wood as a resource, transport along the wood supply chain is very important and not only influences costs, but also has a significant impact on quality, among other things. *Kogler* shows this very clearly in his article.

Energy simulation is now also being considered more frequently in the context of production and logistics. There is considerable potential, particularly in terms of sustainability. The article by *Barth et al.* shows how simulation can support the holistic planning of AC/DC energy grids.

The topic of supply chain simulation has been present at ASIM in particular for many years, and several applications were also represented this year.

For example, *Kippenberger et al.* analyzed the risk of bottlenecks in supply chains for emergency services under incomplete data.

Meisner et al. investigated the design of simulation models for rescue chains with the aim of analyzing and improving them based on various scenarios.

Next, *Schmitz and Stenzel* present an approach to designing layouts for flexible production systems, with a particular focus on the requirements of AGVs.

Some of the papers at the conference focused on modular assembly and matrix production systems, where adaptable workstations and also autonomous vehicles are used to transport production orders between stations. *Bergmann & Ehrle* compared traditional matrix layouts with alternative options such as single-lane lanes and non-matrix layouts such as honeycomb or star shapes and evaluated their potential impact on system performance using simulation-based analysis.

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 Dresden in September 2025, see www.asim-fachtagung-spl.de.

Sincerely, the SNE 34(2) Special Issue Editors

Soeren Bergmann, TU Ilmenau;
Niclas Feldkamp, TU Ilmenau;
Steffen Strassburger, TU Ilmenau;
Sigrid Wenzel, Universität Kassel
in the name of the ASIM Dedicated Conference SPL

SNE covers of previous SNE Special Issues on *Simulation in Production and Logistics*
(SNE 27(2), SNE 30(4), SNE 32(2))

Innovative Transport Simulation for Sustainable and Resilient Wood Logistics

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Abstract. Wood is the renewable, flexible, and regional resource of our time contributing strongly to a sustainable development. Climate crisis induced abiotic natural disasters such as windstorms followed by biotic forest calamities in form of insect and fungi infestations threaten forest ecosystem services challenging the management of surrounding socio-economic systems. Resilient and sustainable logistical processes are essential for coping with the increasing frequency and severity of risks to secure green supplies for increasing production demands of wood products. Simulation methods offer beneficial approaches to consider those risks as well as resulting bottlenecks, interacting queues, and waiting times. Discrete event simulation provides an excellent methodology for a digital representation of wood supply chains focusing on straightforward business processes. Consequently, unique models for unimodal, multimodal, and multi-echelon unimodal wood transport are presented, which enable multicriteria-based transport strategy development, optimal fleet configurations, and wood quality preservation in challenging scenarios. The presented models were applied in scientific, educational, and managerial settings and set the stage for knowledge transfer in serious-game-based workshops, advanced risk management, and contingency planning.

Introduction

Sustainability, a term that is omnipresent nowadays, has its roots in forestry, expressing the principle of only felling as many trees as will regrow in the same period of time.

In Austria, forests are growing steadily, so that trees storing CO_2 for more than 100 years cover almost half of the national territory, exceeding both the EU-wide (45%) and global (31%) benchmarks [1].

Current challenges for forest ecosystems include increasingly frequent and severe forest calamities such as storms, fires, snow pressure, and ice breakage. Furthermore, the natural protective mechanisms of trees, strained by heat waves and periods of drought, are unable to cope with the exponential increase in insect infestations. In particular, bark beetles recently caused a large-scale dieback of Norway spruce trees (i.e., dominating the Austrian tree landscape with a share of 57%) and are now threatening critical protection forests in mountain valleys [2]. Wood value chains are increasingly overwhelmed by the resulting large quantities of salvage wood leading to critical bottlenecks of harvesting and extracting capacities in steep terrain, locally available self-loading log trucks with skilled and experienced drivers as well as storage and processing capacities of wood-based industries [3]. In addition, there are also inefficiencies due to an unwillingness of conservative actors in this sector to cooperate in data exchange as well as a lack of digitalization and quantitative decision support [4].

Wood supply chain resilience is characterized by the adaptive capability, flexibility, and invulnerability of the collaborative acting stakeholders of wood supply chains to withstand crisis through risk management (analyze and prepare), contingency planning (decide and act) and knowledge management (reflect and learn) aiming to recover to an economically, ecologically and social more sustainable post-crisis state [5]. If the complex logistics processes with their numerous interactions are not planned, managed and controlled in a resilient and sustainable manner, supply bottlenecks and supply chain disruptions cause long lead times resulting in critical wood quality and value losses on the last transport meters.

Consequently, innovations for wood transport are needed to meet the challenges of this essential renewable raw material shaping our world in times of climate crisis. Decision support by transport simulation is crucial for sustainable and resilient wood logistics, which is driven by answering the following research questions:

1. How can unimodal and multimodal transport strategies for a more sustainable and resilient wood supply be virtually tested in risk scenarios and what opportunities does this create for contingency planning?
2. What is the potential of wood transshipment from self-loading log trucks to semitrailer trucks and what is the optimal fleet configuration for this multi-echelon unimodal wood transport?
3. How does the procurement lead time (time between harvesting and arrival at the industry) influence the wood quality loss and which proactive logistic risk management strategies can be applied to avoid the associated wood value loss?

1 Background

The wood supply chain is a complex, dynamic network of material, service, information, and financing flows between and within numerous stakeholders.

Wood can either be delivered directly from the forest to the industry (i.e., unimodal transport) or indirectly, including (multiple) transshipment processes at truck (i.e., multi-echelon unimodal transport), rail or vessel terminals (intermodal or multimodal transport). Figure 1 provides illustrative examples of the wood transport types, which can be distinguished by the specification of the means of transport, mode of transport, and loading unit.

Wood supply chain management covers planning, designing, operating, controlling, and monitoring the growing, harvesting, extraction, transporting, storing, (pre-)processing, (re-)using, and recycling of wood. [6]

Wood transport is the link between stakeholders and system components, with self-loading log trucks as their backbone. The highly specialized transport equipment limits the opportunity for backhauling or transport of other goods.

Stakeholders include forest owners, authorities, interest groups, lobbies, harvesting, wood transport, and wood trading companies as well as production and further processing industries. Wood-processing sawmills as well as pulp, panel, and paper industries produce mass products such as sawn timber, pulp, pellets, boards, and paper. Further processing industries including wood construction and furniture manufacturing produce a variety of high value-added products such as cross-laminated timber, furnishings, and prefabricated wooden houses.

The forest functions and ecosystem services are crucial to achieve the Sustainable Development Goals, the Paris Agreement on Climate Change and the Aichi Biodiversity Targets [7]. The eco-social welfare function of forests ensures that all people, animals, and plants benefit from forests as a place of retreat, carbon reservoir, air and water purifier and as a bastion against soil sealing and land consumption. The recreational function invites respectful guests to slow down, rest and exercise in both Austria's public (18%) and private forests (82%). The protective function safeguards living and settlement areas from the forces of nature such as avalanches, rockfalls, landslides and floods. The utility function of forests provides 300,000 jobs in 172,000 companies along the Austrian wood supply chain achieving a production value of 12 billion euros with a positive trade balance of 4,5 billion euros [8] resulting in a global top six export ranking (Table 1).

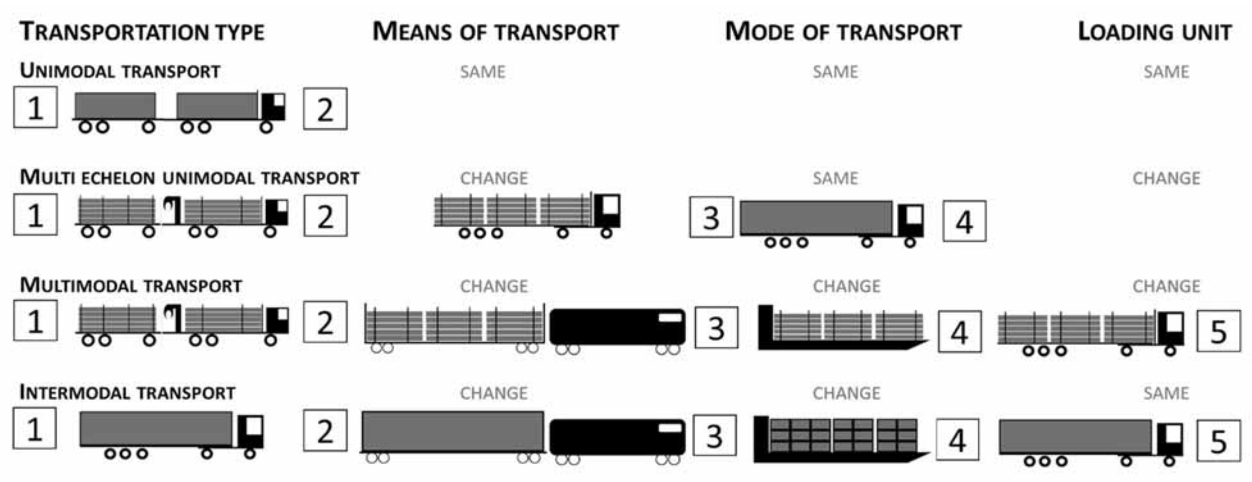

Figure 1: Examples of wood transport types with distinguishing criteria.

Export ranking	Country	Export share	Import share	Balance per capita ranking
1	Canada	11%	2%	33
2	China	10%	12%	111
3	Germany	7%	6%	19
4	USA	6%	19%	144
5	Russia	5%	0%	43
6	Austria	4%	2%	2
7	Sweden	3%	1%	13
8	Poland	3%	1%	12
9	Brazil	3%	0%	42
10	Indonesia	3%	0%	32

Table 1: Global Top-10 ranking on wood and articles of wood exports and imports in 2022 [9].

2 Method

Simulation facilitates decision support beyond the limits of analytical solutions by modeling dynamic systems featuring non-linear behavior, time and causal dependencies, uncertainty, non-intuitive influences between variables, and a large number of parameters.

Discrete Event Simulation (DES) enables the straightforward, realistic and digital mapping of wood supply chain processes. Quantitative analysis of modelled system components such as processes, entities, and resources in risk scenarios based on key performance indicators provide decision support.

This research method with strengths in integrating stochastic elements, time dynamics, and queuing systems is especially suitable for observing bottlenecks, utilizations, lead times, complex interactions, and system capacities. The straightforward focus on business process and visualization of the system behavior over time enhances stakeholder involvement in model development, experimental design, verification, validation, and analysis [10].

The opportunity to communicate results intuitively in animations and interact through what-if questions provides decision makers a better understanding of the real system and model internals, which establishes trust and credibility.

3 Literature

The DES method has been used in wood transport research primarily by scientists from Chile [11], Canada [12], Sweden [13], Finland [14] and Austria [15]. Two thirds of the studies published in the last 15 years covered exclusively unimodal transport, but during the last five years the focus shifted to multimodal and multi-echelon unimodal wood transport simulation models including terminals with complex transhipment processes.

For insights regarding the differences in global unimodal wood transport refer to [16], who observed and compared maximum gross vehicle weight limits, unimodal transportation shares, average distances, and costs in a recent study based on an international expert survey.

Comprehensive systematic and narrative literature review studies addressed wood transport simulation related topics published from 1983 until 2021 (Table 2). Identified research gaps are addressed in this article by presenting simulation models for detailed modeling of more sustainable transport modes (i.e., multimodal, multi-echelon unimodal) and development of resilient management strategies (i.e., contingency planning, simulation workshops) as well as modeling of wood quality devaluation and derivation of logistics strategies for proactive risk management.

Reference	Publication year	Review period	Reviewed studies	Citations
[17]	2022	1989–2020	43	12
[18]	2021	2011–2021	45	17
[19]	2021	2000–2020	138	27
[20]	2019	1987–2018	99*	61
[21]	2018	1995–2017	132	72
[22]	2018	1997–2017	44	81
[23]	2017	1989–2017	31*	43
[24]	2017	1990–2015	25	25
[25]	2014	1983–2012	136*	142
[26]	2013	1986–2013	34	46

Table 2: Ten most relevant literature reviews of the last decade addressing simulation and wood transport topics (*based on the bibliography of the narrative reviews).

4 Wood Transport Simulation

The models presented in this article simulate unimodal, multi-echelon unimodal, multimodal, and quality-preserving wood transport strategies.

Alongside providing scientific impact and practical insights, the DES models are particularly suitable for usage in serious game-based workshops. These empower stakeholders of the wood supply chain, students, and researchers to test new approaches in simulation experiments without having to fear negative real consequences (e.g., high costs, hazardous risks, long durations) due to complex and unpredictable interactions. The simulation models can be applied to promote cooperation, knowledge, and risk management as well as increase resilience, improve sustainability, and save costs.

A scientific simulation model was redesigned, tested, and revised in line with feedback received from students, researchers, and stakeholders of wood supply chains to provide intuitive usability for serious game-based simulation workshops [27].

Figure 2 shows the scenario building view of the resulting software application allowing to parametrize (e.g., costs, durations, volumes) and configure the simulation model interactively through sliders and buttons as well as predefined or adjustable plans, and input data (e.g., spreadsheets, data tables).

The control view (Figure 3) shows the harvest volumes of each case study region for the upcoming week on the left side (A) and the harvested volumes the previous weeks in the center (B). Taking this into account, the transport plan for the current week can be determined by defining the number of train wagons (1), self-loading log trucks (2), train pick-ups at the terminal per day (3), allocation of transport types (4), and prioritized transport strategy (5).

Following ongoing analysis of the current and past supply chain situation and metrics in supplementary statistics, animation, and logic views, the workshop participants of every group discuss strategic options and agree on a transport plan before they submit the decisions for the current week by starting a simulation run (6).

At the end of the workshop the key performance indicators are exported and discussed with the participants to develop concrete transport strategies for practical application based on the learnings of the game-based simulation workshop experience.

4.1 Multimodal Wood Transport

Multimodal wood transport strategies reduce truck-related environmental burdens (e.g., emissions, noise, hazards) and increase resilience (e.g., additional transport capacity and flexibility after calamities, interim storage capacity at terminals) through short self-loading log truck transports to train terminals and subsequent rail transport of wood. However, multimodal supply chain management is substantially more challenging (e.g., additional transshipment operation, complex transport planning, coordination of more involved actors) than unimodal transport, making the developed DES model a helpful decision support tool.

The model of Kogler and Rauch [28] simulating unimodal, multimodal, and mixed transport strategies includes a unique level of detail [20] as well as the most comprehensive representation of key performance indicators for costs, emissions, capacities, utilizations, waiting and lead times in DES models for wood supply chains (Figure 4). Transport managers can use the simulation model to improve the standard process flow (e.g., capacity, utilization, time and resource planning to avoid bottlenecks) as well as to test new strategies in response to changed circumstances and conditions (e.g., potential for additional rail terminals, limited availability of rail wagons) before implementing cost-intensive changes in reality. In addition, the simulation model provides the basis for time-critical contingency planning after salvage wood events (e.g., storms, bark beetles) or preparation for future disturbances (e.g., fluctuations in demands or productions, breakdown of transport resources) through proactive risk management.

Quantitative decision support for competing planning objectives was provided by developing sophisticated key performance indicator rankings together with industry and research experts. In simulation experiments of different risk scenarios critical key performance indicators for supply chain management such as transport volume, procurement lead time, waiting times at the terminal, utilization of transport, and storage capacities were calculated. Results were structured in intuitive planning tables for short, medium and long transport times as well as one or two train pickups a day to be used in industry practice and derive managerial implications. Conclusions reported that wood supply chains combining unimodal and multimodal wood transport are more resilient and less vulnerable due to the gained substitutability, diversity and flexibility.

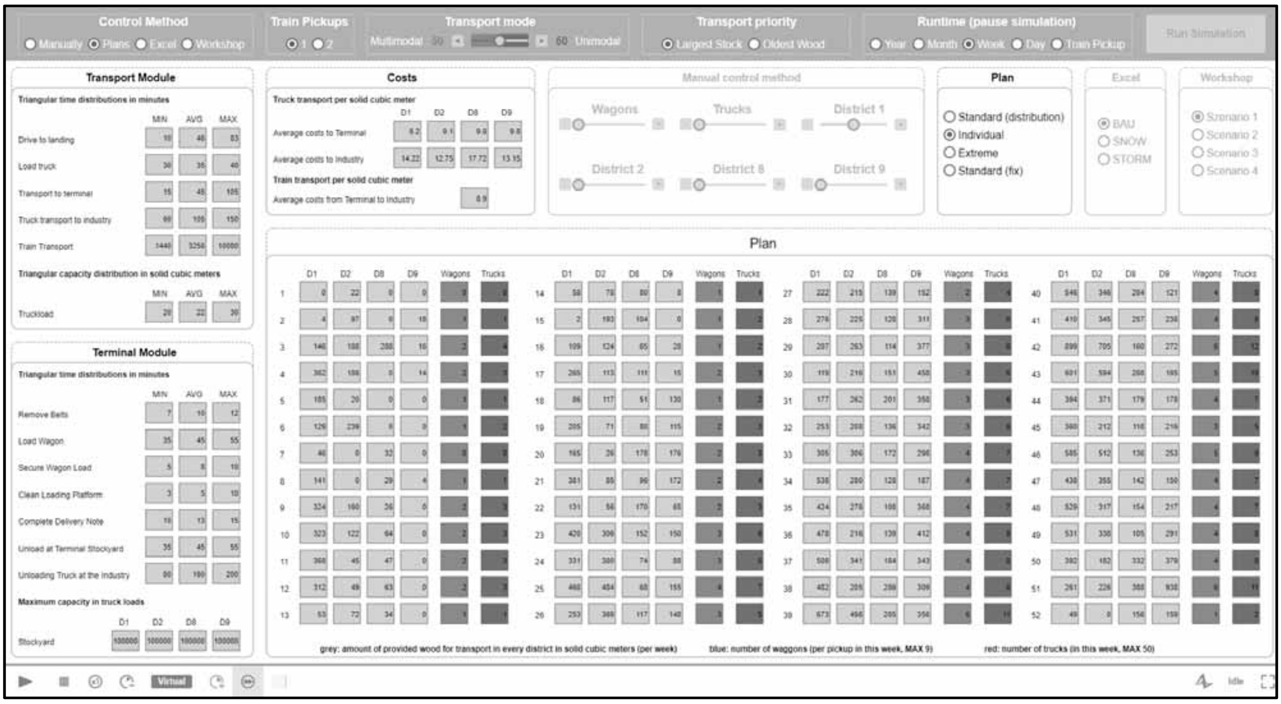

Figure 2: Scenario building view to parameterize and configure the simulation model for intuitive control in serious game-based workshops.

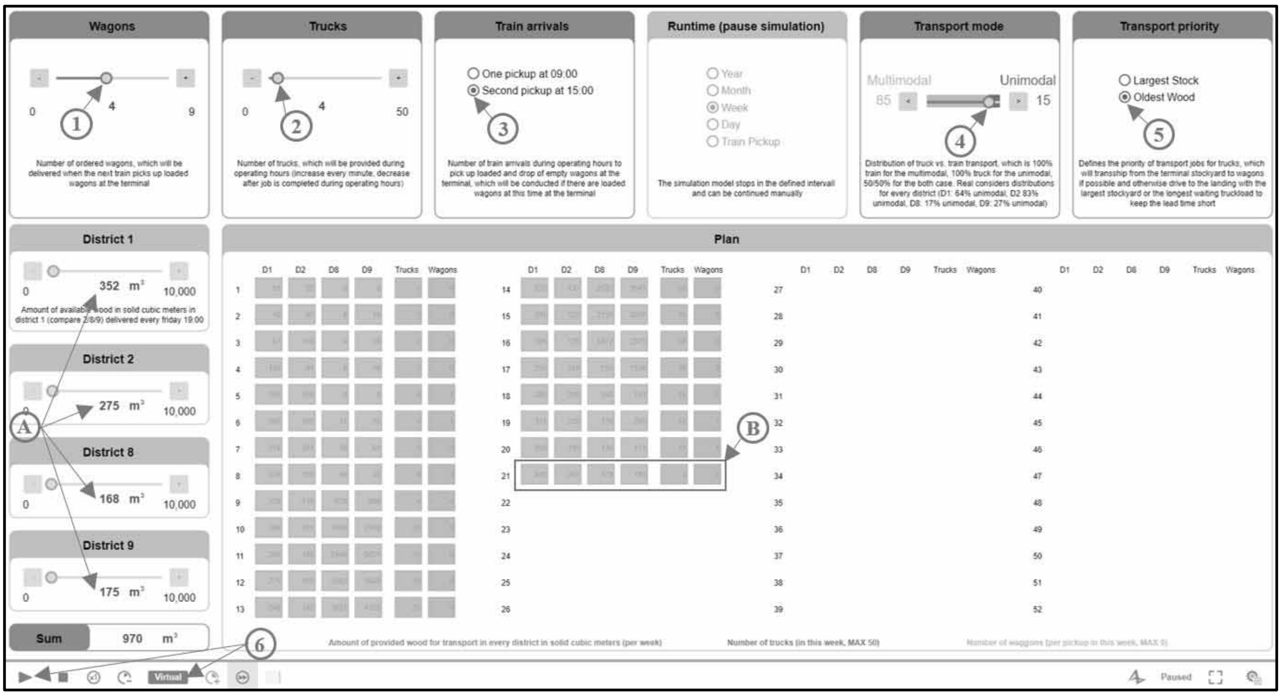

Figure 3: Control view of the serious game-based workshop simulation with scenario information (A and B) and intuitive control elements (1–6).

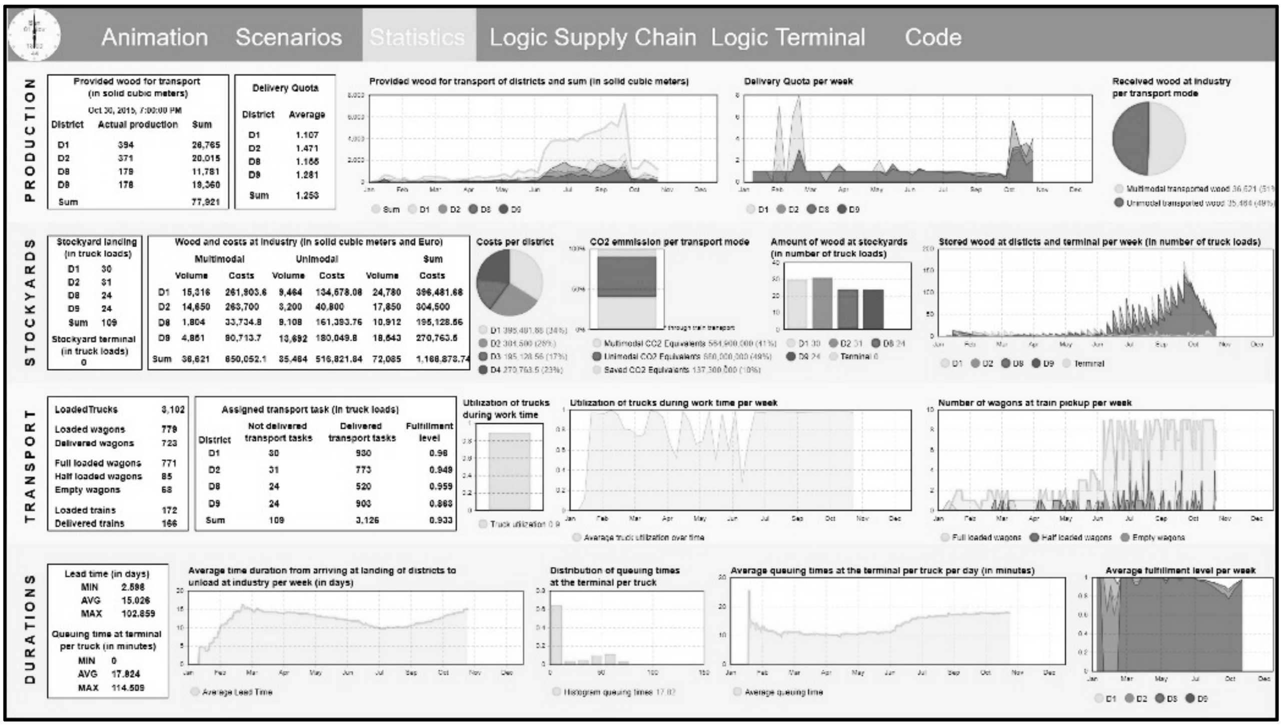

Figure 4: Statistics view of the simulation model with key performance indicators for production, storage, and transport.

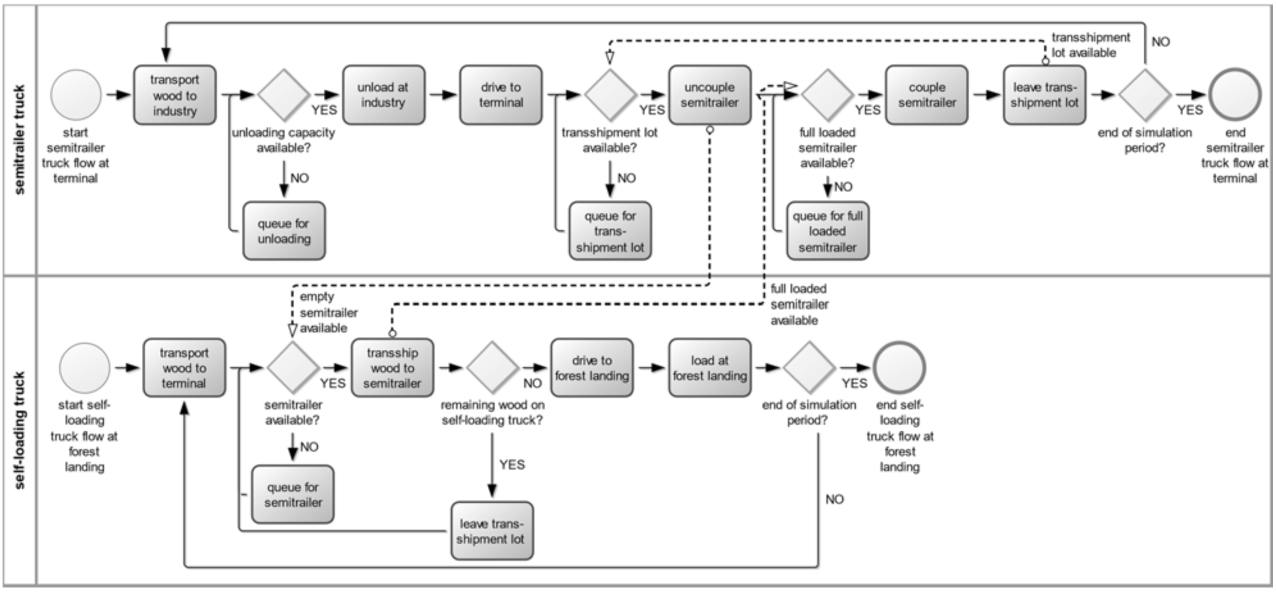

Figure 5: Process flow for semitrailer and self-loading log trucks from the pick-up in the forest via transhipment operations at a terminal to unloading at industry.

4.3 Multi-Echelon Unimodal Wood Transport

Multi-echelon unimodal wood transport strategies build on short self-loading log truck transports to transshipment terminals, where semitrailers are provided (i.e., instead of train wagons at train terminals). After the self-loading log trucks loaded the semitrailers, they get picked-up by prime mover trucks for the remaining transport to industry. Due to the lower tare weight of the semitrailer trucks compared to the self-loading log trucks, wood can be transported more efficiently and the dramatic shortage of self-loading log truck drivers (i.e., decreasing number of truck driving licenses due to high workload, danger, unpopular image in society) can be mitigated.

Figure 5 shows the process logic and interactions of self-loading log trucks, semitrailers and prime mover trucks in a flow diagram modelled in accordance with the Business Process Model and Notation (2.0) standard. Kogler et al. [29] developed the first DES model for the simultaneous optimization of the fleet configuration (number of self-loading log trucks, number of prime mover trucks, number of semitrailers) and handling infrastructure (number of transshipment slots for semitrailers) for individually parametrizable system configurations (e.g., transport distances, costs, volumes). For this purpose, the solution space was restricted to the reasonable factor combinations corresponding to the respective transport capacities (i.e., decision tree method), so that the optimal factor combinations of the simulation results could be determined by means of an exact method of combinatorial optimization (i.e., complete enumeration). Along with the scientific analysis of the results, optimal factor combinations were summarized in planning tables allowing transport managers to implement optimal fleet configurations for their respective situations in practice. For example, they can derive the optimum ratio of prime mover trucks and semitrailers for an available terminal size and regionally disposable number of self-loading log truck fleet. Moreover, practitioners can look up the best supply chain network configuration (i.e., transport duration, terminal size) and optimal fleet constellation to meet the industry targets for required transport volumes (e.g., fulfillment levels, delivery quotas). Findings showed significant cost savings with increasing terminal size for the same turnover, because of shorter waiting times and increasing flexibility at the terminal. Optimal results regarding the truck fleet outperformed unimodal transport cost benchmarks for short, medium and long transport distances by 5.45%, 6.95% and 11.28%, respectively.

4.4 Quality-Preserving Wood Transport

Quality-driven wood transport strategies rely on the significant correlation between procurement lead time and quality loss of roundwood during storage and transport. The DES by Kogler and Rauch [30] integrated for the first-time interfaces to weather-based models analyzing the development of fungi (blue-stain [31]) and insect (bark beetles [32]) infestations as well as their impact on the quality and value of wood stored at the forest street landing.

The animation view (Figure 6) visualizes the wood quality development along unimodal and multimodal supply chains. The wood supply area is illustrated in three different altitude and vegetation levels (left). Piles with fresh wood are shown in green, piles with wood at risk of devaluation in yellow, and piles with already devalued wood in red. The aerial picture shows a typical wood loading terminal with wagons (grey) and self-loading log trucks (red-grey).

Currently utilized wood transport strategies in practice are not based on explicit information on concrete threats of wood value losses and thus served as benchmark strategies. These were compared with the newly developed strategies specifically utilizing the forecast of wood quality development based on the expected weather conditions according to selected key performance indicators including procurement lead time, wood quantity with quality loss during the procurement lead time, and wood value loss due to quality loss (Figure 7).

Knowledge of the quality development and the forecast of the expected devaluation week proved to be particularly important in the event of transport capacity bottlenecks, as wood value losses can be decisively reduced, especially through strategic transport allocation (i.e., on average more than half of the devaluation can be avoided). Increasing multimodal and unimodal transport capacity during peak periods of wood devaluation risks even leads up to almost three quarters devaluation avoidance. Prioritizing transports of wood with high devaluation risk over fresh wood and already devaluated wood has proven to be expedient. The results of extensive simulation experiments in risk scenarios quantify for the first time the importance of including expected wood value losses in the management of the wood supply chain (statistically significant correlation between procurement lead time and wood quality loss modelled in regressions) and show corresponding strategic and tactical transport options for proactive risk management.

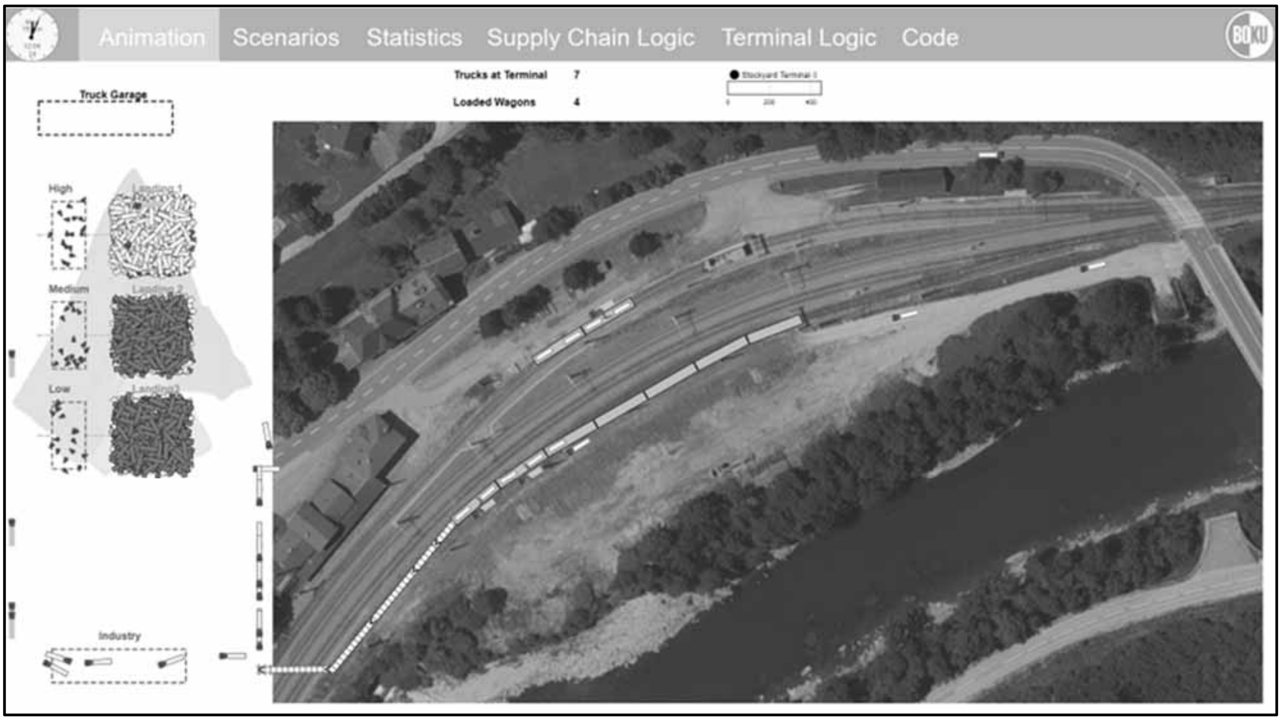

Figure 6: Animation view of a virtual wood supply chain environment visualizing sawlogs, trucks, train wagons, terminal, stockyards, and harvesting regions in three altitude zones.

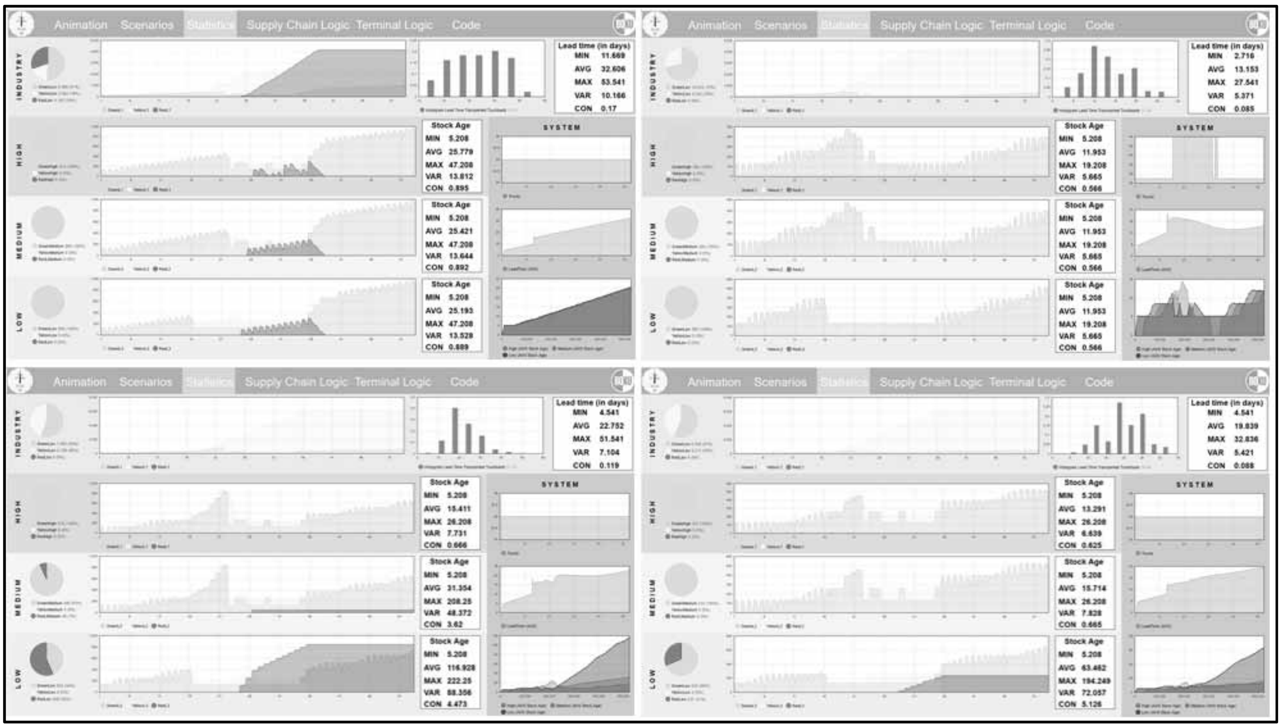

Figure 7: Management cockpits showing statistics of different transport scenarios for fresh sawlogs (green), roundwood facing devaluation (yellow) and devaluated roundwood (red).

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5 Conclusion

Current and future challenges call for innovative, digital, and quantitative decision support tools for the traditionally conservative stakeholders along wood supply chains. The DES models presented in this study demonstrate the high suitability and intuitive applicability of this method for cooperative contingency planning (e.g., concrete transportation planning tables), proactive risk management (e.g., climate crisis-related extreme scenarios), and strategy development (e.g., serious game-based simulation workshops) in wood transport logistics. This provides key contributions to sustainability and resilience of the wood value chain.

The scientific impact of the three models presented for wood transport simulation include:

1. an unprecedented level of detail in the modeling of multimodal wood supply chains as well as the most comprehensive representation of key performance indicators in DES models for wood supply chains,
2. the first simultaneous optimization of fleet configuration and transhipment infrastructure for individually parameterizable initial situations and intuitive visualization of the results in transport planning tables, and
3. first-time quantification of wood value losses caused by the procurement lead time and avoidance of such losses through the development of logistics strategies for proactive risk management.

Innovation comprises both the development of new methods, techniques, and models as well as the application and implementation of new ideas and knowledge in reality. The stakeholders along the wood value chain benefit from the findings and managerial implications through knowledge transfer within conventional (e.g., lectures, consulting, publications in industry magazines) and innovative communication formats (i.e., serious game-based simulation workshops for strategy development, simulation games with a variety of scenarios for hands-on application of transport planning tables).

Crucial advancement pathways for simulation research include the knowledge discovery in simulation data [33] as well as integration of real-time data [34] and artificial intelligence [35] (particularly machine learning [36]) in comprehensively verified and validated simulation models [37].

Developing digital twins and using the opportunities of artificial intelligence for wood transport simulation opens up great research potential for further innovative contributions to sustainable and resilient wood logistics.

Organizational efforts are required to ensure internal system readiness for the implementation of technological developments along traditional wood value chains and their conservative actors. For this purpose, it is expedient to accompany the technology-driven implementation of new processes with sound change management and process reengineering to establish the necessary organizational culture (e.g., willingness to innovate through data-based decision support) and structural trust (e.g., willingness to cooperate for transparent data exchange) across the forestry and wood-based industry.

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Holistic Concept for Simulation-based Planning and Design of Hybrid AC/DC Energy Grids for Production Systems

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Abstract. This paper proposes a simulation-based planning concept and a simulation architecture for the design of hybrid AC/DC grids, which have the potential to significantly contribute to the energy transition. The paper discusses the lack of knowledge for the design of these grids, and presents a simulation approach to efficiently design hybrid grids and analyze them based on an electrical simulation. The authors also address the need to include process-specific characteristics in the planning and analysis of the electrical network, which is why common simulation tools for production processes are included in the approach. This allows economical, ecological, safety-relevant and technical aspects to be integrated into the planning process. The proposed concept is further discussed and planned for validation on the basis of a demonstrator currently under construction.

Introduction

The use of alternating current for general and widespread electrification was not set from the beginning. The war of currents was fought between the proponents of direct current (DC) and alternating current (AC) represented by Thomas Alva Edison and George Westinghouse respectively. The invention of the transformer in 1881 made it possible to transport electrical energy efficiently over long distances. This central aspect shapes our current electricity grid, which is based on alternating current.

Nowadays, the widespread use of electronic devices has led to questions regarding the usefulness of generalized AC electrification. Most electronic devices require DC supply, which has to be generated from the AC mains through an internal rectifier. Taking a closer look at production facilities, it reveals that many electronic devices, such as converters, inverters, and other consumers, are coupled to the AC mains via rectifiers, taking up space and reducing the efficiency of the devices [1]. In addition, the energy transition with its DC-based generators and storage systems necessitate a reassessment. In this context, system structures based on centralized rectification of AC mains voltage and bidirectional connection of all DC-based consumers and generators via this grid branch have been established in various research projects and are already being used in the first industrial and domestic test networks.

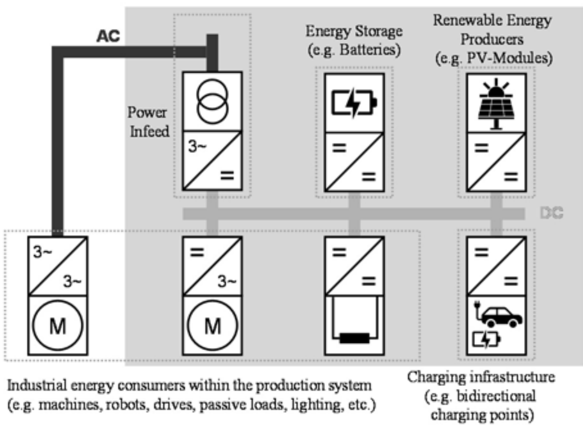

Figure 1: Industrial hybrid AC/DC grid with exemplary generic grid participants.

An exemplary hybrid AC/DC grid with industrial consumers, storage technologies, renewable energy sources and the connection to an electric vehicle charging infrastructure on the DC sector is shown in Figure 1.

The largest previous project works in Germany are DC-Industrie 1 and its follow-up project DC-Industrie 2, which deal with the design of industrial DC grids [2, 3]. The Open Direct Current Alliance (ODCA) of the ZVEI was in turn founded to be the general follow-up research alliance for DC grids [4].

Participating project partners are involved, for example, in the development of power electronic components, switching and protection components as well as the associated standardization in international standards and guidelines. Numerous other research projects like DC-Schutzorgane, DC-Smart or SiC4DC have resulted in a wide range of studies that investigate suitable protection concepts or the use of wide-bandgap semiconductors in power converters, the interaction of grid components and the potential for integration of regenerative energy use and storage or recuperative energy use [5, 6].

For this hybrid AC/DC grid structure, the first quasi-standards and prototypes were developed in the projects, but the general knowledge of economical, ecological and safe planning is still limited to a few experts who are involved in such research projects.

For this reason, there are few people who are able to design such grids correctly so that the systems can be put into operation safely. [4, 7, 8]

This publication presents a concept on the cross-sector integration of research content, new prototypes and proposed standards. Furthermore, it outlines how these areas can be profitably integrated into a simulation environment to facilitate the safe and economic planning and construction of hybrid grid structures promoting distribution of scientific and economic knowledge.

The presented planning concept is based on a modeling approach to efficiently assemble these hybrid grids within a simulation environment and to analyze them based on an electrical simulation for safety-related factors, network stability and load flow behavior.

On the other hand, connecting the electrical grid analysis to simulation tools commonly used in the field of production planning are made possible. This will allow process-specific properties to be incorporated into the planning and analysis of the electrical network.

1 Goals and Purposes of DC Grid Design

Software-based solutions for electrical system planning have great potential in terms of analyzing and optimizing systems for efficiency, economy, safety, and system stability. This chapter provides an overview of the goals and purposes that are relevant for the planning of industrial DC grids.

1.1 Economic Planning

First, knowledge about the grid participants or prosumers must be available so that the electrical energy demand of the grid connection and the technologies for generation plants and storage can be selected and dimensioned appropriately. A simulation of the power demand of the grid shows the utilization of the planned energy converters, the coverage of energy by generators and helps with optimally dimensioning storage devices in terms of charging and discharging power as well as capacity [9]. Coupled with acquisition and operating costs, the simulation data can be used to carry out a profitability analysis, which is often indispensable for the investment decision in the new technology [10].

This results in requirements for planning on an energy-related design and the return and understandable preparation of economic KPIs for the implementation of investment decisions.

1.2 Planning of the protection concept

Personal safety and object protection are essential requirements for electrical installations. In standardization, the aspects basic protection, fault protection and extended protection are concepts that must be considered in a protection concept. This includes protection against electric shock, overcurrent protection of equipment and transmission units as well as the mitigation of fire hazards, e.g. due to insulation faults [11]. Depending on the type of network and the associated earthing concept, different components are necessary to form a reliable protection concept [12]. If, in addition, the aim is to achieve the highest possible system availability with selective protective devices, the design of DC networks with sensitive electronics, storage units and comparably high grid voltages and associated arcing risk is particularly complicated due to the lack of voltage and current zero crossings [7, 13, 14].

For power distributions in the AC voltage range, the planning experience is available and software-based design has been established for a long time (e.g. Simaris Design, Curve Select, Hager CAD etc.). In DC based systems, software solutions and simulations to check the selection and combination of switching and protective devices are lacking.

For modeling, protection device tripping characteristics as well as essential data sheet parameters and electrical properties in the components are required. If these are not provided by the manufacturer, empirical values should be available. Warnings and error messages should be issued if the planning does not comply with the rules.

1.3 Verification of the System Stability

After all grid participants, energy converters, the power system and the switching and protection devices have been suitably selected, there is still the risk of instability of the system. For this, detailed information about the dynamic behavior and parameters such as the current control of the power electronic components as well as the line lengths and resistances, capacitances and inductances are relevant. This detailed information is often unknown to planners and is frequently only provided in anonymized models. The mathematical calculations regarding the overall system resonances and stability criteria are so elaborate and complex and therefore error-prone that simulations validated in practice are the only practical solution.

The requirements for the simulations are, in particular, very detailed models of the power electronics with uniform interfaces, which can be integrated in a combined manner as far as possible with regard to know-how protection for manufacturers. The simulation must cover high dynamics in the time and frequency range.

1.4 Measurement and Automation Technology

Every automated production cell requires at least one supervisory control system, typically a PLC. In addition to process control, it's necessary to manage grid functions such as preloading, switching connection of grid branches, and partially coordinating functional safety according to IEC 61508 [15] and ISO 13849 [16]. In addition, there are measurement functions related to power supply and energy storage systems, as well as monitoring of the grid condition. Especially in complex energy grids with generators and storage systems, it is advantageous to use these control modules to control the connected power electronics and to coordinate the converters with each other. In this way, functionalities such as price-based control of electricity can be integrated.

For software-based grid planning, it is therefore important to consider these control functions and communication interfaces to individual functional components such as switching and protection devices, functional safety, and the energy management.

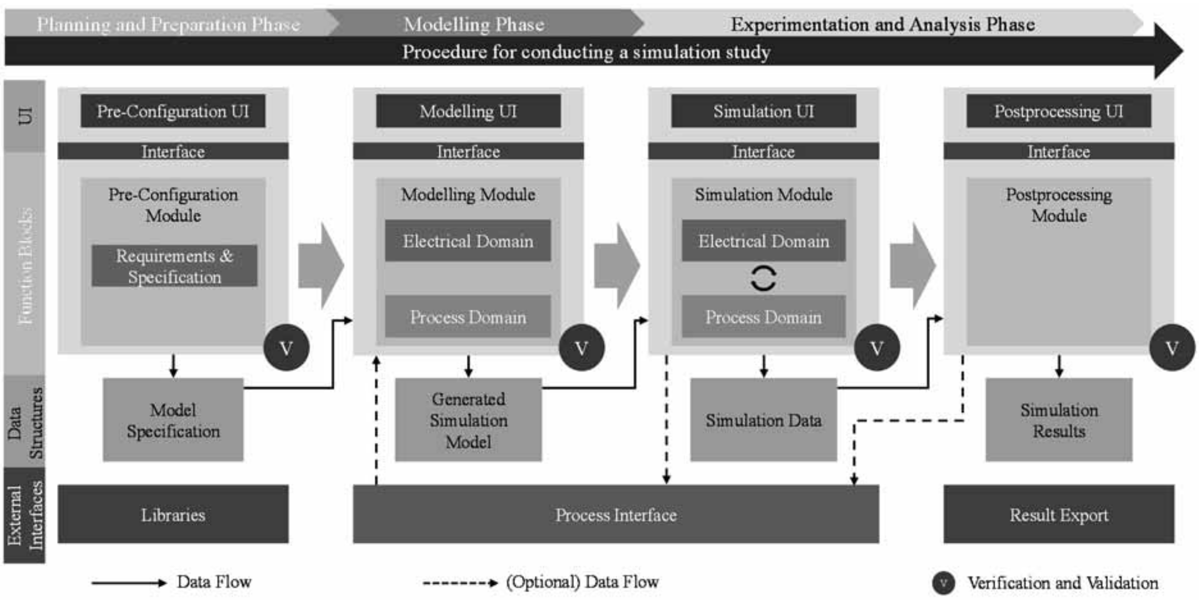

Figure 2: Software Architecture for Simulation-based Planning of hybrid AC/DC Grids.

2 Software Architecture for Simulation-based Planning of Hybrid AC/DC Grids

According to the requirements of the previous chapter, a concept for a simulation-based software for planning hybrid AC/DC grids has been developed. The concept of the planning software is based on an intuitive and user-friendly operation that guides the user step-by-step through the use of the simulation study and is oriented towards the use of common E-CAD tools. The resulting software architecture is shown in Figure 2.

This software should enable the user without the need for simulation skills to optimize these networks with regard to their load flow behavior, to design components sensibly and safely and to carry out analyses with regard to network stability and fault cases.

The software architecture is based on three core concepts: a modular software structure, the chronological execution of a simulation study according to VDI 3633 [17], and the domain coupling from the electrical domain of the electrical grid, as well as the process domain of the production system, which specifies the electrical load and allows production-dependent factors to flow into the analysis.

The modularity of the software architecture is based vertically in the division into a graphical user interface (GUI), function-specific modules, and defined data structures for data exchange. Furthermore, external interfaces form the connection to various model libraries and simulation tools as well as to the data exchange of the simulation results.

The horizontal arrangement of the architecture describes and arranges the functionality of the different modules according to the temporal procedure of a simulation study according to VDI 3633.

The mentioned standard describes the procedure of a simulation study, beginning with a description of the objective and task definition. Based on this, the system analysis, model formalization and implementation follow for the model creation, as well as the aspects of data acquisition and processing in parallel.

Finally, the created simulation model is used to generate added value through the execution of experiments and analysis. Additionally, every aspect of this process is subject to verification and validation activities [17].

Based on this, the proposed simulation tool supports the user in conducting the simulation studies of AC/DC grids in the sections of modeling, simulation, experiments and analysis without the need for an in-depth understanding of simulation and analysis methods. The functional structure of the tool is therefore divided into the modules pre-configuration, modeling, simulation and post-processing which are described in more detail in the following chapters. The tool guides the user through these functions chronologically, picking up the results of the previous function block in each case.

The last core aspect is the coupling of the process domain of the factory with the domain of the energy grid. Energy-related simulation of production systems has become increasingly important in today's world due to the rising significance of energy costs and the CO_2 footprint. It is used for various purposes such as forecasting energy behavior, load-shifting, optimizing energy consumption and energy costs, as well as designing and dimensioning of the energy infrastructure in production systems [18].

In order for realistic and production-related power curves of the individual grid participants within the factory to flow into the analysis of the electrical grid, it is essential to connect and model the energetic behavior of the factory’s resources and processes.

In addition to analyses of the hybrid network, this will also allow energy optimization to be derived in the future with regards to the use of stored recuperation energy, process-oriented energy management as well as the influence of energy storage systems on the process. The coupling strategy is described in more detail in chapter 3.

2.1 Pre-Configuration Module

The use of the simulation tool begins with the pre-configuration phase. Within this module, basic settings are made with regard to the libraries and interfaces used. In the technical sense, basic, unchangeable model properties are set.

Considering common design approaches in Systems Engineering, such as the V-Model or the Quality-Gate Model, requirements and specifications are defined [19]. These properties are stored within the model specification and can be reused in the following modeling module.

2.2 Modeling Module

With the help of the modeling module, the user is able to intuitively design the electrical network in a similar manner to established E-CAD tools.

By using model libraries, no detailed modeling of the electrical components is required by the user, only parameterization. This allows the network to be put together in a plug-and-play manner. The processes at the production level, which as prosumers provide the electrical loads or sources of the network, can also be modeled or coupled to external applications in this module and linked to the network. A detailed description of the modeling of the electrical components as well as the process participants and prosumers within the factory is given in Chapter 3. As a result, the modeling module generates an executable simulation model which is continued in the following simulation module.

2.3 Simulation Module

The Simulation Module is used to run the created simulation models and to define simulation experiments. Basic simulation settings, such as the simulation duration to be carried out and simulation time increments, can be set. Furthermore, basic simulation parameters for the experiments such as the possible dimensioning parameters of an energy storage can be selected and parameterized.

The module provides the raw simulation data as results, which can be analyzed in more detail in the following Post-Processing module. The raw simulation data are primarily the generated current, voltage and power curves of the various network components over time. In the case of the desired stability analysis, the corresponding impedance curves in the frequency range are also transferred.

2.4 Post-Processing Module

The last module analyses the generated raw simulation data in post-processing. The data is analyzed, statistically processed and visualized here to provide the user with a simple, intuitive and provable statement about the simulation results. Depending on the different types of analyses, load flow analysis, fault analysis and stability analysis, appropriate visualization and evaluation forms are selected automatically.

In addition to the fully automated calculation and identification of KPIs and potential patterns in simulation data through established data mining approaches, intuitive visual representations of the processed result data utilize the existing human ability to recognize patterns in visualizations, allowing semi-automatic evaluation and thus supporting the planning process [20].

The most important key figures for decision-making in relation to the design of the components, the security and the profitability of the network should be handed over to the planner through the preparation and the suitable visualization of the simulation results in KPIs.

2.5 Verification and Validation

Verification and validation (V&V) are integral parts of the simulation study process, as per the VDI3633 model. They are not one-time actions but consistently accompany the entire simulation process [17, 21].

Therefore, in each module of the presented architecture V&V is addressed explicitly. It should be noted that V&V also needs to be implicitly considered, for example, when integrating external simulations through the Process Interface (see Chapter 4).

Verification ensures the correct implementation of the conceptual model into the executable simulation models. Validation, on the other hand, guarantees that the model accurately describes the system behavior for the corresponding use case [22]. Various methods for the verification and validation of simulation components are described in [22–24].

The architecture presented verifies and validates the partial results of each module for functionality and compliance with the specified requirements. Automation of these procedures is pursued to relieve the network planner of this task, ensuring a time-efficient and reliable planning process.

3 Modeling and Simulation Concept

3.1 Electrical Simulation of the DC Grid

Pre-Configuration and Modeling Module: Input and Model Generation

The electrical grid of the production plant is modeled and simulated separately from the production process. General system characteristics such as grounding type and grid voltage schemes are set using the interface of the pre-configuration module as previously explained. The grid topology, components, grounding points, as well as electrical parameters are entered into the program using the graphic user interface of the modeling module.

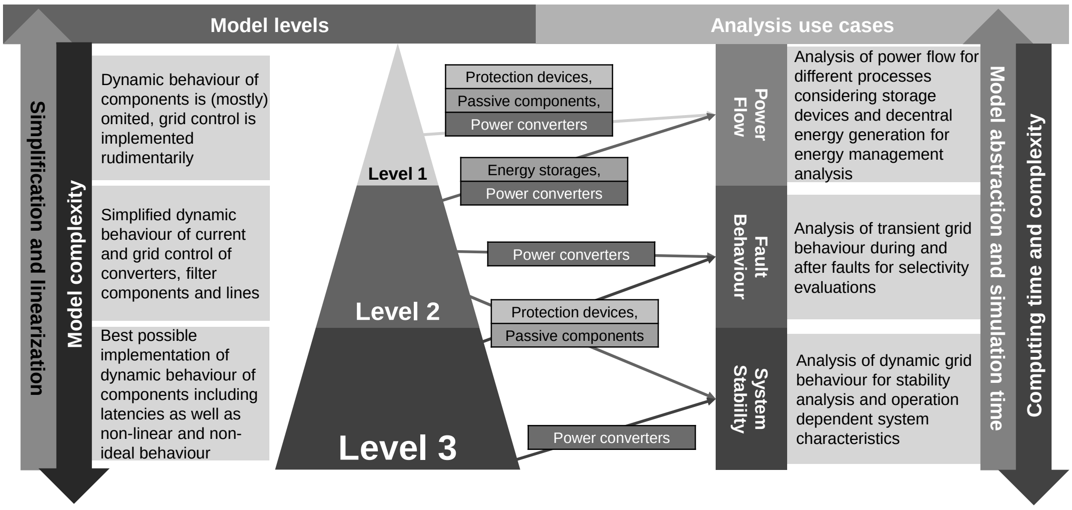

Figure 3: Level Concept for Modelling Grid Components.

Since the computing time of the simulation increases with the size and complexity of the models, different analysis use cases are introduced [25]. For each use case a grid model is generated which uses models with differing level of complexity for the same component. As a result, power flow and energy management simulations with no dynamics but long simulation times do not require as much computation time as using the most complex models for system stability analysis.

Simulation Levels and Use-cases

Three analysis use cases are introduced to keep computing time as low as possible. The use cases employ models of different complexity levels. A summary of the use cases and their respective characteristics is shown in Figure 3. The complexity level models utilized in the grid models of the individual use cases are based on the respective component functionality group: power converters, passive components, and protection devices.

The analysis use cases, and the level models are grouped as follows:

Use case 1 - Power flow and energy management evaluation:

Level 1 component models for protection devices, passive components such as lines and filters, and power converters are used. If large energy storages are directly connected to the grid, or low dynamics are observed in power converters, their level 2 models need to be included into power/energy management simulations.

Use case 2 - Fault behavior and selectivity evaluation:
Level 3 models with non-linear and non-ideal behavior are used for protection devices and passive components. The level of power converter models used depends on whether the control actively regulates faults. If the power converters impact on the fault behavior is negligible simplified level 2 models can be used, if not level 3 models must be chosen.

Use case 3 - System stability and dynamic response evaluation:

Power converters are modeled using non-linear complex level 3 models while passive components and protection devices are modeled using level 2 models as long as there is no impactful operating point dependent change of impedance.

Simulation Module Output: Data Structure Simulation Output

In the simulation module the models are parametrized for the different analysis cases. Furthermore, complex simulations for fault behavior and system stability analysis require data from the respectively less complex simulations. This data is used to set initial conditions for the simulation that define the operating point of the individual grid components. Therefore, the simulations for the use case models must be carried out in a certain order: from least to most complex. These parametrized models are then simulated.

The raw output data includes the voltages and currents of all grid nodes for the different parameter sets and use cases.

This large amount of raw data is the basis of the evaluations carried out in the post-processing module mentioned in the previous chapter.

3.2 Usage of Metadata

The utilization of metadata to provide additional descriptions of grid components is a central aspect of grid planning, especially in the areas of modeling and post-processing, but also in the subsequent project phases of grid planning. Metadata offers supplementary information about the components and facilitates clear assignment between the component in the simulationmodel and the future physical device. The planning process results in a Bill of Material for the energy grid due to the direct connection between the model and the physical component. Additionally, metadata provides further information about the component, such as its type, operating location, manufacturer specifications, and price information, allowing for extended post-processing considerations. Advanced analyses, such as considering the operating location and the associated sizing of control cabinets and their cooling units, are thus possible. In the future, it may be possible to analyze material savings by incorporating metadata about space requirements, weight, and materials used.

The process of selecting and modeling descriptive metadata for an asset depends significantly on its future application to ensure high-quality usage [26]. To consider current use cases in the electrical industry, well-established standards within this industry, such as e.g. the ECLASS Standard, and emerging sub-models of the Asset Administration Shell are employed.

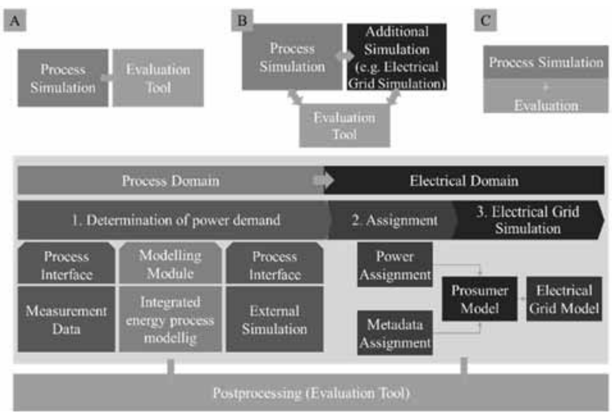

Figure 4: Coupling Paradigms for Simulation of energy flows in Production Systems, adapted from [27] (Top) and Coupling of Process and Electrical Domain (Bottom).

3.3 Coupling and Modeling of the Process Domain

In the realm of energy-related simulation of production systems, coupling is often described in the literature using three paradigms, illustrated in Figure 4 (top):

A) Modeling and simulating the production system in an application for process simulation (e.g., Plant Simulation). The consideration of energy influences of the process takes place in a separate evaluation tool.
B) Coupling different simulation domains e.g. through co-simulation to consider dynamic properties of energy flows. Optionally, an evaluation tool can be included.
C) Monolithic integration of energetic influences into the simulation application of the process domain. [27]

The presented work involves an adaptation of simulation paradigm B. In the process simulation, various methods enable the modeling of energy behavior. These are coupled in a unidirectional linkage to the simulation of the energy grid. The coupling concept presented between the process domain and the energy domain is shown in Figure 4 (bottom).

In the first step, the energy behavior of individual components within the process domain is determined. This includes evaluating the energy consumption of industrial consumers and the energy generation from sources such as renewable energy, like PV systems. In [28] various approaches to categorize modeling methods for the energy behavior of production systems are presented. The energy behavior of production systems can span all hierarchical levels, from individual components and machines to a network of factories.

When modeling the energy network and its respective components, it is crucial to choose an appropriate hierarchical level to accurately capture the energy behavior for the corresponding use case and energy grid analysis. In this case, the modeling of the energy behavior of the process domain can occur in three different ways:

1. Connection of measurement data
2. Linking of external applications or simulations as a Co-simulation
3. Integrated energy process modeling within the tool.

In the second step, the determined power curve is transferred to a prosumer model together with relevant metadata about the corresponding component.

The information about the energy behavior of the components, as well as the metadata, is used in the third step for simulation and the subsequent evaluation in the post-processing module.

Measurement Data

The simplest option is to connect measurement data via the standardized Process Interface in the presented software architecture. Table-based time series of the performance curve can be assigned to various prosumers in the electrical network. This means that the connection and analysis of existing production systems and their behavior can be mapped in the tool without the need of complex simulation of the process. Through this connection, the user is empowered to analyze the electrical DC grid through the load behavior of existing plants in the brownfield.

Usage of External Applications or Process Simulation Tools

Furthermore, it is possible to connect external applications and simulation tools such as material flow simulation software like Plant Simulation or other common tools for virtual commissioning of machines and plants (e.g. NX MCD, ISG virtuos, iPhysics) via the presented Process Interface. In this way, existing simulations in the greenfield can be used to analyze the influence of the electrical network in addition to the analysis of the process behavior. This variant has the greatest effort in regard to the design of the electrical grid, as the process behavior of the factory must first be modeled and, based on this, the electrical behavior model for characterizing the load flow must also be created. Although this approach presents a challenge due to the increased resources and effort required for model creation, which is often seen as a barrier to the industrial adoption of simulations for virtual commissioning [29], it enables more sophisticated analyses for energetic process optimization.

Furthermore, a standardized interface enables the integration of other tools, such as the forecasting tool presented in [30] for predicting the energy produced by PV modules.

Integrated energy process modeling

Lastly, the third variant, which creates a compromise between the two previous methods in terms of detailing and effort, is the integrated modeling of the power curves of the process components. The load behavior of the components can be modeled by the user within the modeling module. Common and proven methods that describe the energetic behavior of the components at different levels of detail and levels within the factory are considered here.

These include procedures and modeling methods similar to the EnergyBlocks method according to [31], state-based procedures as in [32] and physical and analytical modeling procedures as in [33], to further model dynamic components like electric drives.

4 Discussion and Conclusion

This paper describes the advantages of DC grids in production environments and the resulting requirements for the design process of these grids. In order to simplify planning, the paper presents a basic concept for grid design and planning with consideration of connected process participants within a factory by using simulations. The user does not need to have in-depth knowledge of modeling, simulation, grid analysis or statistics. The simulation of the electrical network is based on a use case dependent approach to create a compromise between computing time and detail. Through the connection of external simulation tools, measurement data and the simple modeling of the power curves of the process participants, the electrical network can be planned, analyzed and designed in every life cycle of an existing or planned factory. In future publications, the individual modules, the modeling concepts and the validation by means of a hardware demonstrator currently under construction will be dealt with in more detail.

Acknowledgement

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Ensuring Supply for Emergency Services – Modeling Supply Chains with Incomplete Sets of Data

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Abstract. Supply chain simulation could be used to identify the risk of bottlenecks due to disruptions in global supply chains and to improve the availability of products and materials for emergency services. However, these stakeholders do not have the capabilities and in-house know-how about their supply chains required for reliable simulation results. To overcome this issue, this manuscript provides a method to enable the modeling of supply chains without a comprehensive knowledge of all process parameters and nodes. It consists of generic data containers, each representing typical nodes within a supply chain with plausible generic process parameters, boundaries, and distributed values. We present the conceptual feasibility of the approach through a case study and demonstrate the methodology for modeling a supply chain for detailed bottleneck analysis and automated risk assessment of a public health and safety supply chain.

Introduction

Societies around the world have been confronted with numerous challenges during the last years, which have been further intensified in the context of recent crises like the COVID-19 pandemic and the Ukraine war. These crises occurred in rapid succession and across several economic areas.

Manufacturing companies and wholesalers in particular were faced with the challenge of maintaining their globally interconnected supply chains. With highly dynamic demand and interrupted productions, process variables such as transportation times and costs were also greatly affected [10]. This did not only have consequences for the manufacturing industry. Additionally, sectors that previously deemed supply chains as secondary, such as public health, safety services, and healthcare, were also impacted by these disruptions. In addition to drugs [4], shortages were reported for numerous products necessary for patient care or the protection of personnel [13]. Thus, in addition to the prevailing shortage of personnel, the limited availability of supplies, consumables, and drugs also jeopardized the security of supply in critical infrastructures. The need for resilient supply chains and the possibility of identifying impending supply bottlenecks at an early stage were thus impressively illustrated.

An established method for analyzing the impact of disruptions on supply chains is supply chain simulation. It allows the impact of disruptions on the entire supply chain to be examined on a scenario basis and bottlenecks to be identified [12]. Cope et al. (2007) and Hermes (2011) describe different methods using model building blocks to facilitate supply chain modeling and the transfer of models into a simulation environment [6, 11].

Supply chain simulations are primarily used by manufacturing companies, which have in-depth knowledge about their supply chain - even beyond 1st-tier suppliers [17]. When this information is accessible, it enables the meaningful and reliable analysis of processes [2].

However, in the sectors of public health and safety services, such information is often unavailable due to the procurement practices involving wholesalers. To facilitate the use of supply chain simulation within public health and safety services, it is imperative to address the challenge of incomplete supply chain data.

1 Related Work

The issue of incomplete data is recognized in the literature as a topic relevant to practice and has been addressed through scientific research [9]. The emphasis is placed on methodologies designed to handle missing quantitative data, as discussed in [20]. Oliver et al. (2022) address this issue with a modeling study of national supply chains in the United States in the context of natural disasters [18]. They use stochastic methods to describe key parameters such as order quantities and transportation times at an aggregated product class level (e.g., "package meal").

To conduct a supply chain simulation, it is essential to model both quantitative and qualitative data. This paper presents a methodology that supports filling data gaps and enables the application of supply chain simulation.

2 Case Study

Within the context of this use case, we consider the supply chain of an emergency medical service for two essential products: syringes and the medical ingredient Acetylsalicylic Acid (ASA). This scenario involves a multi-stage supply chain, as depicted in Figure 1. This supply chain model acknowledges the potential risks associated with overseas shipments between producers and wholesalers, a factor that is critical to the reliability and efficiency of emergency medical services [15].

The emergency service's demand for syringes and ASA is met by a wholesaler, who procures syringes from two different producers. These producers, in turn, are supplied with necessary raw materials by a variety of suppliers. On the other hand, ASA is sourced from a single producer, which similarly depends on several suppliers for its raw materials. This structure highlights the complexity and interconnected nature of supply chains in the healthcare sector, emphasizing the importance of robust and risk-aware supply chain management.

3 Methodology

Each relevant object of a supply chain is represented by a node in the simulation model. Each node is characterized by its type – such as a producer, transport route, or warehouse – and its corresponding process parameters, which might include transport time or warehouse capacity. By specifying successor nodes, these individual nodes are interconnected to form a network that represents the specific structure of the supply chain.

This results in certain information requirements that are necessary for producing meaningful outcomes of the simulation. Although the overall structure of the supply chain can be examined at an abstract level with relative ease, acquiring detailed process parameters for the individual nodes is either impossible or requires significant effort. For example, it can be assumed that the active ingredient ASA is produced in Asia and shipped to Europe, where it is further distributed through road transportation [15]. However, product-specific transport times, production capacities, or suppliers are usually unknown.

To address the challenge of incomplete data, a strategy of modularized abstraction for sub-processes is adopted. This approach involves generalizing processes, such as transportation from the country of manufacture to the country of consumption, to a higher, generic level. These generalized processes are then described in broad terms within a "data container," allowing for a more flexible and adaptable simulation framework that can accommodate the gaps in specific data points. The description is based on publicly available data sources, expert estimates within the domain, and analogous cases. The resulting process parameters of the simulation nodes are finally made available as data containers. For instance, there may be a data container for shipping from Southeast Asia to Europe that contains common transportation times and capacities. A supply chain under investigation can thus be modeled and simulated within a modular framework, utilizing both existing real data and generic data containers. The assumptions embedded within these data containers can be revised or substituted with more appropriate data containers at any point, ensuring the model's adaptability and accuracy.

To evaluate the resilience of the supply chain against disruptions, the process parameters are enhanced with plausibility limits, including minimum and maximum values, alongside a distribution, in addition to the default values.

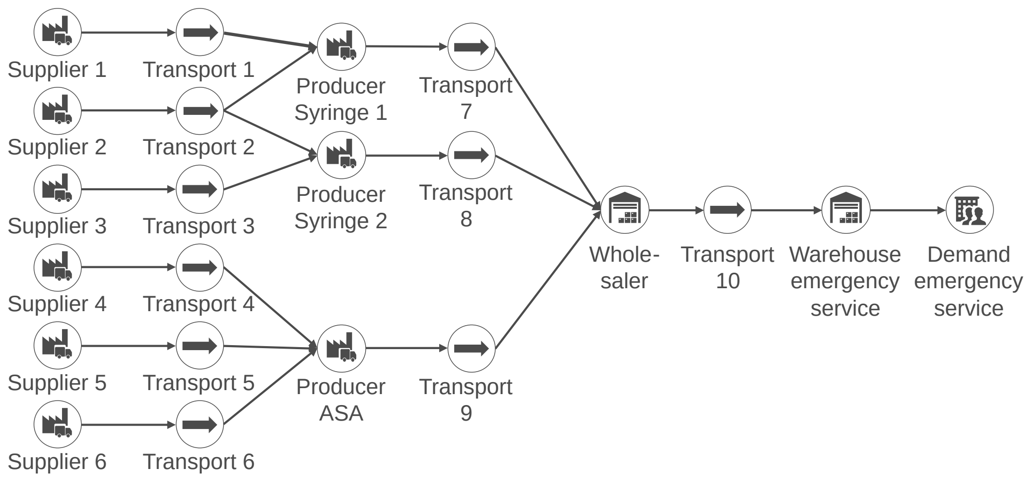

Figure 1: Simplified sample supply chain for an essential device (syringes) and a medical ingredient (ASA) for an emergency medical service.

Using this data, the supply chain can be simulated manually or automatically with different configurations in order to examine the effects on the entire supply chain. During an acute crisis, the simulation can be adjusted to reflect disruptions, allowing for an investigation of their effects on the resilience of supply and to assess potential mitigation strategies and their effectiveness.

4 Results and Discussion

The case study serves as an illustration to demonstrate the methodology for developing generic data containers to facilitate the modeling of a supply chain. Additionally, it simulates and evaluates the impact of disruptions on supply-related metrics, thus demonstrating and confirming the methodology's applicability.

This approach underscores the importance of a resilient supply chain structure in enhancing the robustness against potential disruptions, and - in consequence - leading to a more consistent and reliable supply chain performance.

4.1 Introducing Generic Data Containers for Supply Chains

The development of data containers is exemplified through the use case of the medical active ingredient ASA.

It is chosen from a comprehensive inventory of 569 products, including 68 medical active ingredients, provided by an emergency medical service in Germany. This methodology is similarly applicable to describing the process parameters for consumable material.

ASA is a widely used active ingredient in preclinical emergency medicine, adhering to current guidelines for its anti-inflammatory, analgesic, and antipyretic effects, in particular in the prevention of heart attacks, ischemic strokes, and blood clots [1, 14]. The active ingredient is no longer patented. This results in its availability under various brands such as Ascriptin, Aspergum, and Aspirin. In Germany, only the commercial product 'Aspirin i.V. 500 mg' from the manufacturer Bayer Vital AG is approved for intravenous use. The Federal Institute for Drugs and Medical Devices (BfArM) reported a persistent shortage of this specific product throughout 2023 [3]. To mitigate this, the importation of Aspégic, which is an alternative product available in France, was permitted under §73 AMG. Although the shortage was resolved at the beginning of 2024, this highlights the vulnerability associated with reliance on single manufacturers.

First, the locations of production sites are approximated using the addresses of the holders of the Certificates of Suitability (CEP) issued by the European Pharmacopoeia [7]. A valid certificate is a critical element in the approval procedures for pharmaceuticals within the European Economic Area [8].

Specifically for the active ingredient acetylsalicylic acid, four valid certificates authorize its marketing in the European Economic Area. The holders of these certificates, located in La Felguera (Spain), Zibo (PR China), Tanuku (India), and Ecully (France), are highlighted with square markers in Figure 2, indicating their potential roles as production sites for suppliers of the active ingredient *ASA*.

Second, a distance matrix was employed to calculate the times needed. For road transport routes originating from the production site in La Felguera (ES) and Ecully (FR), the calculations were based on driving and rest times according to German legislation assuming an average of six daily driving periods of nine hours each. This model does not account for special circumstances such as occasional extensions of driving times or reductions in rest periods over weekends. For sea transport, transportation times were estimated for shipments in less-than-container (LCL) mode from the ports closest to the production sites in Zibo (CN) and Mumbai (IN).

The effort to approximate the production characteristics for syringes is fraught with uncertainties compared to pharmaceuticals. While the marketing of pharmaceuticals is regulated at the European level, allowing for possible production sites to be identified through publicly available databases, syringe bodies, as medical devices, are governed by national regulations.

BfArM oversees marketing authorization for medical devices and offers a national database (DMIDS), which is subject to a fee, for searching manufacturers of medical devices [5]. In addition, in a hypothetical crisis scenario, the production of plunger syringes, as defined by the DIN EN ISO standard 7886-1 and using polyolefin granules, could be undertaken by numerous manufacturers equipped with the necessary molding technology, scale printing, and thermoforming along with the means for subsequent sterilization.

To generate a global view of production sites for syringes, data "Healthcare" and "Chemicals" sectors published by the Open Supply Hub initiative were used[19]. This led to the hypothesis that syringe manufacturing could be predominantly situated in Bangladesh, the USA, or Eastern China. The data sources used for node parameterization are detailed in the Additional Materials section.

4.2 Simulation Results

To validate the data containers, that were previously developed, the simulation tool OTD NETWORK ("Order-To-Delivery-Network") was used. OTD NETWORK, which was developed by Fraunhofer IML, is a discrete-event simulation environment designed for modeling, simulation, and analysis of supply chains. Its abstract, object-oriented architecture allows for versatile applications across various industries and a wide range of specific issues [16].

The simplified supply chain, as shown in Figure 1, was modeled. This model includes a scenario where the sea route between the ASA producer and the wholesaler (identified as Transport 9) experienced a disruption. The simulation also integrated data that the emergency medical service has from its supply agreements with the wholesaler. The inventory management for both the wholesaler and the emergency medical service was designed around the minimum stock levels and the range of stock specified in these contracts, in addition to the standard procurement times. Figure 3 presents a selection of the simplified supply chain model, how it was parameterized, and an indication of the sources of the data used.

Various simulation trials were conducted with different parameter settings using this supply chain model. The disruption led to significant delays in sea shipments from the ASA producer to the wholesaler serving the medical service, causing a critical bottleneck. This issue is depicted in the left section of Figure 4. As a result of these delays, the ASA inventory at the wholesaler progressively decreases, eventually dropping below the agreed-upon minimum stock level and depleting entirely for ten days. Subsequently, the emergency medical service's warehouse, which maintains a smaller reserve stock, also experiences a stock out, lasting for two days, albeit with a slight delay.

This predictive analysis enables the initiation of measures to enhance resilience in advance. For instance, identifying alternative suppliers could facilitate immediate replacement shipments to bridge the bottleneck. The inventory projection depicted in the right section of Figure 4 shows that the bottleneck could be circumvented by engaging an alternative ASA supplier based in France.

Additionally, it is possible to use a scenario-based variation of the parameters (e.g. duration of disruption) to investigate the inventory strategy's limits and facilitate adjustments to the inventory parameters as needed.

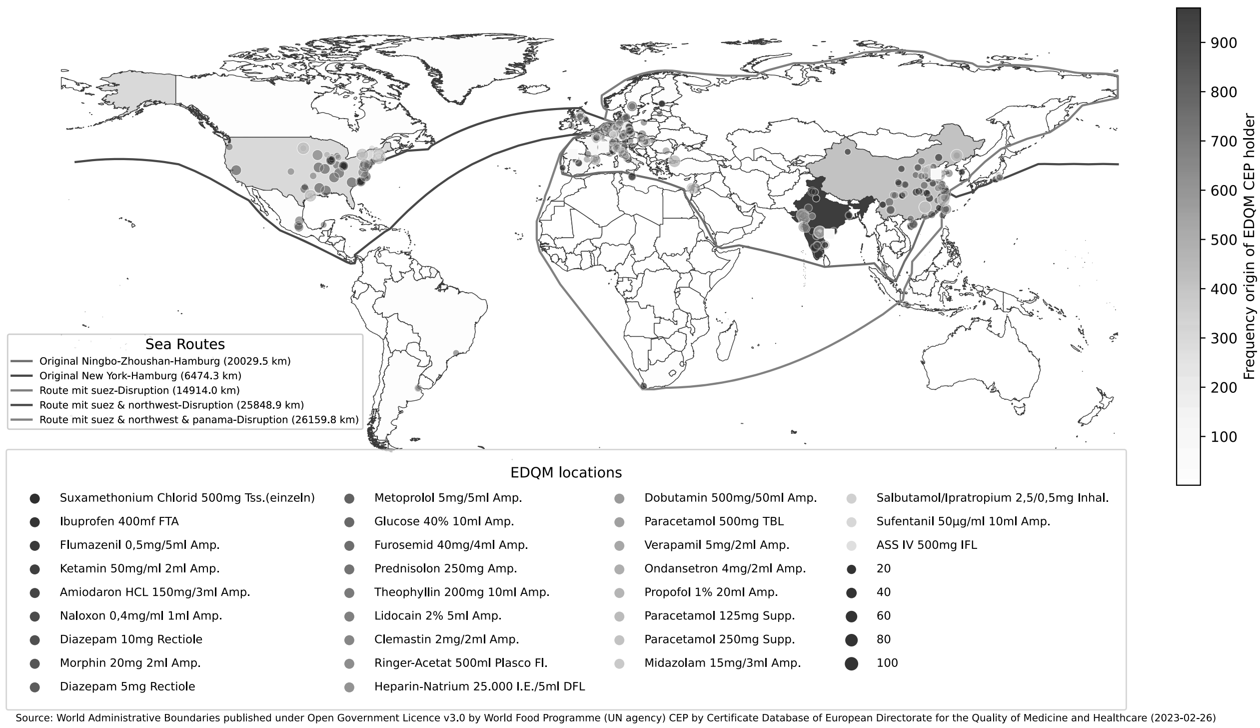

Figure 2: The Distribution of certificate holders, serving as a proxy for production sites of each active ingredient within the product portfolio, is visualized through a cumulative sum for each country. The size of each scatter point corresponds to the number of Certificate of Suitability(CEP) holders. Additionally, approximated sea routes are mapped out, highlighting potential bottlenecks from New York (USA) and Ningbo-Zhoushan (PRC) to Hamburg (GER), providing a geographical context to the supply chain's vulnerability. Data: [7]

Trends in inventory levels, influenced by varying durations of transportation delays, can be explored in the Additional Materials section.

The simulation results for the different scenarios outlined above align with the anticipated behavior of the supply chain, considering the established minimum stock level. The previously developed data containers have successfully facilitated the incorporation of detailed supply chain information, which is typically not a feature enabled for emergency services, into the model. This integration has enabled a credible inventory forecast and bottleneck analysis, demonstrating the practical utility of the data containers in enhancing supply chain modeling and analysis.

4.3 Transfer to Application

The service for evaluating supply security (EvaVe), developed within the scope of the ResKriVer research project, exemplifies how data containers can be applied to applications (Figure 5).

This service is designed to assess the impact of disruptions on supply chains. If bottlenecks occur, it presents crucial key performance indicators on a dashboard. Moreover, it employs artificial intelligence to recommend parameter adjustments to users, aiming to prevent or mitigate the anticipated bottleneck scenarios. This approach enhances decision-making by providing actionable insights based on simulated supply chain dynamics.

On the left-hand side of the dashboard, the service displays analyzed supply chain events, in particular disruptions, along with their consequences and effects. It also shows the simulation period and the various nodes within the supply chain. At the top of the dashboard, a visualization of the inventory trend for the analyzed product is provided. This section also provides a summary of delivery reliability and features a traffic light system to quickly indicate the presence of any bottlenecks. The lower part of the dashboard is dedicated to showcasing solutions proposed by AI.

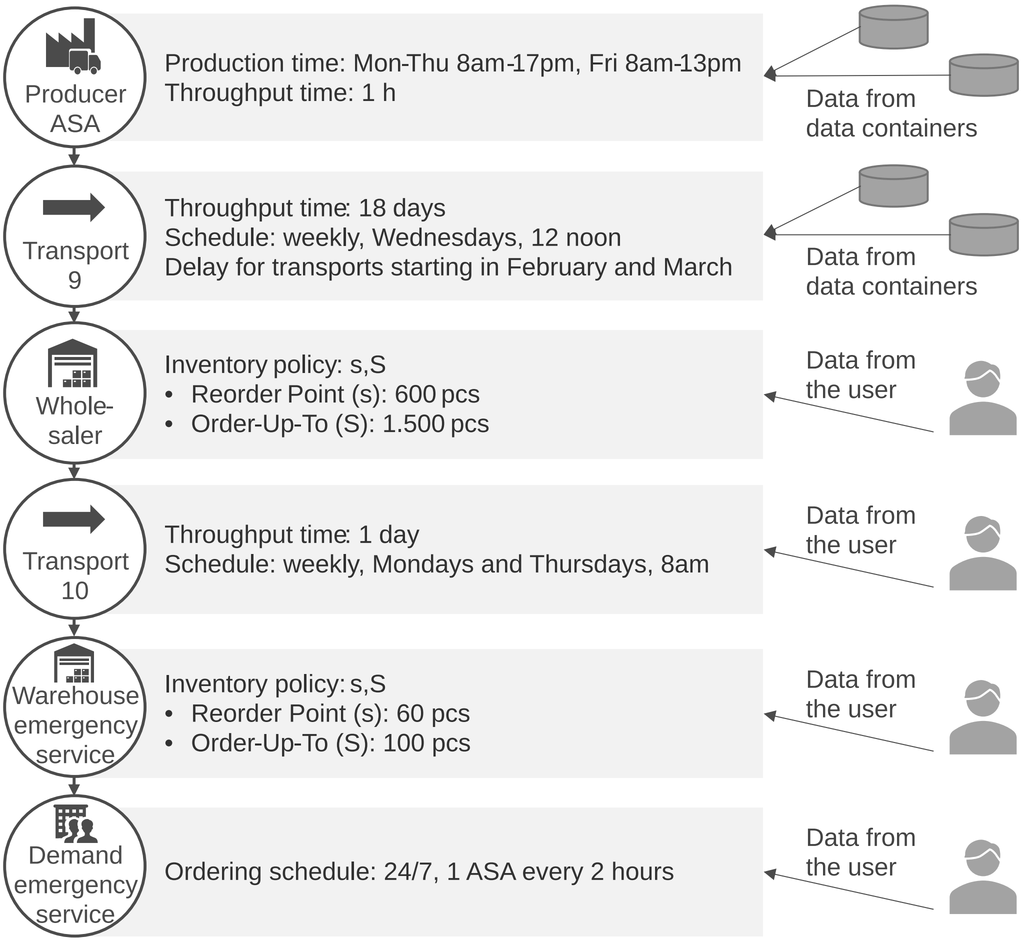

Figure 3: Selection of process parameters.

For each suggested solution, a forecast of the inventory trend and a summary of delivery reliability are presented, offering a comprehensive view of potential outcomes following the implementation of these solutions. This service exemplifies simulation-based services that require comprehensive data for effective utilization, a need that the data container methodology adeptly supports.

4.4 Limitations

The quality of simulation outcomes generated by OTD NETWORK is significantly influenced by the precision of the model parameterization. This intrinsic limitation underscores the necessity for careful evaluation and validation of simulation results, especially those derived from data containers, which are a composite of numerous assumptions and generalizations.

Thus, at the cost of precision, information gaps are closed with approximations. Plausibility cannot be guaranteed without the involvement of domain experts.

In addition, creating data containers demands considerable research effort and, often, extensive domain expertise, presenting a balance between generalization and specificity. While data containers need to be detailed enough to yield relevant results, they must also maintain a level of generality to be applicable across various scenarios and usecases.

Simulations offer the flexibility to vary parameters, enabling the investigation of various scenarios. Due to the emergent nature of complex systems, structural changes in the model may affect all nodes and edges. It is therefore advisable to integrate alternative paths already in the modeling stage in close coordination with domain experts and to characterize them with additional data containers if necessary.

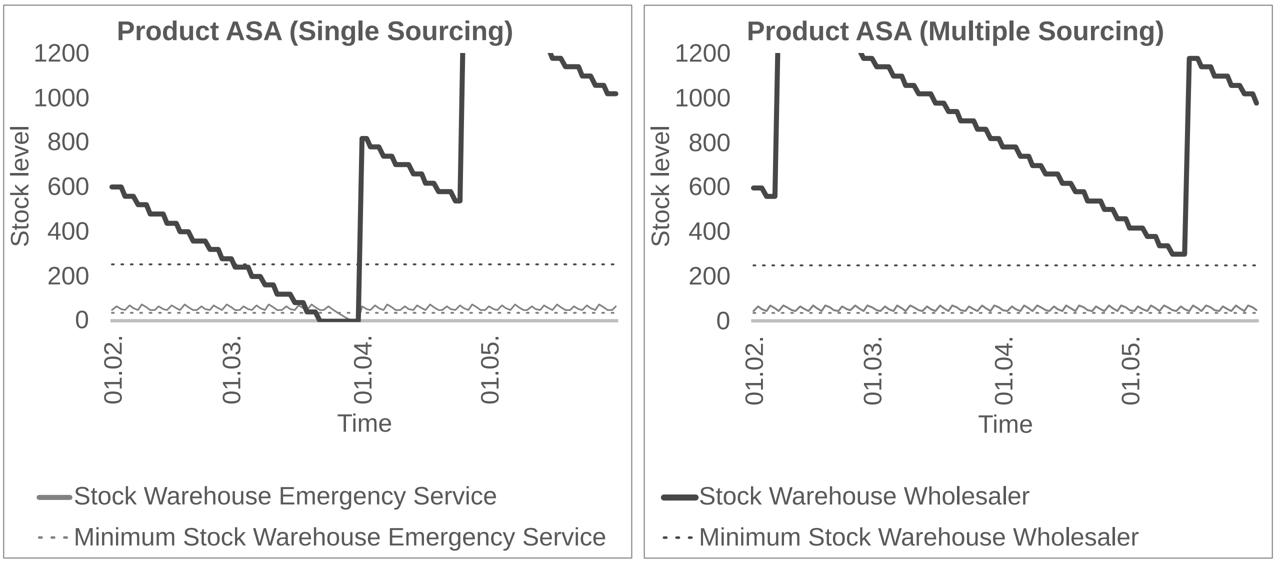

Figure 4: Inventory development as a function of time for the active ingredient ASA depending on the selected sourcing strategy, single sourcing (left) and multi-sourcing (right).

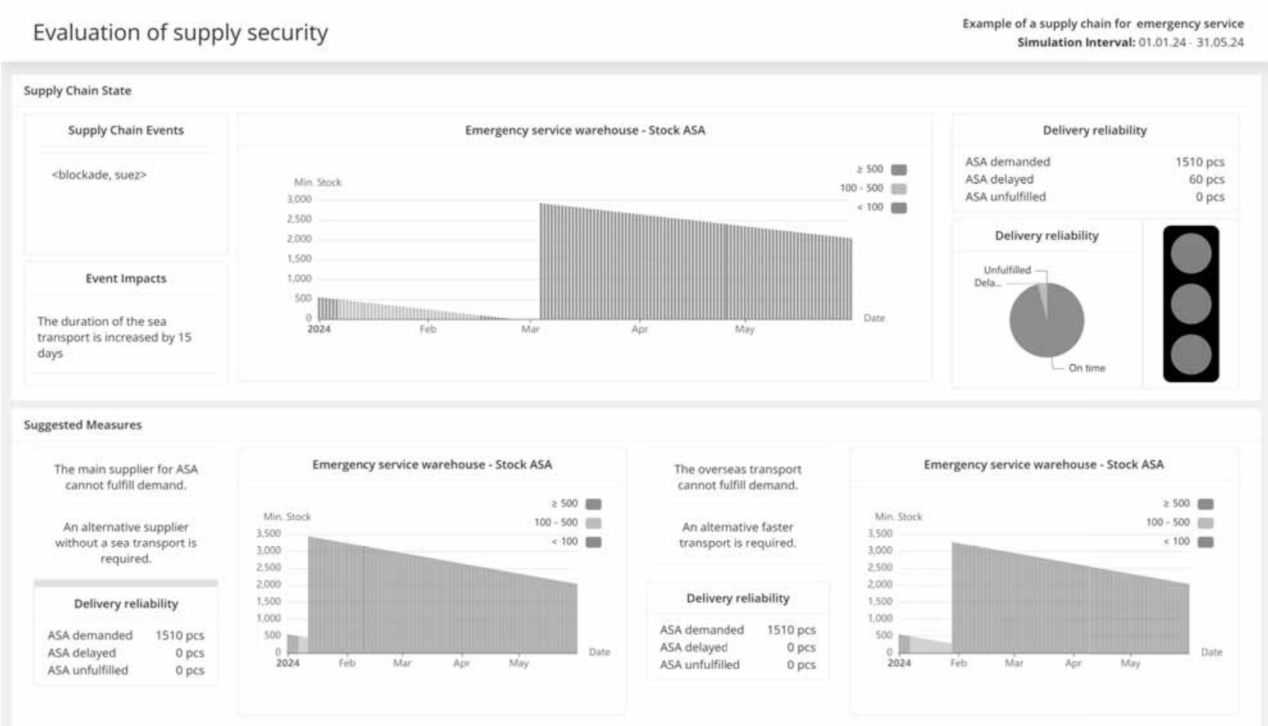

Figure 5: Dashboard from the service for evaluating supply security (Evave).

5 Conclusion

Internationally interconnected supply chains are complex systems characterized by numerous attributes and interdependencies, making the prediction of disruption impacts on supply resilience challenging.

Scenario-based supply chain simulation offers a methodological approach to examine these interdependencies systematically and mitigate disruption impacts immediately.

A fundamental requirement for modeling and simulating supply chains is a comprehensive understanding of their structure and process parameters. This knowledge is often lacking in emergency services due to their reliance on wholesaler procurement.

The data container methodology presented in this paper enables the substitution of absent supply chain information with generic, preliminary assumptions.

Using these generic build blocks, users with incomplete data are empowered to identify the impacts of disruptions on the supply security of their organizations and to initiate countermeasures. Furthermore, they can evaluate scenario-based preventive approaches for increasing supply chain resilience. Thus, the developed methodology contributes to the reduction of dependencies on regional actors in the German healthcare sector and the emergency services on international supply chains.

However, the considerable effort and domain expertise required to create high-quality data containers are notable limitations of this methodology. A potential solution could be the establishment of a (open-access) platform for data container exchange, facilitating the creation and sharing of a library of data containers across various fields.

Integrating these data containers directly into existing simulation software could further streamline their use. Achieving this would necessitate standardizing the structure for data containers.

Additional Material

Further information, the model parameters used for the simulation as well as the data containers used for parameterization are made available permanently and freely under CC BY 4.0 license under the doi 10.5281/zenodo.10809378

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Simulation of the Medical Evacuation Chain: A Conceptual Model

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Abstract. The casualty numbers of the ongoing war in Ukraine significantly surpass the ones of recent conflicts. Since medical resources are limited on the battlefield, efficiently utilizing the available capacities is crucial. At the same time, planning and coordinating this constantly changing logistic network is challenging due to the high dynamic of combat. As data is limited, current planning base on expert assumptions. This process can be supported by simulation models, allowing to analyze the interplay of assumptions and planning decisions. Recent studies showed that flexible dispatching policies can lead to a better utilization of the available capacities and, therefore, to better patient treatment. To further investigate different dispatching strategies in several dynamic combat scenarios, we propose a conceptual model covering the entire medical evacuation process.

Introduction

Since the Russian attack on the Ukraine, traditional warfare for national and alliance defense has once again become the cornerstone of NATO's strategic orientation [1]. Current reports of the ongoing war in the Ukraine indicate a level of combat intensity significantly surpassing the ones NATO has faced in the Afghanistan mission [2, 3]. Concurrently, the number of individuals sustaining life-threatening injuries tends to rise significantly. At the same time, the medical resources available in such conflicts are severely constrained, and the time required to evacuate the injured is prolonged [4].

To provide the best possible treatment to injured soldiers, efficiently utilizing the available medical resources is crucial. For this purpose, the patients must be evenly distributed to the medical facilities and transporters. At the same time, the specific needs of each patient, depending on the injury, needs to be taken into account. This leads to a complex logistic network that is further subject to constant changes due to the combat dynamics. The standard for medical support within the NATO is described in the regulation AJP-4.10 [5]. It shows, that the current planning process of the medical evacuation is based on expert assumptions used to estimate casualty figures and injury patterns.

From here, plans for the most likely scenarios are formulated based on expected patient flows, derived from these estimates. Consequently, there is a static planning process for a highly dynamic logistics system.

In prior work, we have demonstrated, that simulation can be applied to support this planning process [6]. This especially applies to large-scale combat scenarios, as we can currently observe in the Ukraine, where high numbers of patients must be treated with limited resources. For this purpose, a flexible simulation model is required, allowing to test a wide range of dispatching strategies for medical resources in different combat scenarios [6]. Based on these earlier considerations, we present a conceptual model covering the evacuation and preclinical care of injured soldiers.

The paper is structured as follows: First, we briefly describe the medical evacuation chain as the system under examination. In Section 2, related simulation models are briefly discussed, leading to our preliminary considerations presented in Section 3. The conceptual model is introduced in Section 4 covering the different simulated objects with underlying submodels. Finally, the paper concludes with a summary and an outlook.

1 Medical Evacuation Chain

In war, it is only rarely possible to access an existing healthcare system. Therefore, it is imperative to establish a medical service system on-site to ensure the provision of medical care. Nowadays, combat scenarios tend to occur over extensive areas, which results in prolonged evacuation times for injured soldiers. At the same time, life-threatening injuries are common and the assessment with proper treatment of such patients is time-critical. Therefore, evacuating the patients while providing timely preclinical treatment is of utmost importance for the patient's chance of survival [4].

To ensure timely evacuation of patients while providing adequate treatment, the medical evacuation chain was established [4, 7]. This chain is hierarchical and consists of different treatment levels, as visualized in Figure 1. Here, each rectangle represents one level of medical care, while the arrows represent the transportation between them.

First, injured soldiers are brought to a casualty collection point (CCP), where they receive first aid and are handed over to the medical service. From there on, the patients are treated along four successive roles, namely Role 1 to Role 4.

Each role represents a set of medical facilities with increasing capabilities and resources. For example, Role 1 facilities provide emergency care, stop major bleeding, and prepare patients for transportation to a Role 2, where first surgical interventions can be provided. Role 3 facilities extend these capabilities by providing further medical specialists, reaching the standards of a university hospital. Finally, the rehabilitation of patients takes place in Role 4, which is usually located in the patient's home country.

Transportation between these roles can either be performed ground-based or airborne. The selection of the appropriate transporter depends on both the current combat scenario and the needs of each individual patient. Plans for treating patients along the medical evacuation chain must meet the NATO clinical timelines [5].

Accordingly, critical patients must receive Role 1 treatment within one hour of after getting injured. Within two hours of injury, Role 2 must be reached. After the first surgical intervention, the patient must be evacuated to Role 3 within an additional two hours.

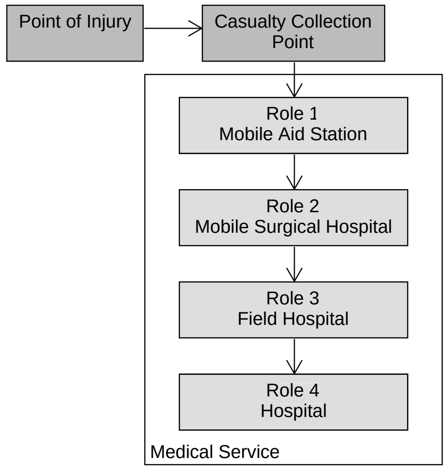

Figure 1: Patients are collected at a casualty collection point and receive treatment in four successive roles with increasing medical capabilities.

2 Related Work

For planning the medical evacuation, two different subproblems are commonly studied [8]. The location-allocation problem studies the best layout of the medical resources in combat scenarios.

The dispatching problem investigates different policies of utilizing the available resources to respond to the different requests. In addition to static planning, the response to various effects of battle dynamics must be considered, too [9]. For example, these effects can be triggered by resource shortfalls which then may require a dynamic relocation or redistribution of resources.

It has already been shown, that simulation is a useful tool to evaluate both of these subproblems and, therefore, assess the planning process of the medical evacuation chain [6]. Several models were described covering different aspects of the medical evacuation. For example, a model for investigating the transporter dispatching for the patient evacuation to Role 1 was presented [10].

Another research extends this approach by additionally analyzing the Role 1 treatment [11, 12]. Further, a model covering the medical evacuation until the Role 3 for an artillery strike scenario was proposed [13].

A simulation covering the medical evacuation from the CCPs to Role 3 is currently utilized by the Bundeswehr Medical Service [14, 15]:

Here, the patient arrival rates and injury patterns, as well as the quantitative and spatial distribution of medical resources such as facilities and transporters are adaptable.

3 Preliminary Considerations

First experiments with the existing model of the Bundeswehr Medical Service revealed that patients do not receive their required treatment due to limited surgery resources in Role 2 facilities [16]. An approach to avoid these bottlenecks is to skip early roles [4]. In this case, the intended treatment of both roles is provided in the higher one. This process is visualized in Figure 2. Here, the roles that can be skipped according to NATO [5] are presented with dashed arrows. For example, patients can be transported from Role 1 to Role 3 immediately, saving resources in the Role 2. This works since the higher roles extend the previous ones by additional capabilities and resources [4].

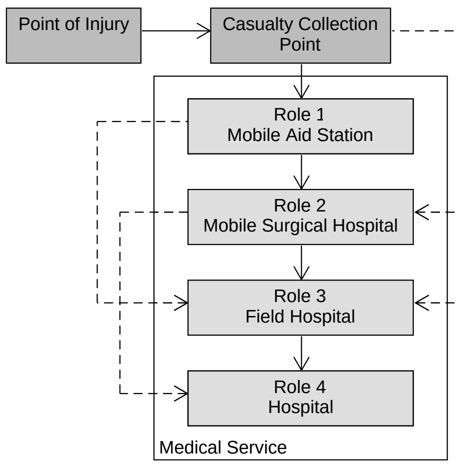

Figure 2: Certain roles of the evacuation chain can be skipped to avoid bottlenecks in early roles.

In another experiment, we investigated how flexible dispatching of transporters can affect the evacuation process [17]. For this purpose, a model covering the evacuation process from two CCPs to a Role 1 facility was utilized. It turns out, that the ability to reroute already dispatched transporters can significantly improve the evacuation process in terms of transporter utilization.

Furthermore, the waiting times of critical patients at the CCP could be reduced up to 30%, helping to comply with the NATO clinical timelines.

The earlier conducted experiments show, that patient evacuation can be significantly improved by applying flexible concepts like skipping roles and dynamic transporter rerouting. While real-world experience in this context is limited, conducting live exercise experiments to test different concepts are expensive, time consuming and therefore not sufficient. At the same time, the simulation model currently utilized by the Bundeswehr Medical Service does not offer the flexibility for testing such concepts [6]. Further, it was shown that none of the existing models allows sufficient investigation and optimization with regard to the introduced problems [6].

4 Conceptual Model

To allow a simulation-based analysis concerning the location-allocation and dispatching problem in a variety of dynamic scenarios, we propose a conceptual model for a flexible simulation.

We aim to cover the whole evacuation process, including the preclinical care from the CCP to the accomplished Role 3 treatment and the subsequent transportation to Role 4.

In our previous work, we proposed to perform the static evacuation chain planning via input data and parameters to adapt the simulation model [6]. The dynamic behavior of the objects, however, should be realized using submodels that can be flexibly adapted and exchanged without adjusting the simulation model itself. By providing a first prototype, we could verify the feasibility of this approach [18].

Based on our earlier considerations, we describe the different submodels in this section. For this purpose, we consider three different types of objects in our simulation model of the medical evacuation chain:

1. **Patients** are treated along the rescue chain. A treatment plan, which defines the necessary treatment steps, is derived from an assigned injury pattern. The patient's condition can deteriorate to the point of death, if treatment is not provided in time.

2. **Facilities** can accommodate patients and provide treatment. They differ in the kind of treatment that can be provided .

3. **Transporters** move patients between different facilities. They differ in the kind and number of patients that can be transported.

The different object types, together with their interactions, are visualized as gray rectangles in Figure 3. For analyzing different dispatching rules in various scenarios, the dynamic behavior of the simulated objects has to be adjustable easily. It must be possible to map a wide range of resource-dispatching strategies, particularly considering various evacuation concepts. At the same time, the combat scenarios, in which the concepts are tested, must be adaptable, too. This applies, for example, to the definition of changing patient arrival rates, troop movements, or resource breakdowns.

In order to achieve the required dynamics and flexibility, components of the simulation that need to be adapted are decoupled from the actual model as submodels. For each object type, a submodel is defined, encapsulating the structure and behavior of the associated object type. These submodels are visualized as yellow boxes around the different object types in Figure 3. The submodel *Patient*, for example, defines how the patient reacts to treatment as described in Section 4.1. It informs the submodel *Treatment* about state changes in the patient's health, which then might require a treatment adaptation. The submodels *Treatment* and *Transportation*, described in Section 4.2 and 4.3, respectively, define the internal behavior of the assigned object type. The allocation of the medical resources, however, is delegated to another submodel called *Resource Dispatching*. This submodel is introduced in Section 4.4.

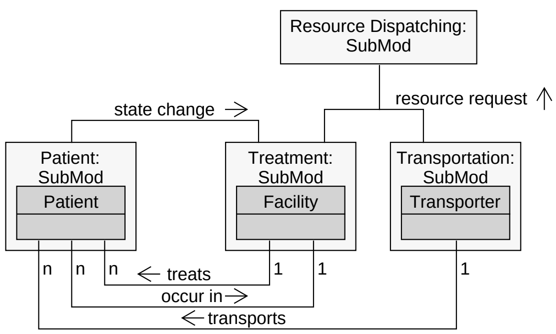

Figure 3: The model is composed of four different submodels (SubMod, yellow) and three types of simulated objects (gray).

4.1 Patient Submodel

Patients are transported and treated along the medical evacuation chain. Here, we subsume both injured and sick soldiers as patients. The corresponding submodel is shown in Figure 4 and is described in the following.

To ensure good adaptation, we divide each submodel into different subordinated submodels, each encapsulating a specific functionality. Here, we differentiate structure and dynamic behavior describing submodels.

The first one is visualized as a gray rectangle, the latter one as blue rectangles in Figure 4. The same applies to the submodels described later in this paper. Submodels describing the structure of simulated objects cover attributes and general internal behavior. While these are assumed to be fixed, we aim to ensure good adaptability for the dynamic behavior describing submodels by providing interfaces that can be used to implement own behavior.

The submodel *Patient Pattern* describes the static structure of the simulated patients. *Patient Arrival* generates patients and assigns injury and sickness patterns as well as the according treatment plan. For defining the arrival rates, different aspects like the number of troops in contact and the current combat situation can be considered.

Currently, we generate the patients using a Poission process with arrival rates determined by domain experts. Later, we plan to derive the patient arrivals from another combat simulation. The dynamic behavior of each patient is described in the corresponding submodel *Patient Behavior*. It defines how the health state of each patient changes based on a treatment plan.

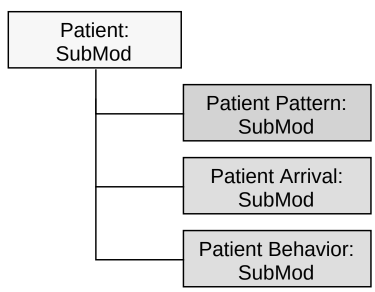

Figure 4: The submodel (SubMod) *Patient* consists of one structure describing submodel (gray) and to behavior describing submodels (blue).

The treatment plan of a patient is defined as a state machine. Each state describes the current patient's condition and defines the necessary treatment step and requirements for transportation. In both cases, we distinguish three different types of preconditions that must be met by a facility or transporter:

1. **Capabilities** are the most general precondition. They must be met by the facility or transporter but do not get claimed or consumed by patients.
2. **Resources** extend capabilities as they are claimable by patients. Therefore, each resource can only be used by one patient at a time.
3. **Consumables** extend resources as they can only be seized once and become unavailable afterward.

Further, a time to treatment failure (TTF) is assigned to each step. Expiration of the TTF leads to a condition worsening and, therefore, a state change. This process is visualized in Figure 5, where the current patient state is presented as a gray box. As green and red boxes, the possible subsequent states are displayed, signifying a health improvement or worsening, respectively. If the required treatment step is applied in time, its success probability can be defined. An unsuccessful treatment also leads to a health worsening. In case of a successfully applied treatment step, the health condition improves. This way, the treatment plan has a tree structure, where the leaves indicate the end of the treatment process. Possible scenarios for ending the treatment are the patient's death, the return of the soldier to combat, or transportation to Role 4.

4.2 Treatment Submodel

The submodel *Treatment* describes the structure and behavior of the medical facilities. It consists of three subordinated submodels and is visualized in Figure 6. The structure and internal behavior of the facilities is described by the submodel *Facility*. As internal behavior, we designate the general treatment process as described later in this section. The dispatching of medical resources, however, is not part of this submodel, as explained earlier. The dynamic behavior of facilities includes breakdowns and relocations, modeled via *Facility Breakdown* and *Facility Relocation*, respectively. As breakdowns we consider facilities being destroyed and therefore not being available anymore to accommodate and treat patients.

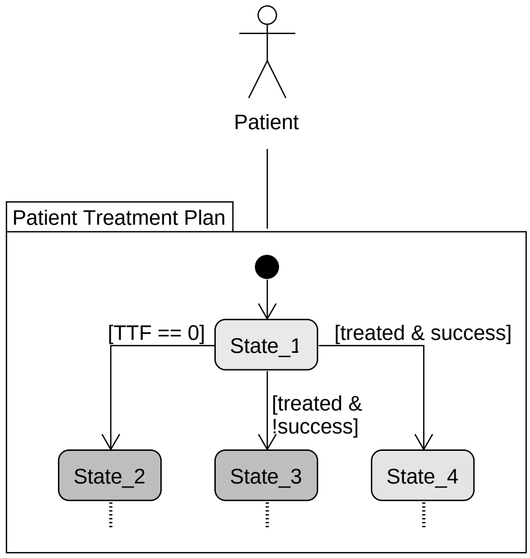

Figure 5: The treatment plan describes different health states together with the required treatment steps. Consecutive states represent a health improvement (green) or worsening (red).

Relocating a facility requires dismantling, transporting, and building up the considered facility. Therefore, each relocation includes a temporary facility breakdown. Initially, breakdowns and relocations are defined by schedules based on the results of a combat simulation.

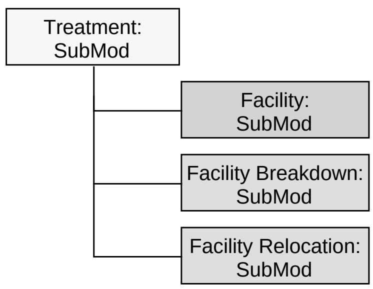

Figure 6: The submodel (SubMod) *Treatment* consists of one structure describing submodel (gray) and two behavior describing submodels (blue).

The internal behavior, modeled in *Facility*, describes the general treatment process applied to patients in the facilities. This process starts with a patient arriving at a considered facility. The following procedure is visualized in Figure 7.

In the first step, the facility checks whether the patient requires treatment. If not, the patient leaves the facility and exits the simulation. This is for example the case, if the considered facility is a Role 4, where modeling the treatment is beyond the scope of our simulation. If the patient needs to be treated, the facility checks whether the required treatment step can be performed.

For this purpose, the facility ensures that the required capabilities, resources, and consumables are available. If the treatment step can be completed, the facility requests the execution of the actual treatment. Otherwise, a transporter is requested to take the patient to a suitable facility.

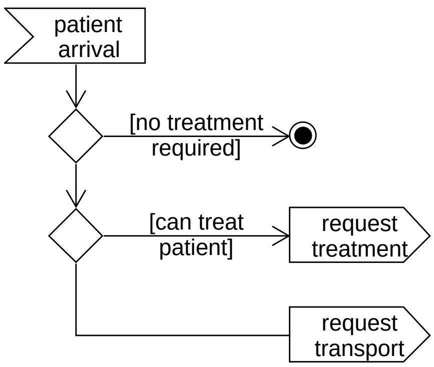

Figure 7: For arriving patients, the submodel *Facility* checks if the patient needs to be treated and whether the treatment step can be performed. Accordingly, transportation or treatment resources are requested.

The treatment resources and transporters are dispatched by the submodel *Resource Dispatching*, explained in Section 4.4. Once the treatment is scheduled, the facility receives a treatment task together with its prioritization, as displayed in Figure 8. Based on this task, the required consumables are assigned, if they are available.

In case they are not, the already assigned consumables from lower-prioritized tasks can be reassigned, if the treatment has not started yet.

In this case, the lower prioritized patient must be transported to another facility. If there is no reassignable consumable available, a transporter is requested to move the considered patient to another facility.

Once the consumables are assigned, the required resource is requested. The assignment is done based on the prioritization of the treatment task. To avoid deadlocks, we assume only one resource to be required for each step. This assumption aligns with the current simulation model of the Bundeswehr Medical Service mentioned in Section 3.

Once the required resource is available and assigned to the patient, the actual treatment is performed. The duration of this process is defined by the treatment step. Afterwards, a new patient arrival is sent, and the process from Figure 7 is restarted. This way, all subsequent treatment steps that can be performed in the current facility are executed. This procedure aligns with the assumptions of domain experts.

During the entire process, the patient's health condition can worsen, leading to a patient state change and different treatment requirements. In this case, the currently assigned treatment task is discarded, and a new patient arrival is sent. For the sake of clarity, we do not visualize this process in both Figures 7 and 8.

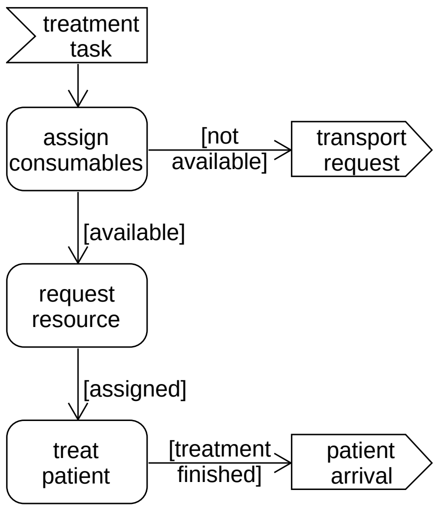

Figure 8: Facilities receive treatment tasks together with a prioritization. Available consumables and resources are assigned accordingly.

4.3 Transportation Submodel

The submodel *Transportation* is structured similarly to the previously described *Treatment*. It consists of two subordinated submodels, describing the structure and behavior of the transporters. It is visualized in Figure 9 and is described in the following.

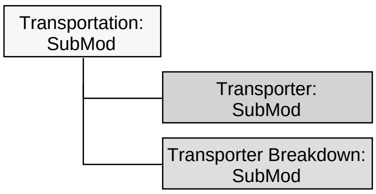

Figure 9: The submodel (SubMod) *Transportation* consists of one structure describing submodel (gray) and to behavior describing submodels (blue).

The submodel *Transporter* describes the structure and internal behavior of the transporters. In this submodel, the general processing of transport tasks is modeled, as explained later in this section. Again, the dispatching of transportation resources is not part of this submodel but is described in Section 4.4. The dynamic behavior of transporters includes breakdowns modeled via *Transporter Breakdown*. Transporters affected by a breakdown are not available for dispatching anymore. Similar to the breakdowns of facilities, they are initially defined by a schedule based on the results of a combat simulation.

Transporters receive transport tasks from the *Resource Dispatching* submodel. Each task is processed according to the diagram visualized in Figure 10. To each task, a facility as its destination is assigned together with the patients to be loaded and unloaded at this facility.

In the first step, the transporter drives to its destination and unloads the specified patients. To start the treatment process, the *Treatment* submodel gets informed about the patient's arrival. In the next step, the patients get loaded according to the task. Patients in a transporter seize a resources, similar to the treatment process in the facilities. At the same time, transporters can have different configurations, specifying the type and number of resources available. Accordingly, for loading the patients, a suitable configuration must be determined by the transporter.

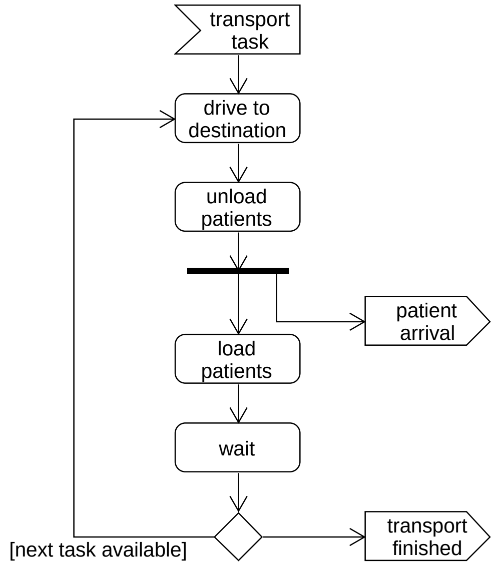

Figure 10: Transporters receive transport tasks specifying its destination as well as the patients to be loaded and unloaded there.

In case there is none, a new transport request is created for the patients who cannot be transported. After the patients have been loaded or unloaded, the transporter can wait for a specified amount of time at the facility for further patients to occur. In this time, the transport task can be adjusted by the *Resource Dispatching*, if required. Finally, the current transport task is processed, and the transporter checks whether a subsequent task is available. If yes, this task gets processed, too. Otherwise, the *Resource Dispatching* submodel gets informed about this transporter being available again.

4.4 Resource Dispatching Submodel

The dispatching of treatment and transportation resources is done by the *Resource Dispatching* submodel. It is divided into two subordinated submodels as shown in Figure 11.

The *Treatment Dispatching* coordinates the treatment of patients within the facilities. It receives treatment requests from the *Treatment* submodel, prioritizes the patients, and creates treatment tasks. These are then processed by the *Treatment* submodel as explained in Section 4.2. Selecting the facility for the patient treatment, however, is out of the scope of this submodel and is done by the *Transporter Dispatching*.

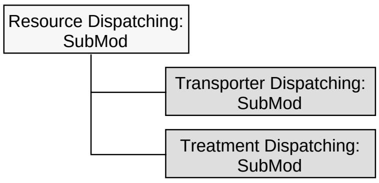

Figure 11: The submodel (SubMod) *Resource Dispatching* consists of *Transporter Dispatching* and *Facility Dispatching*, coordinating transportation and treatment resources, respectively.

For this purpose, incoming transport requests get prioritized. Then, the submodel checks whether a suitable transporter is available or if the requests can be added to existing transport tasks. Here, the submodel must consider both the for transportation and the following treatment in the approached facility required capabilities, resources, and consumables.

Transport requests that cannot be answered immediately are deferred. If a transporter becomes available, deferred requests can be assigned. If there is no open request, the transporter can be relocated. The *Transporter Dispatching* also must react to both, transporter and facility breakdowns. If a transporter is destroyed, new transportation requests are created for the patients already planned in future tasks of the considered transporter. In case of a destroyed facility, the transporters that are about to approach this facility need to be rerouted.

5 Conclusion and Outlook

In this paper, we proposed a conceptual model for a simulation of the medical evacuation chain. The goal of our model is to provide enough flexibility to test different dispatching strategies in various combat scenarios.

The underlying logistic problems were introduced and existing simulation models were discussed. Preliminary experiments showed, that the treatment of patients can be improved by applying dynamic dispatching concepts.

Currently available simulations, however, do not allow testing such concepts in highly dynamic combat scenarios.

Our conceptual model covers patients, medical facilities, and transporters as simulated objects.

For each object type, a submodel was proposed, which is further divided into subordinated submodels describing the structure, internal and dynamic behavior. Especially for the latter one, we ensure a high adaptability by providing appropriate interfaces.

This way, a wide range of dynamic combat scenarios can be modeled. Further, the dispatching of the treatment and transportation is outsourced to another submodel, offering the same adaptability. Here, we define which decisions have to be made in different situations while the rules used to make the decision can be easily adapted later.

With the proposed conceptual model and its high adaptability, we aim to support the planning process of the medical evacuation chain in the future. It allows testing different flexible dispatching strategies in a wide range of dynamic scenarios.

Therefore, we cannot only detect current bottlenecks but can test strategies for a more efficient usage of the currently available resources. In the next step, we aim to implement the executable simulation model. For this purpose, the interfaces of the different submodels need to be defined. This way, we want to ensure that various problem solvers and machine-learning approaches can be utilized for the dispatching submodels.

Acknowledgement

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Simulation Model for AGVs in Production Environments under Consideration of the Facility Layout Problem

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Abstract. In Flexible Manufacturing Systems (FMS), an Automated Guided Vehicle (AGV) is often used for material transport. To simulate this system, a production environment with aisles and I/O points is required. The arrangement of individual areas within a production environment can be done by solving the Facility Layout Problem (FLP). However, the previous methods only consider individual aspects and there are hardly any solution methods that consider the entire production system with regard to the material transport. Due to this, a FLP solving method that also considers aspects regarding the material handling system is useful so that the created production environments can be simulated and/or used in practice. Therefore, both topics - FLP and AGVs - should be considered together.

Introduction

Flexible Manufacturing Systems (FMS) – a specific type of multi-stage production system [10] – often use an automated guided vehicle system (AGV-System) for material transport [12, 11]. One possibility for optimizing AGV-Systems is the arrangement of various facilities, which can represent, for example, machines, storage locations, workplaces, production locations [13, 15], I/O points (where Automated Guided Vehicles (AGVs) can load and unload material), parking areas for AGVs as well as necessary AGV travel areas within a production environment. The problem of arranging these facilities is known as the Facility Layout Problem (FLP) and aims to minimize the costs of material transport of the resulting production environment so that they are as low as possible [13, 14, 15]. One problem with the previous solution methods of the FLP is that often aspects for the use of a real AGV-System are not taken into account. These include the driving areas of the AGVs, the connection of the I/O points to the AGV driving area and the consideration of routing, dispatching and scheduling for the AGVs [2] on the basis of the generated production environment.

Reference to simulation In this paper, a simulation model is developed which, on the one hand, can be used to the requirements of an AGV-System when creating the layout of the production environment (FLP). On the other hand, the dynamics of the AGV-System are already taken into layout by means of an abstract simulation of the AGV routing. For example, it is checked whether the AGV-System is capable of handling all necessary transport orders within a certain period of time.

1 State of the Art

In this section the basics are presented. The FLP is explained first, followed by the AGV-System and all related aspects.

1.1 Facility Layout Problem

The FLP positions a fixed number of facilities within a limited area so that the cost of material transport is minimized [13, 15, 14]. The FLP belongs to the NP-hard combination problems and has been researched for decades [15]. Due to this, there is a multitude of solution methods with different approaches.

Many of these only consider selected aspects, such as the determination of I/O points. Steps one to three from Figure 1 are known from the literature.

In [13] a FLP approach for the arrangement of facilities based on a special data structure – Slicing Tree (ST) – was developed. This offers the possibility of inserting an aisle structure in the layout with a simple procedure. In [9] the FLP solution procedure extended by the determination of the I/O points. Thereby, an I/O point could be positioned within one of the four corners of the facility. This is useful for the subsequent connection to the transport aisles – the insertion of the transfer areas – makes sense. In [15] they added the transport aisles depending on the transport relationships and intensities between the the facilities within the production environment for material transport. However, this method does not take into account the aspects of AGV routing.

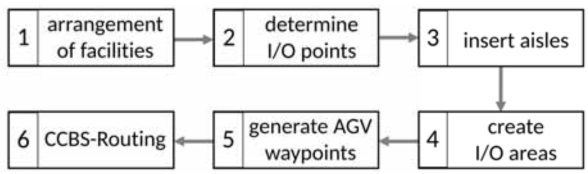


Figure 1: Illustration of the steps to generate a FLP layout for the creation of an production environment. Steps one to three can be found in the literature. Steps four to six should be considered with regard to aspects of a material handling system and should also be taken into account during the creation.

To evaluate a layout, the material transport costs C are determined [13, 14, 15]:

$$C = \sum_{i=1,j=1}^{M} (t_{ij} \cdot d_{ij}) \tag{1}$$

This sum is defined by the distance d_{ij} from facility i to facility j weighted by the transport intensity t_{ij}. The transport intensity can be taken from the transport matrix and corresponds to the material units that are transported between the facility pairs. M is the number of facilities to be placed in the layout. The distance d_{ij} is calculated differently depending on the FLP approach. The FLP approaches in [13, 7, 8, 6] calculate the distance between the centers of gravity of the facility. With regard to AGVs, this assumption of the travel distance between the centers of gravity is unrealistic. In the method of [9], it is assumed that the AGVs travel along the boundaries of the facility. I/O points are determined which lie at the edge and the distance is calculated between them along the boundaries of the facilities.

The physical space to travel in is missing. In the approach of [14], it is assumed that the travel paths are always in the middle of the corridor. The path-based distance is calculated between the I/O points taking the aisles into account.

1.2 AGV-System

An AGV-System consists of one or more AGVs. It can now be found in almost all industries and production areas and is therefore an important part of intralogistics [1]. According to the VDI 2510, AGVs are defined as indoor, floor-based systems with automatically controlled vehicles for the handling of material transport [1]. In order to coordinate the AGVs, the AGV needs to know about the possible routes. One possibility is to create these in the form of topological graphs [19].

Topological graphs A topological graph $G = (V,E)$ is a planar graph with a finite set of nodes N and edges E [18]. Each edge connects two nodes. In the context of AGVs, the edges of the topological graph represent paths or roads for the AGV. Intersections and important stops, e.g. stations for loading and unloading material at the facility, are represented by graph nodes. To create the topological graph, an approach further developed at the Fraunhofer IML called Roadmap Graph Creator (RGC), based on [19] is used.

Readers are referred to the literature [20]. The topological graph is used to calculate the distance between the I/O points (path-based distance metric). The simulation model for routing requires the topological graph to determine the paths for the AGVs to execute the transport orders.

CCBS-Routing An abstract simulation model is created to take into account the dynamic behavior of the AGVs in the created production environment. For this purpose Continuous-time conflict-based search (CCBS) is used. CCBS is an algorithm for searching paths for multiple AGVs in a defined environment, so that each each AGV reaches its destination without causing conflicts with other AGVs [17, 16]. In doing so, a set of transport orders is defined where the start and destination are defined by nodes of the topological graph. For each transport order one AGV is assumed. The paths of the AGVs are selected via the topological graph.

As a result, CCBS returns certain characteristic metrics for the routing of the set of transport orders, including the makespan m.

$$m = M(\Pi) \tag{2}$$

The makespan corresponds to the time it takes the last AGV to reach its destination. CCBS plans in batches, i.e. no new transport orders can be issued to an AGV until all AGVs have reached their destination [17, 16].

2 Requirements regarding AGV-System

Before a solution can be developed, the requirements with regard to layout and topological graph for use within an AGV-System must be defined. Based on these criteria, the solution procedure is further developed so that a production environment model that is well matched to the requirements of the AGV-System can be generated. This model can be used for simulation and/or implemented directly in practice if required.

2.1 Layout Requirements

In order for the layout created on the basis of the FLP to be suitable for use within an AGV-System, the following aspects should be fulfilled: Transport aisles for the AGVs between the individual facilities should be defined [14, 15]. Additional several I/O points for each facility should be created, instead of only one I/O point for each facility like in [9]. With regard to application in the AGV-System, only one I/O point can lead to a problem. For example several AGVs arrive at the same facility and at the same time. First of all it must be clarified which AGV is allowed to drive to the I/O point to load or unload the materials. This means waiting for the other AGVs. The waiting AGVs could obstruct other AGVs that are in the process of fulfilling other transport orders. This leads to congestion and delay in the entire FMS. Therefore, it may be necessary if multiple I/O points can be identified. In our approach we use an I/O area for this purpose (see later section 3.1).

2.2 Graph Requirements

The topological graph and thus the waypoints for the AGVs are to be generated on the basis of the aisle structure. The topological graph must fulfill two requirements for use within an AGV-System.

First, it must be ensured that from one node every other node in the graph can be reached via the edges. This property can be tested via the graph coherence, if this is one, the requirement is fulfilled [3]. Furthermore, it must be checked whether all facilities also have a connection to the aisle structure via graph nodes and edges. For this purpose, it is checked whether at least one graph node is located within the I/O area.

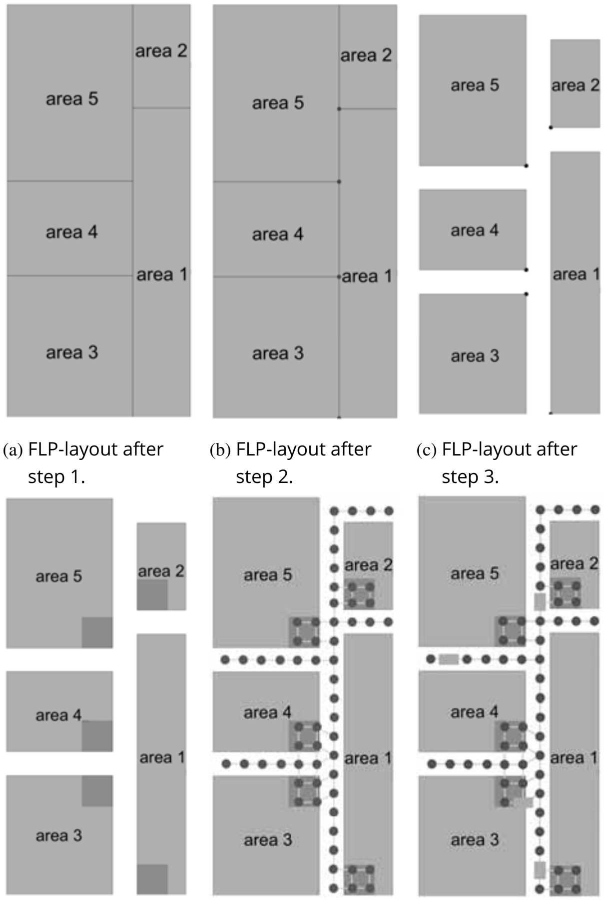
3 FLP - Solver

Due to the FLP solution procedures known to us, which do not consider the requirements with regard to the application in an AGV-System, we have developed our own approach. This means that the production environments created can be used in practice. Steps one, two and three (see Figure 2) are known from the literature. Our further development of the FLP solution method includes steps four to six from Figure 2, which take into account the requirements with regard to the AGV-System. For this purpose, the FLP solution procedure of [13] is extended. The individual steps are explained below.

3.1 Arrangement of the Facilities and Determination of the I/O Points

In order to solve the FLP, a number of input data are generally required [13]. These include the dimensions of the location support, the number of facilities to be placed, the required area for each facility, the dimensions of each facility and the transport matrix. The transport matrix indicates how much material needs to be transported between the individual facilities [13]. Based on this required random STs are generated in order to determine the final positions of the facilities and thus their arrangement (see Figure 2a).

To determine the I/O points (= stations for AGVs to load and unload material at the facility), the procedure of [9] is applied. First, candidates of I/O points are identified based on the dominant region. For each corner of the facility a node is added to a graph. The boundaries of the facilities are represented by edges. The dominant region consists of one or more contiguous facilities that have at least one vertex or graph node for each facility. These nodes in the dominant region represent the candidates of I/O points. We have resolved the restriction of [9] that a dominant region must be rectangular.



(a) FLP-layout after step 1. (b) FLP-layout after step 2. (c) FLP-layout after step 3.

(d) FLP-layout after step 4. (e) FLP-layout after step 5. (f) FLP-layout in step 6.

Figure 2: Representation of the generated production environment according to the steps from Figure 1.

In our approach, the dominant region can also be a polygon. After the candidate transfer points have been determined, the facility pairs are sorted in descending order according to their transport intensity. For each facility pair, the two I/O points with the smallest distance to each other are selected (see Figure 2b) [9].

3.2 Creation of the AGV Driving Areas

The structure of the STs is used to create the driving areas. The idea is based on [13] and was adapted for our purpose. Each cut node in the ST is considered. The right child of the intersection node and all nodes are shifted along the x- or y-axis in a positive direction by a predefined path width. This creates the driving areas for the AGVs (see Figure 2c).

3.3 Inserting the I/O Areas

On the basis of the I/O points determined in step 2 (see Figure 2b), I/O areas of a predefined size are inserted. All I/O areas are of the same size (see Figure 2d). The idea is to treat these transfer areas also as driving areas for the AGVs. This automatically generates a set of I/O points for each facility related to the next step: generation of the AGV waypoints. All graph nodes of the topological graph within the I/O areas can be identified as I/O points.

3.4 Generation of the AGV Waypoints

The generation of the topological graph is carried out over the open space, consisting of the driving and I/O areas using the RGC software tool (see Figure 2e). It is important that the graph fulfills the two requirements mentioned (see section 2.2), otherwise the created layout cannot be evaluated.

3.5 Simulation of the AGVs with CCBS Routing

To evaluate the layout, the CCBS makespan is used in our approach (see eq. 2) and replaces the cost function from the literature (see eq. 1). This leads to the consideration of the dynamic driving behavior of the AGVs and the parallelism of the transport orders to be processed in the layout, which is not considered in other evaluation criteria for the FLPs layout (e.g. in eq. 1). For this purpose a set of transport orders must first be generated. Then, taking into account a time window (see section 3.6), CCBS is executed with the generated transport orders and the makespan is assumed to be the cost of the layout. If CCBS does not find a solution within the time window, twice the longest distance in the layout is calculated for evaluation:

$$c = 2 \cdot \max(d_{i,j}) \tag{3}$$

This can be done, because in CCBS the assumption is made that the AGV has a velocity of 1 m/s [17, 16]. The longest path therefore also corresponds to the makespan. In order to evaluate this solution more negatively, since CCBS has not found a solution, the longest path is considered twice.

3.6 Parameters

There are a number of parameters for the FLP-solver that influence the result. In principle, the FLP-solver distinguishes between the necessary input data and the parameters to be set for the best possible result. The following input parameters are required for each data instance: the number of facilities to place, the dimensions of the entire layout or maximum allowed size for the FLP-layout to be generated e.g. the production hall, the minimal and maximal width and length of each facility, the area for each facility and the transport matrix containing the transport intensities for each pair of facilities.

The parameters to be set for the best possible result can be further differentiated. The first group of parameters influences the layout itself, e.g. the size of the I/O area (see section 3.3). The width of transport aisles (see section 3.2) can also be defined and thus the number of parallel roads within a transport aisle. A time limit is set at two points when creating a layout. When creating the topological graph (see section 3.4), the time limit is determined depending on the size of the layout and the width of the transport aisle. To determine the costs via CCBS (see section 3.5), a time limit of 10 seconds is set, which is based on previous studies [20].

The second group of parameters influences the search for the best FLP-layout, because the number of STs considered is limited so that the runtime remains within a certain period. These parameters are already known from the literature e.g. [13]. An example is the parameter `iterations`. The parameter defines how often a random ST is created for searching a best FLP-layout.

One problem in creating a production environment is finding the optimal parameters so that the runtime remains within reasonable limits and the result is still as satisfactory as possible. To find the right parameters, we focused on the runtime. So that production environments can be created in a reasonable time for us (see Table 2, 3, 4, 5).

4 Evaluation

For the evaluation, we have compared several data instances (DI) from different publications and compared their results with our approach. For this we took into account different numbers of steps from the literature to generate a layout (see Figure 1). The evaluations were performed on an AWS server instance EC2 C5A.XLarge [4]. Table 1 shows the four different versions. The specified minimum and maximum side lengths of the individual facilities could not always be adhered due to the selected cuts in the ST.

The limitations for the side lengths are not taken into account in the evaluation. Tables 2 - 5 compare our results with the best results from the literature. The numerical value in the columns "best result" and "our result" represents the material transport cost C for the respective DI. The value "nr. of STs" corresponds to the number of valid ST found for the listed run of the FLP-solver.

FLP-solver	**literature**	**distance metric**	**considered steps** for generating a layout (see Figure 1)
V1	[13, 7, 8, 6]	center of gravity distance	1
V2	[9]	contour-based distance	1 and 2
V3	[14]	path-based distance	1, 2 and 3
V4	our approach	path-based distance via topological graph	all steps seen in Figure 1

Table 1: Overview of evaluation applications V1 - V4.

4.1 FLP-solver: Arrangement of the Facilities (V1)

Table 2 shows that the results from the literature for the FLP procedure with center of gravity distance. With the exception of data instance AB20, all results are better by an average of 7.53%. It is likely that with further elaboration for data instance AB20 a similar or better result could be obtained.

4.2 FLP-solver: Determination of I/O Points (V2)

The results in [9] could not be achieved (see Table 3. One reason for this is the adherence to the dimensions of the layout. While [9] allows layouts with larger dimensions, our approach only allows layouts that lie within the specified dimensions. This is more practical, since the necessary space, e.g. a production hall, is limited. To enlarge the hall afterwards is unrealistic. As before, there is also the chance to achieve better results with further designs.

data instance	best result ↓	our approach			deviation ↓
		best result ↓	nr of STs	runtime [HH:MM:SS]	
OE7	131.57 [7]	108.78	5	00:00:06	-17.32%
OE8	242.73 [8]	220.94	7	00:00:16	-8.98%
OE9	235.84 [7]	207.51	9	00:00:25	-12.01%
VC10	19994.10 [6]	19183.98	6	00:02:58	-4.05%
BA12	8021 [13]	8071.28	34	00:02:21	+0.63%
BA14	4628.84 [13]	4469.25	19	00:04:27	-3.45%
AB20	5073.82 [6]	67725.68	1	00:10:46	+92.51%

Table 2: Results of FLP-solver V1: arrangement of the facilities.

data instance	best result in [9] ↓	our approach			deviation ↓
		best result ↓	nr of ST	runtime [HH:MM:SS]	
OE7	21.64	36.85	7	00:00:12	+41.28%
OE8	52.09	66.64	6	00:00:25	+21.83%
OE9	53.29	76.32	7	00:00:32	+30.18%
VC10	3097.91	18134.46	6	00:04:46	+82.92%
BA12	3089.91	4747.06	27	00:08:25	+34.91%
BA14	2188.33	3318.85	21	00:15:19	+34.06%
AB20	1185.99	89280.45	2	04:02:16	+98.67%

Table 3: Results of FLP-solver V2: arrangement of the facilities and determination of the I/O points.

4.3 FLP-solver with Aisles (V3)

The comparability between [14] and our approach is difficult due to some differences, e.g. the procedure for inserting waypoints and the individual parameters, which additionally influence the result [13].

In comparison with the four published data instances in [14], data instance BA14 performs best. Here, too, there is a chance to achieve better results with further versions.

4.4 FLP-solver: I/O areas and CCBS-Routing (V4)

Table 5 presents the results for our own metric, which takes into account CCBS routing and thus parallelism in the AGV-System and FMS.

Just as before there is a chance for better results with further executions, since with each execution random data instances are generated. Based on this random ST the optimization is carried out [13].

5 Discussion

In the following we will pick out some aspects and look at them more closely. To do this, we will first examine how much time it takes to create a layout (see section 5.1). Then we will look at the question of why STs are created randomly (see section 5.2). Finally, we will briefly show that the approach cannot create standard layouts exclusively (see section 5.3).

5.1 A Runtime Analysis - Data Instance BA12

This section presents the results of a runtime analysis of data instance BA12. For this purpose, the runtime analysis is split into two parts. The first part aims to analyze which steps for creating a layout (see Figure 1) take the longest in terms of runtime. In the second part, some experiments are carried out to show the effects of the optimization and some input parameters.

For the first part, the optimization itself plays no role. Only a layout is created using a ST. To do this, a ST is first generated randomly. This is then passed to all four FLP-solver versions (V1- V4).

data instance	best result in [14] ↓	our approach			deviation ↓
		best result ↓	nr of STs	runtime [HH:MM:SS]	
VC10	7116.14	27315.12	15	04:43:27	+73.95%
BA12	5561.12	8105.33	1	00:15:28	+31.39%
BA14	3784.47	3964.14	1	00:20:27	+4.53%
AB20	1529.63	89516.26	3	08:26:22	+98.29%

Table 4: Results of FLP-solver V3 with aisles.

data instance	our approach		
	best result ↓	nr of STs	runtime [HH:MM:SS]
VC10	59,31	2	04:21:18
BA12	14,85	1	00:34:03
BA14	15,15	1	00:41:37
AB20	62,15	1	08:17:12

Table 5: Results of FLP-solver V4 with aisles and CCBS-Routing.

This increases the comparability with regard to the runtimes during the creation of the layouts.

The total runtime is recorded as well as the runtime for certain steps (see Figure 1) during layout creation. Step 4 is not considered because the final position is already given by the I/O point and thus this step consists only of cutting rectangular areas. As the previous time display [HH:MM:SS] is not suitable at this point, all running times determined are recorded in seconds. For this evaluation, a timeout of 30 seconds is selected for the creation of the topological graph. The time to start and end the ROS-nodes to create the topological graph is also measured, but the pure creation is limited to 30 seconds. The CCBS has a time limit of 10 seconds.

Table 6 shows an example of an evaluation for the scenario described. As expected, the time required to create the random ST is the same, as the same ST is used for all FLP-solver versions (see column initialization in Table 7). No time is required for steps 2, 3, and 5 with V1, as this FLP-solver version does not carry out these steps. The same applies to V2 with steps 3 and 5. Each step takes approximately the same amount of time to complete. Obviously, the most time-consuming step is the creation of the topological graph. The more steps are carried out to create the layout, the more time is required overall (see column total time in Table 7).

To find out whether the runtimes from Table 6 are average values or exceptions, the scenario described is repeated 100 more times. The average value is determined from these 100 evaluations in Table 7. When looking at the results, it was noticed that some of the random STs are not suitable for creating a layout. These invalid STs were filtered out in order to recalculate the average values for the 82 remaining STs (see Table 7 at the bottom). This gives a clearer picture of the runtime to create a layout. It is striking that CCBS was not even used in all 100 results. The time to calculate the costs in V4 is lower than 10 seconds (see Table 7). This phenomenon should be analyzed in detail in the future. Just like the fact that some of the randomly generated STs for the FLP-solvers V2, V3 and V4 are invalid. Perhaps the solution space can be narrowed down even more beforehand. This would lead to a reduction in the total runtime in connection with the optimization, as invalid STs are no longer considered from the outset. To summarize the first part of the runtime analysis: the values in Table 6 correspond to the general average from Table 7 (lower part) when considering the valid STs from the initialization. In the case of data instance BA12 in combination with the selected parameters, a layout can be created in all FLP-solver versions within 60 seconds. The longest part in terms of runtime is the creation of the topological graph. The aforementioned phenomena should be investigated further in the future.

The second part of the runtime analysis is about the optimization time. Again for each FLP-solver (V1, V2, V3, V4) the same ST is used. In principle, there are no major changes, but (in contrast to the previous analysis) the optimization of the created layout is carried out after each step. The time required for the optimization and how many different layouts (= STs) are created and checked during the optimization are examined.

In the first experiment, the parameter `iterations` is set to one. Table 8 shows the results. Compared to the previous results (see Table 2, 3, 4, 5), Table 8 shows a significantly longer total runtime for data instance BA12. This highlights a problem with the heuristic procedure: depending on which ST is randomly created at

FLP-solver	time in seconds						
	initial	arrangement (step 1)	I/O points (step 2)	aisles (step 3)	topo graph (step 5)	costs (step 6)	total time (steps 1-6)
V1	0.02362	0.0017	0	0	0	0.0015	0.00321
V2	0.02362	0.00132	0.18767	0	0	0.00578	0.19479
V3	0.02362	0.00173	0.18379	0.00814	47.89754	0.02436	48.11566
V4	0.02362	0.00144	0.18852	0.00832	49.2727	0.08869	49.55979

Table 6: An example of an evaluation for the first part of the runtime analysis of data instance BA12. For each FLP-solver version (V1 - V4), the same ST – randomly generated ST in the initialization – is used to create a layout. The total runtime and selected steps for creating the layout (see Figure 1) are recorded. The time is displayed in seconds.

FLP-solver	nr of evaluations	averaged time in seconds						
		initial	arrangement (step 1)	I/O points (step 2)	aisles (step 3)	topo graph (step 5)	costs (step 6)	total time (steps 1-6)
V1	100	0.01822	0.00154	0	0	0	0.00149	0.00304
V2	100	0.01822	0.00142	0.14851	0	0	0.00845	0.18018
V3	100	0.01822	0.00144	0.14793	0.00635	39.46056	0.02364	39.66755
V4	100	0.01822	0.00166	0.1525	0.00663	40.71342	0.07399	40.96945
V2	82	0.01846	0.00141	0.18111	0	0	0.0103	0.19284
V3	82	0.01846	0.00143	0.1804	0.00774	48.12264	0.02883	48.34702
V4	82	0.01846	0.00168	0.18598	0.00808	49.65051	0.09023	49.9366

Table 7: Result of the first part of the runtime analysis for data instance BA12. The average times (in seconds) are shown on the basis of 100 evaluations as in Table 6.

the beginning, many STs may be invalid and therefore not considered. Furthermore, the search for the local minimum for BA12 converged relatively late compared to other results. As result, significantly more layouts were viewed than in the previous search (see Table 8).

FLP-solver	layout		
	creation	optimization	nr of STs
V1	[00:00:01]	[00:00:01]	215
V2	[00:00:01]	[00:01:02]	215
V3	[00:00:48]	[07:34:20]	644
V4	[00:00:50]	[02:59:44]	236

Table 8: Runtime analysis of data instance BA12 with layout optimization (iterations=1). The time required to create the first layout is also listed (for comparison with the values from Table 7) as well as the time required to optimize this created layout. A number of layouts are created during the optimization process (see column "nr of STs").

In the second experiment the parameter `iterations` is set to five. This will be used to analyze the impact of the number of iterations in the runtime. Table 9 shows the results. As expected, the number of STs (=layouts) seen has increased: However, only for V1 and V2. For the other two FLP-solver versions, the number of STs has actually fallen. This is also accompanied by the lower runtime. It is likely that the 5 randomly created STs have led to faster convergence to the local minimum than with the previous 3 randomly created STs. The random creation of STs at the start of the approach is always disruptive in this case, as the influencing factors – in this case parameter `iterations` – cannot be analyzed in a meaningful way. This raises the question of how useful the random generation of STs is (see section 5.2).

5.2 The Complexity of Creating Layouts

In this section we discuss the number of possible STs for a given data instance. Figure 3 shows the number of possible STs (y-axis) for a data instance with differ-

FLP-solver	layout		
	creation	optimization	nr of STs
V1	[00:00:01]	[00:00:01]	338
V2	[00:00:01]	[00:01:34]	324
V3	[00:00:48]	[03:29:36]	635
V4	[00:00:50]	[02:32:53]	209

Table 9: Runtime analysis of data instance BA12 with layout optimization (iterations=5). The time required to create the first layout is also listed (for comparison with the values from Table 7) as well as the time required to optimize this created layout. A number of layouts are created during the optimization process (see column "nr of STs").

ent facilities (x-axis). The number of possible STs is growing exponentially.

It can be observed that the number of STs increases with the number of facilities. For example there are 8100 possible STs for a layout with 10 facilities. For a data instance with 100 facilities 98010000 possible STs. The number of possible STs is growing exponentially. As soon as the number of facilities increases, the ST is getting bigger and thus the runtime increases. Therefore we decided to follow Scholz's approach [13] with the creation of random STs and test them to find a local minimum FLP-layout. An alternative would be to calculate the costs for all STs. Based on data instance AB20 with 20 facilities and a runtime of approx. 160 seconds per ST, a runtime of 267.4 days is calculated from the 144400 possible STs. First of all, it was important to create a layout that took material transport aspects (e.g. I/O points, transport aisles and routing) into account. In future, research can be carried out into how the topological graph can be created more quickly so that more layouts can be considered in less time. This would mean that it would no longer be a decision of benefit vs. runtime.

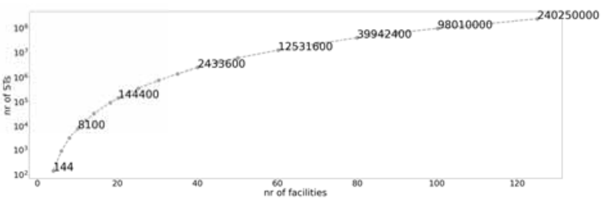
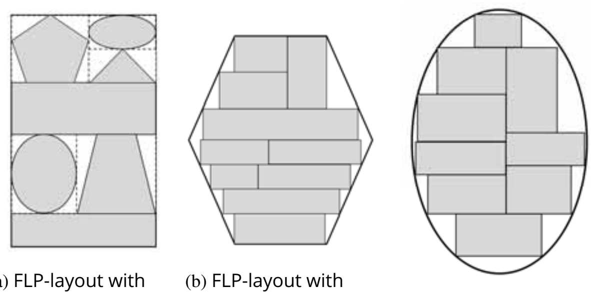


Figure 3: The number of STs in addition to the number of facilities due to a data instance.

5.3 How to Create Non-rectangular Layouts?

With small changes, layouts with non-rectangular facilities and also non-rectangular layouts can be created. To create layouts with non-rectangular plants, a list of nodes of the actual shape must also be stored for each leaf node of the ST. When reading in the input data, a rectangle is placed around each non-rectangular shape. To create layouts with non-rectangular shapes, a list of points (or a function) describing the desired shape is passed instead of the previous two points (min, max) of the area. Figure 4 shows some examples. The vertical and horizontal alignment due to the ST is maintained.



(a) FLP-layout with non-rectangular facilities. (b) FLP-layout with non-rectangular area. (c) FLP-layout in ellipse form.

Figure 4: Representation of possible FLP-layout without the limitation of rectangular shapes.

6 Conclusion

In summary, it can be said that in this publication a practical FLP approach for the generation of layouts for production environments taking into account the requirements for the use in an AGV-System is presented. Each resulting layout of our approach can be used in an AGV-System.

For future research work, on the one hand, optimization should be carried out with regard to the runtime, so that more layouts can be calculated in less time. This increases the probability of a good result. Furthermore, some aspects should be optimized further, such as the question whether transfer areas should be chosen that are adapted to the transport intensities of the facilities. Thus, facilities with high transport intensities could be approached by more AGVs at the same time. Also the procedure for determining the I/O points and thus the positioning of the I/O areas can be adapted, as it is based on the procedure of [9], it is also possible to drive along the outer edges (=boundaries of the facilities).

In reality, however, after insertion of the aisle structure, this is hardly possible, as additional space would be required. Furthermore, the routing itself can be exchanged, for example by using a more practical anytime routing method.

In contrast to the stacked planning CCBS [17, 16], with anytime routing, e.g. CARP [5], an AGV can directly receive a new transport order as soon as the previous one has been completed, without having to wait for the completion of transport orders from the other AGVs.

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Basic Layouts for Modular Assembly Systems – a Simulation-based Comparison

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Abstract. The article discusses the challenges posed by increased individualization of products, shorter product life cycles, and external factors on the flexibility of modern production systems.

In particular, flexible workshop-oriented manufacturing principles are being implemented to replace or supplement traditional assembly lines, with various terms such as "modular assembly" and "matrix production" etc. used to describe similar concepts. The article presents these concepts under the umbrella term of modular production or assembly systems, which utilize adaptable workstations and autonomous vehicles to transport production orders between stations.

The design of such systems is crucial to their performance, with considerations such as task allocation, material supply, and fleet sizing requiring complex interplay. The article compares traditional matrix layouts with alternative options, such as single-lane pathways and non-matrix layouts like honeycomb or star shapes, using simulation-based analysis to evaluate their potential impact on system performance.

Introduction

New challenges based on increased individualization of products, shorter product life cycles, external influences, etc. [18] lead to increased requirements regarding the flexibility of modern production systems. Final assembly in particular must be able to react flexibly to changing conditions and requirements without neglecting the economic efficiency of product assembly or the various product variants [7, 8, 22].

One of the main planning problems here is that the individual tasks (process steps) can be very different, and it is therefore almost impossible to define a uniform system cycle time, see Figure 1. Furthermore, it is increasingly desirable to realize changes in the production system without or at least with very little interruption to the production process.

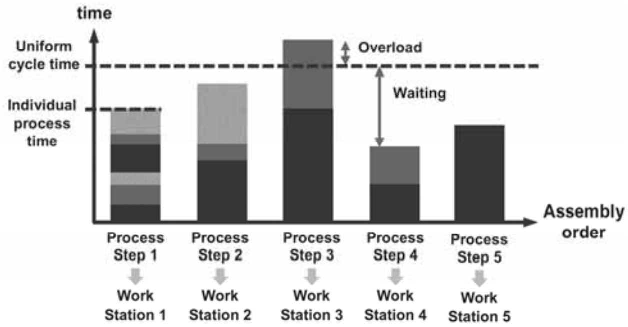

Figure 1: Individual process times vs. uniform cycle time [13].

Traditional flow shop/line production sometimes reaches its limits and is replaced or supplemented by more flexible, workshop-oriented production principles.

A number of pilot projects can be observed in the automotive industry in particular [12], in which different players describe similar concepts using different terms that sometimes only differ in detail. For example, terms such as "modular assembly" [1, 15], "Flexi-Line" [19], "fully flexible factory" [6], or "matrix production" [13] can be found in the literature.

The common goal of all these approaches is to manufacture several product types or their variants efficiently in the same production facility and, in the best case, to avoid lengthy conversions or new builds when introducing new products. In the best-case scenario, new products can even be introduced without interrupting ongoing operations [10]. In this article, these concepts are subsumed under the collective term modular production or assembly systems.

Such modular production or assembly systems consist of adaptable workstations (production cells) with their specific tools and trained personnel, at which one or usually several different production or assembly activities (tasks) can be carried out. The production orders, in the case of final car assembly the car bodies, are transported using automated guided vehicles (AGVs). The specific routing is determined ad hoc by the system, taking into account the existing technical restrictions and the individual task packages of the products or product variants to be manufactured as well as the current status of the overall system [8, 14].

According to Kern [15], the main features of modular assembly systems can be summarized as follows:

- Decoupled stations, in particular the elimination of cycles and assembly lines,
- self-control, both at the level of orders and of all resources,
- integrated processes, particularly with regard to logistics, material provision and quality management, and
- the ability to adapt to changing requirements over time.

The most obvious initial challenge is the operational control of such systems. For example, various levels must be considered when controlling the AGVs alone [8, 9], see Figure 2.

Furthermore, the material supply of the production cells is also a non-trivial task with very specific additional requirements.

In addition to the control system, the system design is crucial for the performance of the entire production system. When designing a modular production system, various design dimensions, which are already complex in themselves, must be considered in their interactions. For example, the allocation of activities/skills to production cells, i.e. which production steps are possible on which production cells, is a crucial point [2, 3]. The design and dimensioning of the AGV fleet, the number and training of workers and much more must also be considered.

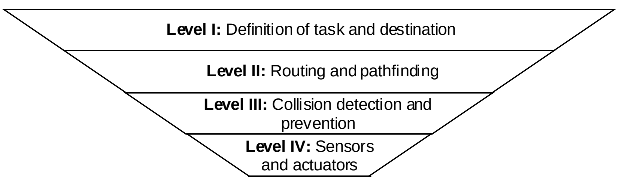

Figure 2: Hierarchy of decision-making [9].

In the vast majority of cases, the production cells have so far been positioned in a chessboard/matrix arrangement with often complete two-lane path systems in the hall layout [13]. This article will use a simulation-based comparison to investigate whether there is general potential for improvement here or whether other equivalent or even better alternatives are conceivable. On the one hand, deviating path topologies for matrix layouts, e.g. single-lane paths or incomplete path networks, will be examined. On the other hand, deviating basic layouts, e.g. an arrangement of the production cell in the form of honeycombs/hexagonal or in a star layout, will be examined. In particular, the achievable system performance (throughput, workloads, etc.) as well as the utilization of the routes, the congestion behaviour of the AGVs or the space requirements of the route network, among other things, must be examined.

In addition, the interaction between the layout and the allocation of activities/skills to production cells will be shown using an initial small test setup.

The article, which is an extended version of the article published at ASIM Dedicated Conference 2023 [4], is structured as follows: The introduction introduces the topic of the article and clarifies the motivation. This is followed by a brief description of the current state of research and the necessary theoretical foundations on the subject of modular production systems, in particular their layout. Building on this, the main part of the article first presents a basic comparative scenario of realistic modular production as well as various layout variants. Where necessary, assumptions and restrictions are discussed. Furthermore, the results of initial simulation experiments on the individual layout variants are briefly presented, as well as a short excursus on the effects of different allocation of activities/skills to production cells. A critical assessment and an attempt to generalize the findings are also made. The article closes with a conclusion and an outlook on further interesting research opportunities in the context of modular production.

1 Layouts of Modular Assembly Systems

In modular assembly systems, which are largely used synonymously for a number of similar terms in this article, the principle of flow production that has often prevailed in final assembly to date is replaced by a more workshop-oriented assembly.

Such systems can often also be understood as cyber-physical systems, whereby the use of data, e.g. sensor data and automated transport systems, enables a certain degree of decentralized autonomous control that can react to the individual situation of the assembly system at any time [5, 15, 16].

Such systems are characterized in particular by

- decoupled workstations (production cells) with individual cycle times,
- several activities / skills per production cell,
- redundancies of skills on different production cells and
- flexible material flows by means of AGVs (automated guided vehicles).

When designing modular assembly systems, various design dimensions must be taken into account, which often interact with each other. These include

- the assignment of activities/skills to production cells [3],
- the design of the control of production orders including AGVs [10],
- the planning of material supply [11] and
- the distribution and arrangement of the production cells (layout).

This article focuses on the influence of layout on the performance of modular assembly systems, although there are significant interactions with other design dimensions, e.g. in the allocation of activities/skills to production cells, control strategies, etc.

In the following, layout is understood as the result of layout planning, i.e. the (often graphical) spatial arrangement of the structural and functional elements relevant to production [17, 20]. One subtask is the planning of transport routes and material flows, which has a significant influence on system performance [20]. As flexible transportation systems such as AGVs are used in modular assembly systems, the route network and buffers, both at production cells and in the warehouse etc., are particularly relevant.

Currently, matrix or chessboard-like arrangements are common in the mostly rectangular halls, in which complete two-lane road networks that can be driven on in both directions usually predominate [10, 21].

To evaluate the performance of modular assembly systems, the broad portfolio of key figures from the context of factory planning [20] can be used.

In the following, static indicators such as the required space, the total length of the route network and the proportion of routes in the total area are calculated and indicators such as the throughput, the average throughput time per product type, the average travel distance/travel time per product and the utilization of the routes are determined by means of simulation experiments.

2 Simulation-based Comparison of Basic Layouts Using a Case Study

Before, as promised, various alternative layouts with the corresponding route networks are considered, a scenario for a modular assembly system will first be introduced. The scenario is designed in such a way that it is sufficiently complex and takes into account many factors known from practice. At the same time, it is explainable and can be described within the scope of the article.

The following assumptions and characteristics are used as a basis: the area available for modular assembly is max. 80x70m, 16 possible production cells (each with its own buffer area for 3 AGVs) are planned. Production cells take up approx. 11x11m of hall space. Lanes require a minimum width of 2m per lane.

production cell no	**assigned activities**
I	A, B, H
II	C, D, E
III	A, B, H
IV	C, D, E
V	J, F
VI	J, F
VII	G, I
VIII	G, I
IX	R, S, T
X	R, S, T
XI	K, M, P
XII	K, M, P
XIII	O, L
XIV	O, L
XV	N, Q
XVI	N, Q

Table 1: basic scenario assignment of activities to production cells.

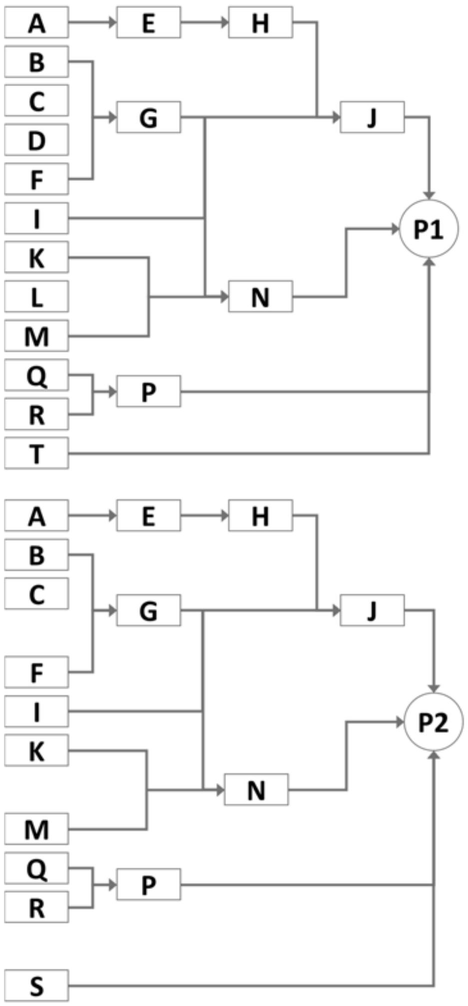

Figure 3: Priority graphs for product 1 (top) and product 2 (bottom).

The assignment of activities to production cells (see Table 1) was defined in advance and is comparable for all basic scenarios. Alternative assignments are introduced in the explanations of the effects of the assignment in interaction with the layouts.

Basically, between two and three different activities/assembly steps are assigned to each production cell. In addition, two product types were defined that occur with equal frequency. Each product type has up to 18 production steps and has its own priority graph (see Figure 3) as well as individual processing times.

AGV control is decentralised and rule-based. Specifically, from the possible production cell, which depend on the currently possible assembly steps, the AGVs select the one with the shortest queue or the one that is not yet occupied.

In the event of a tie between several cells, the closest cell is approached. If this is also not clear, a random choice is made.

The selection of the control method influences the performance of the modular production system and it can also be assumed that there is an interaction between the control and the layout, which is neglected in the following explanations.

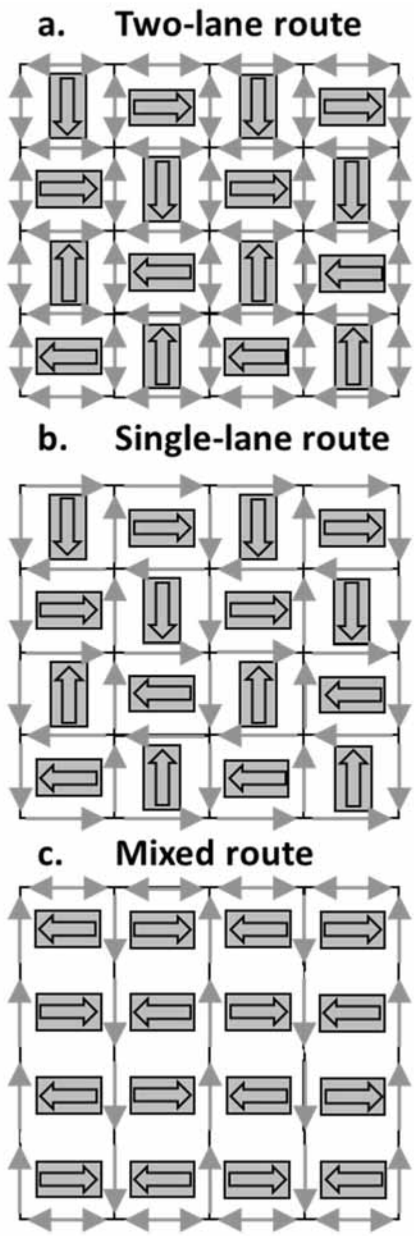

Figure 4: Three variants of matrix layouts.

Furthermore, the number of AGVs and thus the number of orders active in the system at the same time was set to 22 based on preliminary experiments. For the material supply, shopping baskets are assumed which are on the respective AGVs from the outset. This means that an explicit mapping of the material supply can initially be abstracted. The simulation time in the Siemens Plant Simulation simulator was 144 hours (6 days) per experiment run.

In addition to the classic matrix arrangement already mentioned (Figure 4, top) with a complete two-lane route system, 6 other layouts or route network variants were compared (see Figure 4, Figure 5, and Figure 6). It should be noted that the idea of a free arrangement of stations without fixed routes was initially rejected for this comparison due to the lack of comparability.

In addition to the obvious visual differences between the basic variants matrix layout (see Figure 4), honeycomb/hexagonal layout (see Figure 5), and star layout (see Figure 6), the detailed design of the road networks is of particular interest. For all two-lane road systems, it is assumed that all roads have two lanes and are therefore 4 meters wide. This not only enables overtaking, but also allows AGVs to meet on one section of the route. In contrast, all single-lane path systems are assumed to be one-way streets in order to avoid deadlocks. It is essential to ensure that there are no dead ends.

The two variants referred to as "mixed road systems" are special cases in which both two-lane and single-lane roads are present in the road network. In the mixed matrix arrangement, the paths at the top and bottom are two-lane, while all vertical paths in the illustration are single-lane. The direction of the single-lane paths is alternating. In the star-flow arrangement, single and double-track paths are also used in the mixed path system. In concrete terms, the inner ring is a one-lane road and therefore one-way.

layout	Total length / width	Base area [m²]	Path area [m²]
Matrix 2-lane	64m / 64m	4.096	2.146
Matrix 1-lane	54m / 54m	2.916	977
Matrix mix	58m / 55m	3.190	902
Hex 2-lane	80m / 68,5m	4.385	2.221
Hex 1-lane	68m / 58,5m	3.318	1.017
Star 2-lane	62m / 62m	2.907	647
Star mix	62m / 62m	2.907	499

Table 2: Area comparison of the implemented layout and route network variants.

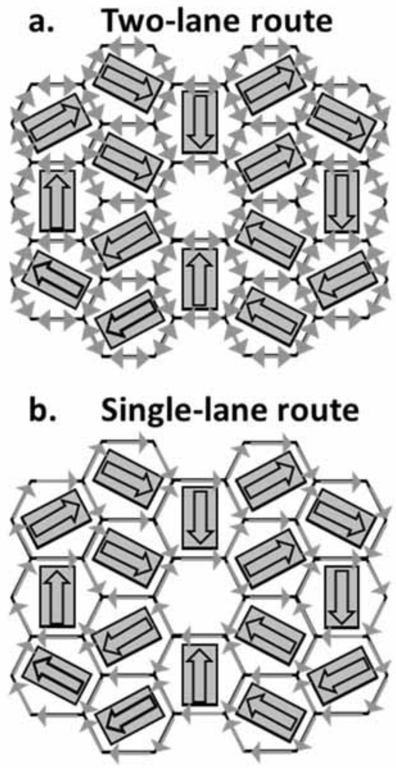

Figure 5: Two variants of honeycomb/hexagonal layouts.

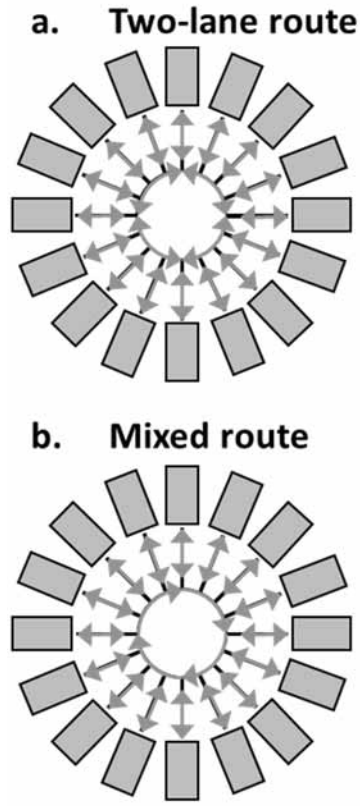

Figure 6: Two variants of a star layout.

As already mentioned, initial key performance indicators for the individual layouts can already be calculated without simulation experiments. The required area and the proportion of paths in the total area differ considerably in some cases (see Table 2).

It is clear to see that the star layout, which at first glance appears quite unusual, has the smallest area requirement in this scenario, whereby the free space created in the interior has been deducted here. However, the practical scalability of this layout to more stations is doubtful. It can also be seen that single-lane routes generally require less space and that the honeycomb / hexagonal layouts require a slightly larger area overall than the classic matrix layout. But, it should be noted that the honeycomb/hexagonal layouts have negative edge surfaces (half hexagons) and that one hexagonal remains completely free. These free areas could possibly be used for other purposes in practice. It can also be assumed that there is further potential for saving space with non-rectangular production cells, ideally also designed as hexagons.

Using simulation, a screenshot of the model for the honeycomb layout is shown in Figure 7, further parameters were determined for all 7 variants; the throughput, the average travel distance per product and the average travel time per product can be seen in Table 3. These comparative values also show clear differences.

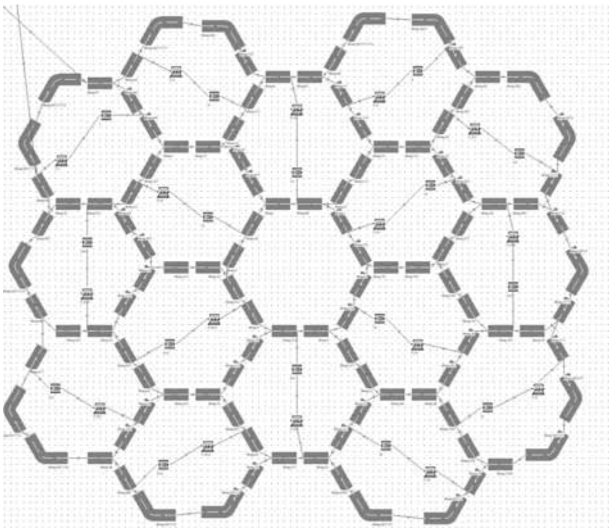

Figure 7: Screenshot of the simulation model for the honeycomb/hexagonal layout in the simulator Siemens Plant Simulation.

layout	Through put [pcs.]	Avg. route length [m]	Avg. movement time [min]
Matrix 2-lane	170	699,85	11,5
Matrix 1-lane	161	1.592,11	26,5
Matrix mix	171	1.482,82	24,5
Hex 2-lane	171	771,12	13,0
Hex 1-lane	170	1.381,15	23,0
Star 2-lane	112	605,04	10,0
Star mix	116	970,47	16,0

Table 3: Comparison of throughput, average route length, and movement time of the layout variants.

A significantly lower throughput can be observed for both star-shaped layouts, as blockages occurred in the simulations that led to a complete standstill in production. The single-lane matrix layout also achieves slightly lower throughput values, as the AGVs occasionally have to wait in front of full buffers, which are then difficult to avoid. Improved control of the AGVs or mechanisms to prevent and eliminate blockages could possibly counteract this problem.

Such effects do not occur with two-lane matrix or honeycomb/hexagonal layouts, as the lanes are not completely blocked and overtaking are possible. With the mixed matrix layout, the possibility of overtaking on the two-lane paths is obviously sufficient to avoid negative effects. The single-lane honeycomb/hexagonal layout shows surprising behaviour, with hardly any blockages occurring despite the lack of overtaking opportunities. This is due to the fact that there are often very good alternative routes between two points. The fact that there are no junctions with four entrances or exits also has a positive effect, which significantly reduces the complexity in the event of a conflict.

In general, however, it can be seen that transportation times do not immediately affect throughput and should therefore not be the main criterion for planning. In contrast, the occurrence of blockages is an important factor that must be taken into account during planning.

In order to provide further insights, the last parameter presented here is the utilization of the routes. The analysis of the utilization of the routes, based on the number of trips per route segment, provides further insights into the system. In order to make the utilization of the routes more comparable, all route segments or subsections were divided into one of four classes.

The classification is based on the number of journeys made on the respective route segments. These classes serve to better differentiate the utilization and allow a comparison of the routes so that bottlenecks and congestion can be identified. The classes are as follows: Green 0-499 travel orders (very low utilization), Yellow 450-899 travel orders (medium utilization), Orange 900-1349 travel orders (high utilization), and Red 1350-1800 travel orders (very high utilization). Table 4 shows the results of this analysis.

It can be seen that in the two-lane matrix and honeycomb/hexagonal layouts, the utilization of the routes is lower overall, as vehicles have the opportunity to overtake and/or use alternative routes. The utilization values tend to be higher for the single-lane routes, as there are no overtaking opportunities and vehicles may have to wait. Interestingly, the star-shaped layouts have lower utilization values, despite the blockages and lower throughput.

This is because the routes inside the star, where the blockages occur, have fewer trips due to the production standstill. The routes outside the star, on the other hand, are relatively free and therefore have lower utilization values.

With single-lane or mixed matrix layouts, on the other hand, a small number of the routes are used much more frequently (orange and red). It can be assumed that this effect can possibly be reduced, but probably not completely eliminated, by adjusting the distribution of activities on the production cells or optimizing the AGV control strategies.

With single-lane or mixed matrix layouts, on the other hand, a small number of the routes are used much more frequently (orange and red).

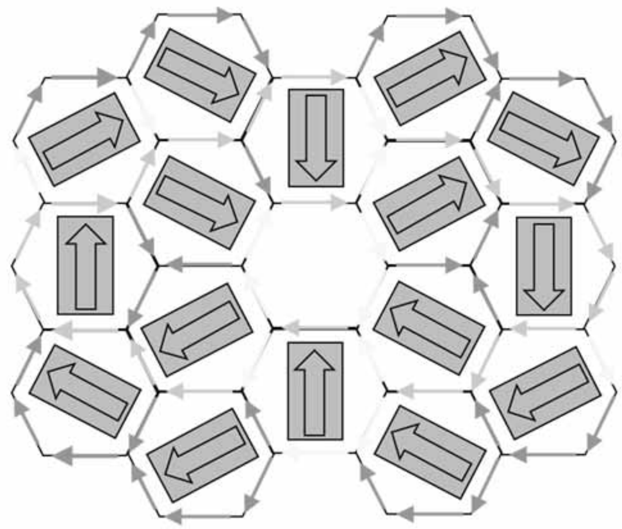

Figure 8: Visualization of the utilization of the routes for the single-lane honeycomb/hexagonal layout.

It can be assumed that this effect can possibly be reduced, but probably not completely eliminated, by adjusting the distribution of activities on the production cells or optimizing the AGV control strategies.

Again, the single-lane honeycomb/hexagonal layout proves to be surprisingly robust in the test, in which some routes have a higher utilization than in the two-lane case, but no very highly utilized routes (red) occur. The visualization of the path utilization, as shown in Figure 8 for the single-lane version, can provide additional insights into problematic areas of the modular assembly system.

The experiments conducted so far do not provide any definitive and generally valid results regarding the advantages of a specific layout for any modular assembly system.

layout	Number of route segments per class				Total number of path segments
	Green (0-449)	**Yellow** (450-899)	**Orange** (900-1349)	**Red** (1350-1800)	
Matrix 2-lane	85	13	0	0	98
Matrix 1-lane	58	28	16	17	119
Matrix mix	25	25	26	10	86
Hex 2-lane	94	20	0	0	114
Hex 1-lane	56	28	30	0	114
Star 2-lane	16	16	0	0	32
Star mix	13	3	0	16	32

Table 4: Utilization of the route system of the implemented layout variants.

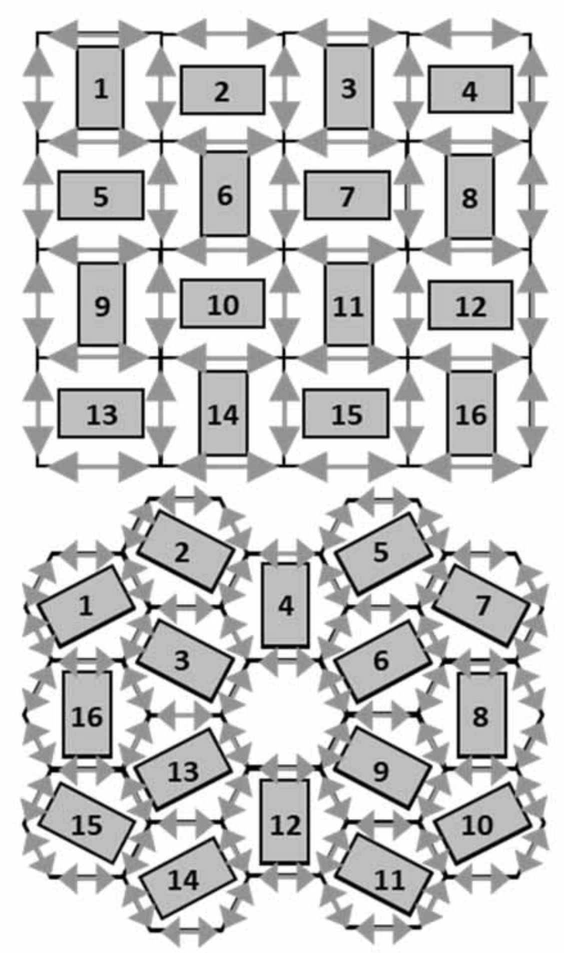

Figure 9: Cell Position in the matrix layout (top) and the honeycomb/hexagonal layout (bottom).

Nevertheless, it can already be summarized that the layout apart from the classic matrix arrangement represents a previously underestimated design factor. The single-track honeycomb/hexagonal layout in particular shows potential in the results presented. They offer a good compromise between system performance and space requirements.

If edge areas (half honeycombs) can be used sensibly and the production cells are not restricted to rectangular layouts, but can ideally be designed in the form of hexagons, the honeycomb/hexagonal layout could represent a serious alternative to classic matrix layouts.

On the other hand, layouts that tend to block, such as star layouts, are not suitable. If such layouts are chosen, it is essential to implement mechanisms to prevent and eliminate blockages.

Short Excursus on the Effects of Different Allocation of Activities/Skills to Production Cells

As already mentioned, it can be assumed that there are dependencies between the design dimensions of modular production systems, so that it is relatively obvious to assume interactions between the assignment of tasks to production cells and the layout.

The following is not a comprehensive study on this topic, but the interactions are shown and qualitatively evaluated in a rather small-scale experimental setup.

Therefore, only two layouts are considered for the following analyses: the two-lane matrix layout and the two-lane honeycomb layout (Figure 9). In order to minimize the direct effects of activity allocation, which have been shown to be very significant (see [3]), no changes are made to the combinations of activities on the cells in the experiments. For example, there are always two cells (I and III) in the system that have the combination of activities A, B, H. All 16 combinations can be looked up in Table 1.

In the experiment, only the positions/station numbers are varied, e.g. in the first experiment the positions of production cell I and V, II and VI etc. are swapped. A total of 5 variants were simulated in both layouts, see Table 5.

Position in the layout	production cell in variant:				
	1 (base)	2	3	4	5
1	I	V	II	IV	VIII
2	II	VI	I	III	IX
3	III	VII	IV	II	III
4	IV	VIII	III	I	XIII
5	V	I	VI	VIII	VI
6	VI	II	V	VII	XI
7	VII	III	VIII	VI	XV
8	VIII	IV	VII	V	II
9	IX	XIII	X	XII	XII
10	X	XIV	IX	XI	V
11	XI	XV	XII	X	VII
12	XII	XVI	XI	IX	XIV
13	XIII	IX	XIV	XVI	I
14	XIV	X	XIII	XV	X
15	XV	XI	XVI	XIV	XVI
16	XVI	XII	XV	XIII	IV

Table 5: Cell positioning variants.

The analysis of the simulation data showed that, at least in this case study and the selected cell positioning variants, there was hardly any influence on throughput, station utilization, etc. For example, the throughput in the experiments deviated upwards or downwards by less than 1%.

Only the utilization of individual routes changed, whereby here too there were no critical (red) loads on routes in any variant, but rather moderate shifts in the loads on routes. Only the matrix layout in variant 5 resulted in a high but not yet critical load on the central intersection, which was already over-utilized in all scenarios. Otherwise, the class distribution compared to the basic variant (see Table 4) was almost identical for all variants.

In summary, it can be said that interactions were shown to be weaker than initially expected; further investigations in other layouts and in combination with different ability distributions seem advisable.

3 Conclusion and Outlook

In this article, a simulation-based comparison of different layouts and route network topologies for modular assembly was carried out. A fictitious scenario was used, and although the results are certainly not universally valid, it was at least possible to show the potential of non-classical matrix arrangements and the influence of the design of the route networks.

Further considerations on layouts and route network topologies for modular assembly systems are certainly appropriate. Several limitations were encountered in our analysis. On one hand, not all possible variants were considered; for example, freely positioned production cells without an explicit route network were excluded due to a lack of direct comparability. On the other hand, further investigations are necessary. Ideally, these would involve real-world scenarios to enable more generally valid conclusions.

Furthermore, some points are still need additional research. For example, the supply of materials for modular assembly systems has hardly been investigated to date. The article assumed a supply with a shopping basket, which is not always possible in practice. However, other material supply concepts may lead to additional traffic on the routes and thus to a considerable increase in the load on these routes, which may increase the risk of blockages, etc.

Furthermore, despite individual publications on this topic, there is still considerable potential for research into the control of modular assembly systems.

Finally, a transition from partial considerations to holistic approaches will be necessary in the medium term because, for example, as indicated here, decisions such as the assignment of tasks to workstations are closely linked to layout design, material supply and control. The excursus on selecting the station positioning could provide a small insight here.

However, mastering the complexity of such comprehensive approaches represents a major challenge.

Furthermore, fundamental research topics from the world of simulation are also relevant here. On the one hand, AI and simulation is an exciting subject area, where a wide variety of approaches are conceivable, e.g. for system control or system design, but also for analyzing experiments or communicating the results.

On the other hand, automation and support for model generation continue to be an issue; in addition to classic data-driven approaches, AI-based methods can also help to achieve good simulation models more quickly.

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EUROSIM Data and Quick Info

ASIM SST 2024 27. Symposium Simulationstechnik
27th Symposium Simulation Technique
4. - 6. September 2024, München, Univ. BW, Deutschland www.asim-gi.org

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SIMS

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MATHMOD 2025 11th Vienna Int. Conference on Mathematical Modelling
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www.mathmod.at

Simulation in Produktion und Logistik Sept. 24-26, 2025, Dresden, Germany www.asim-gi.org/spl2025

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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.

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SNE – Simulation Notes Europe is EUROSIM's membership journal with peer reviewed scientific contributions about all areas of modelling and simulation, including new trends as big data, cyber-physical systems, etc.

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Arbeitsgemeinschaft Simulation

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CEA-SMSG – Spanish Modelling and Simulation Group

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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.

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NSSM – National Society for Simulation Modelling (Russia)

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ALBSIM – Albanian Simulation Society

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- **MIMOS** –Italian Modeling & Simulation Association; terminated end of 2020.

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