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).

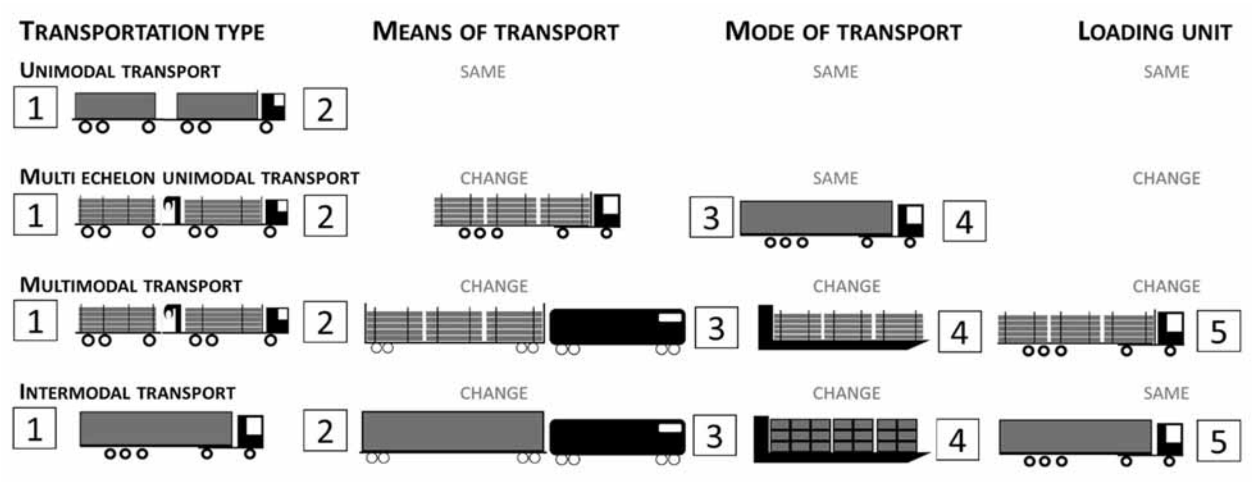

Figure 1: Examples of wood transport types with distinguishing criteria.

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.

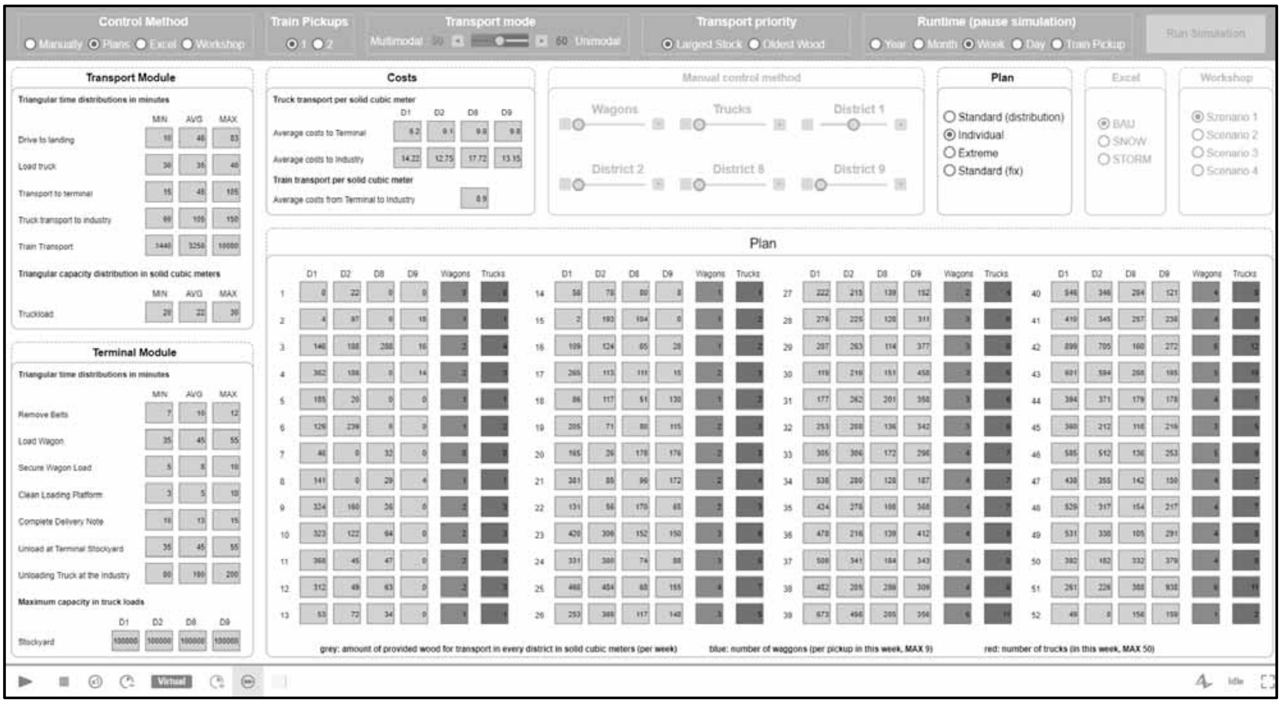

Figure 2: Scenario building view to parameterize and configure the simulation model for intuitive control in serious game-based workshops.

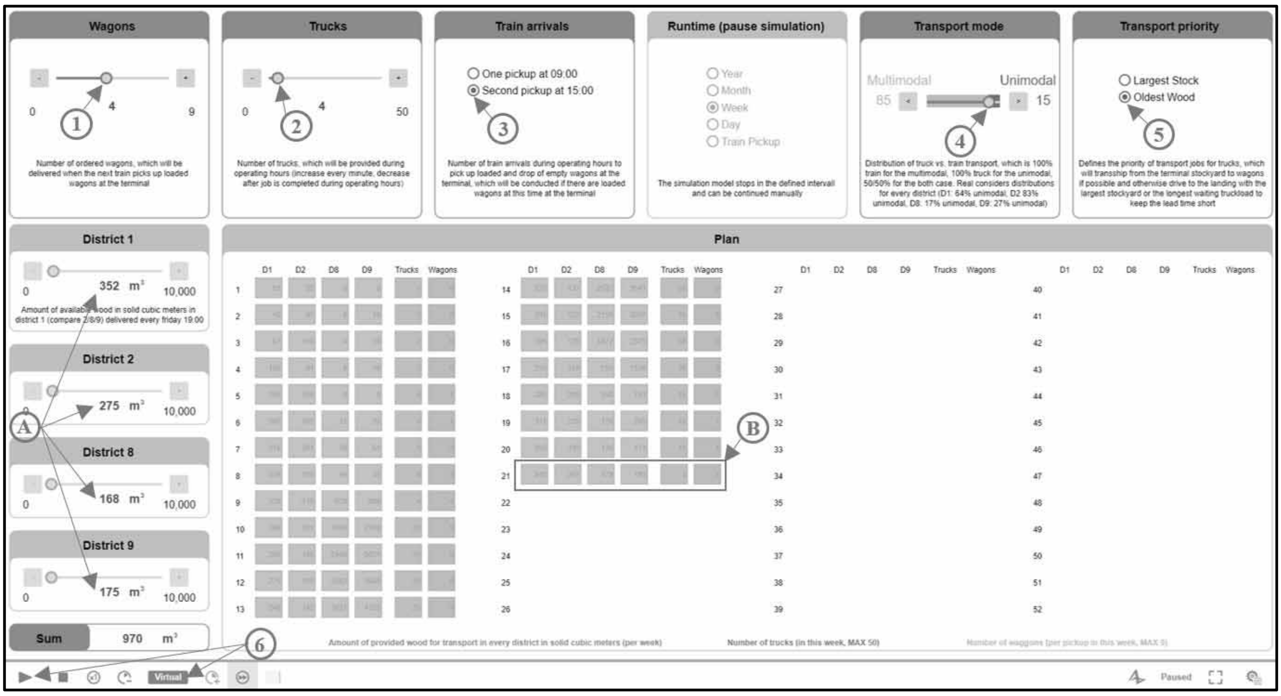

Figure 3: Control view of the serious game-based workshop simulation with scenario information (A and B) and intuitive control elements (1–6).

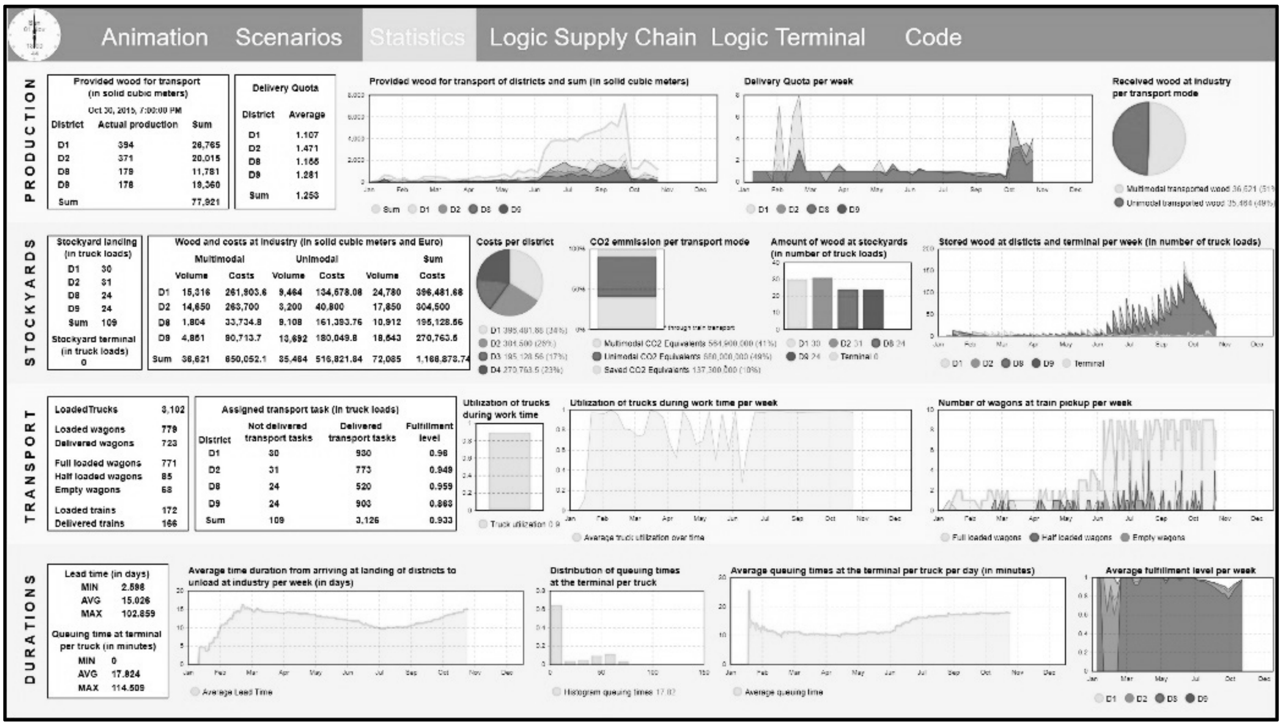

Figure 4: Statistics view of the simulation model with key performance indicators for production, storage, and transport.

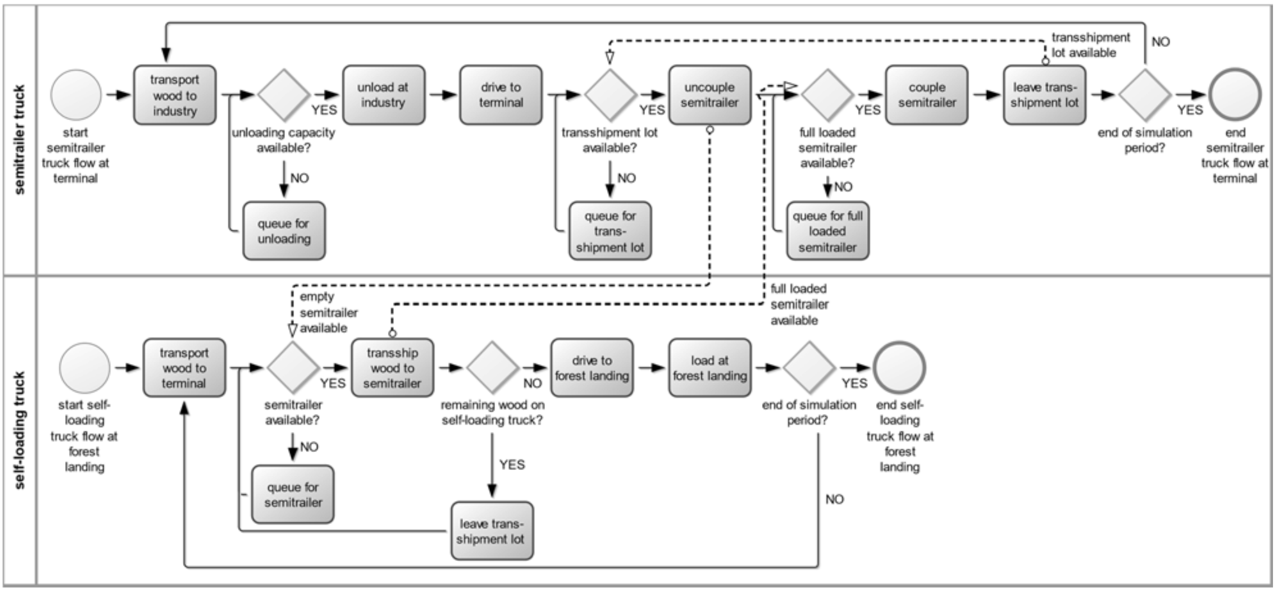

Figure 5: Process flow for semitrailer and self-loading log trucks from the pick-up in the forest via transhipment operations at a terminal to unloading at industry.

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.

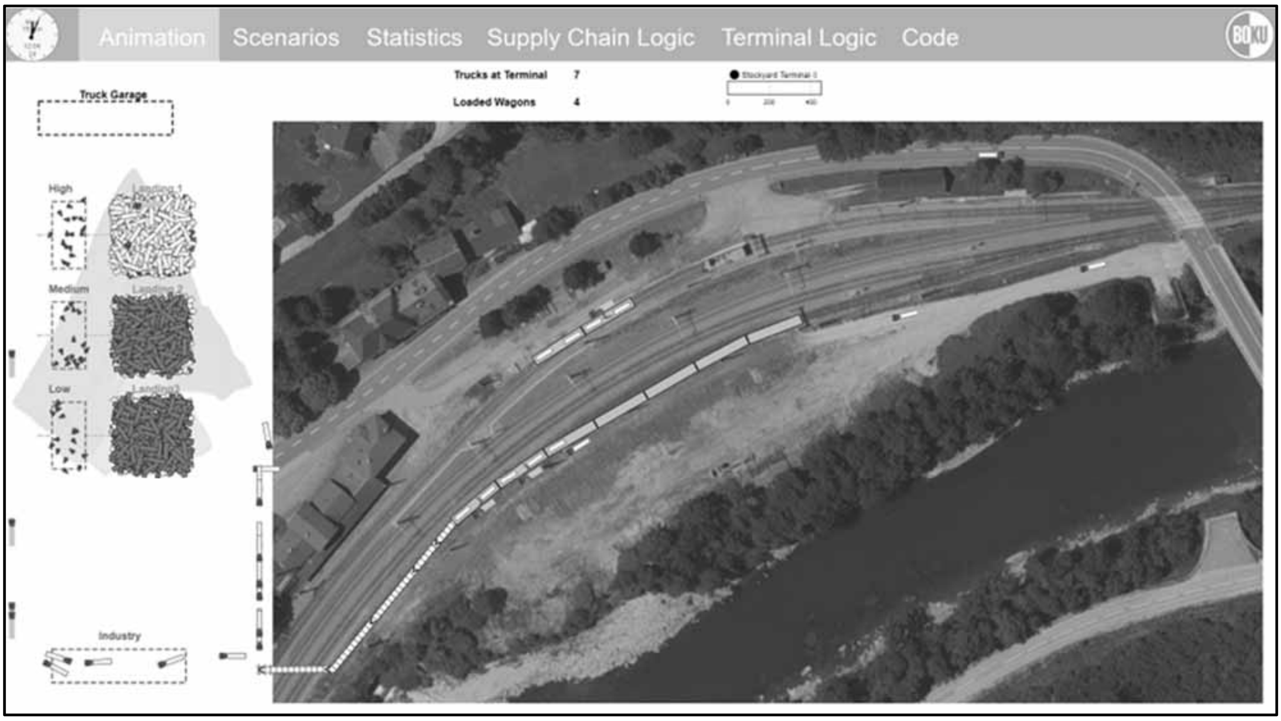

Figure 6: Animation view of a virtual wood supply chain environment visualizing sawlogs, trucks, train wagons, terminal, stockyards, and harvesting regions in three altitude zones.

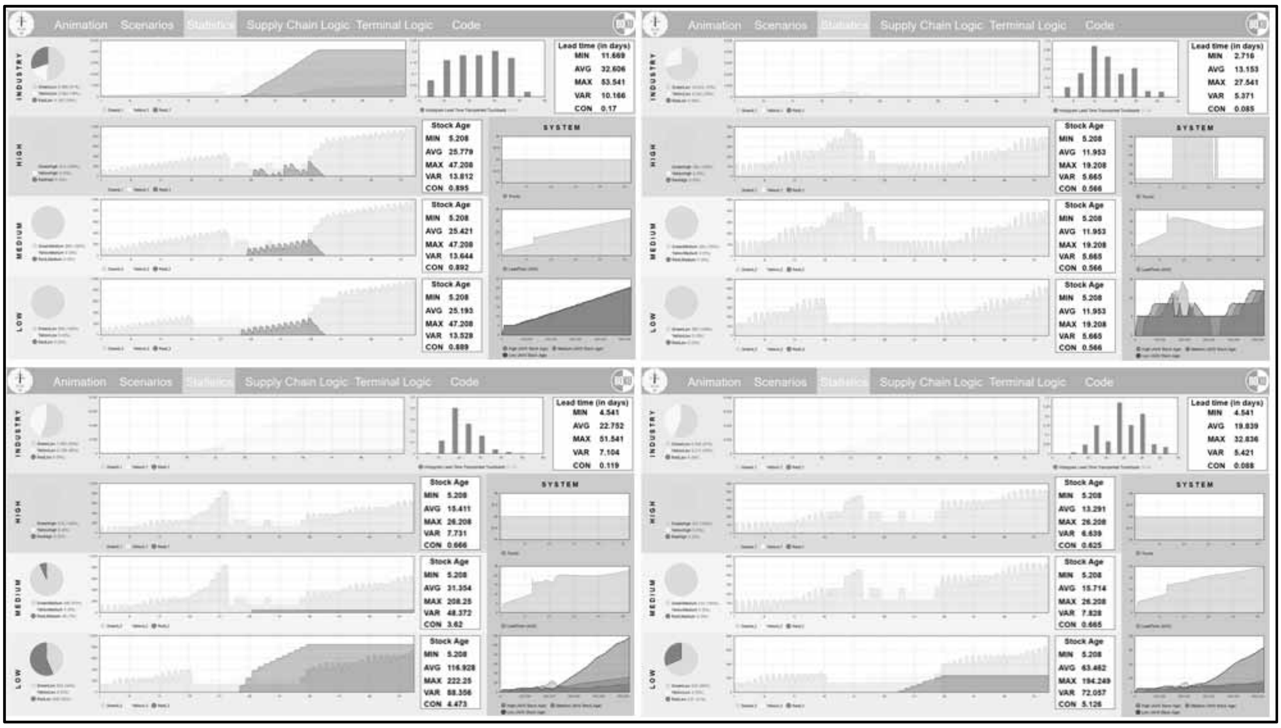

Figure 7: Management cockpits showing statistics of different transport scenarios for fresh sawlogs (green), roundwood facing devaluation (yellow) and devaluated roundwood (red).

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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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