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# Discrete Event Simulation-Based Risk Analysis for Efficient, Sustainable and Resilient Transportation

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**Abstract**

In a resource-constrained world the avoidance of transport-related emissions is crucial to fulfill the sustainable development goals, the Paris agreement on climate change and the Aichi biodiversity targets. Transport simulation enables the development of transport fleet strategies in risk scenarios to further improve efficientcy, sustainability and resilience of supply chains. Discrete event simulation is a valuable methodology for transport simulation, because it focuses on business processes for a digital representation of supply chains and provides an intuitive approach for facilitating stakeholder participation. Consequently, discrete event simulation models for unimodal, multimodal and multi-echelon unimodal wood transport are presented, which enable multicriteria-based strategy development, optimal fleet configuration as well as risk management and wood quality preservation. Furthermore, the verificated and validated discrete event simulation models were used in game-based stakeholder workshops to establish credibility, provide hands-on decision support and facilitate knowledge transfer between science, industry and education. A previous version of this revised and extended journal article was published as conference paper in the Proceedings of the XIV$^{th}$ Junior Forensic Science Conference (JuFoS), 18–19 May 2023 in Brno.

**Keywords:** supply chain management, risk management, logistics, transportation, decision support, game-based learing, simulation workshops.

## 1. INTRODUCTION

Supply chains are dynamic networks of information and material flows between and within different stakeholders and therefore, supply chain and risk management cover crucial decisions to plan, design, operate, control and monitor the entire supply chain. The wood supply chain comprises growing, harvesting, extraction, transporting, storing, (pre-)processing, (re-)using and recycling of wood on strategic, tactical and operational horizons. [1]

The discrete event simulation method enables a realistic, digital mapping of wood supply chains (*i.e.*, business process-based structure, visualization, animation) and their quantitative analysis in risk scenarios (*e.g.*, parameter variation, what-if analyses) based on key performance indicators. Moreover, it has major strengths

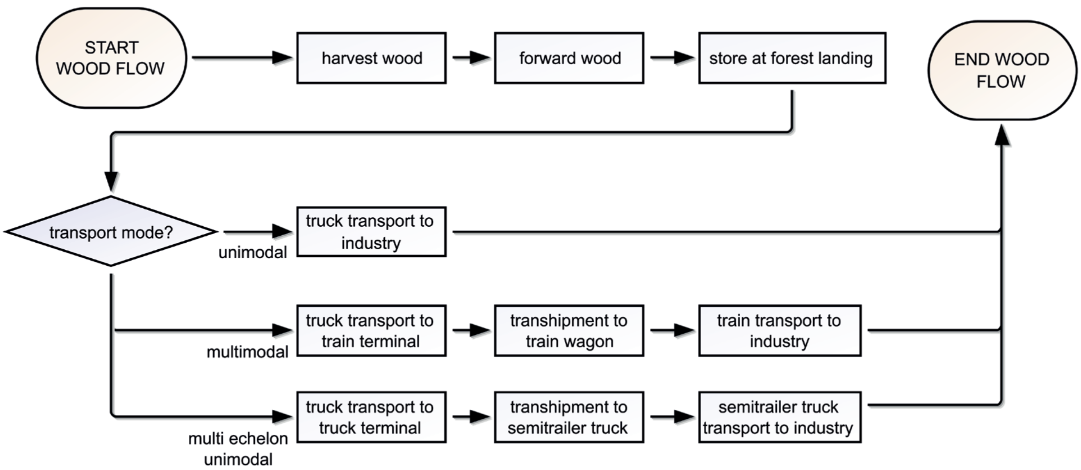


*Fig. 1 Transport modes for the wood flow through the supply chain.*

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in integrating stochastic elements, complex interactions, time dynamics and bottleneck-related queuing systems. [2]

Therefore, discrete event simulation is an ideal method providing urgently needed decision support for stakeholders, researchers and students to improve the efficiency, sustainability and resilience of transportation along wood supply chains. Fig. 1 provides an overview of the relevant transport modes, which are the connective links along wood supply chains. Single echelon unimodal transport defines direct transport from forest landings to the wood-based industry with self-loading trucks. Multi-echelon unimodal transport includes a transshipment operation to a semitrailer truck and multimodal transport covers a transshipment operation to a train.

Wood value chain resilience is the adaptive capability 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. Benchmarking [3] and contingency planning [4, 5] have proven to be helpful tools to implement collaborative supply chain and risk management to improve the resilience and sustainability as well as save costs. Consequently, the following sections provide a compact overview of the application potentials for the discrete event simulation method for logistics, transportation, supply chain and risk management as well as references to further information.

## 2. DISCRETE EVENT SIMULATION MODELS

### 2.1 Quality-preserving wood transport

Quality-preserving wood transport strategies are based on the significant correlation between lead-time and quality loss of logs during storage and transport (mainly caused by fungal and insect infestation). The discrete event simulation model demonstrates the potential of vegetation zone-based risk forecast to develop unimodal and multimodal transport strategies that prioritize wood at risk of devaluation and thus avoid wood value loss.

Fig. 2 shows the animation view of the discrete event simulation model developed in the Java-based AnyLogic software. It visualizes abstract illustrations of forests in three altitude zones (left), a train terminal (right) and piles (representing one truckload of 25 cubic meters roundwood) with fresh sawlogs (green), risky roundwood facing devaluation (yellow) and devaluated roundwood (red) transported by self-loading trucks and trains. For further insights on how quality development of transported goods were tracked and modeled as well as which transport strategies performed best refer to [6] and [7].

### 2.2 Multimodal transport

Multimodal wood transport strategies reduce negative environmental impacts (*e.g.*, $CO_2$, noise) and increase resilience (*e.g.*, additional transport capacity after calamities, storage capacity at the terminal) through short self-loading truck transportation to train terminals and subsequent rail transport. However, multimodal supply chain management is more challenging compared to unimodal transportation, making the simulation model a needed quantitative decision support tool for developing transport fleet strategies based on multi-criteria metrics defined with practice experts.

Fig. 3 presents a management cockpit consisting of key performance indicators, which are automatically updated in real time. The decision relevant statistics for production, stockyards, transport and duration give an overview and interactive feedback of the actual and past performance of the entire wood supply chain. The developed strategies for challenging real life scenario

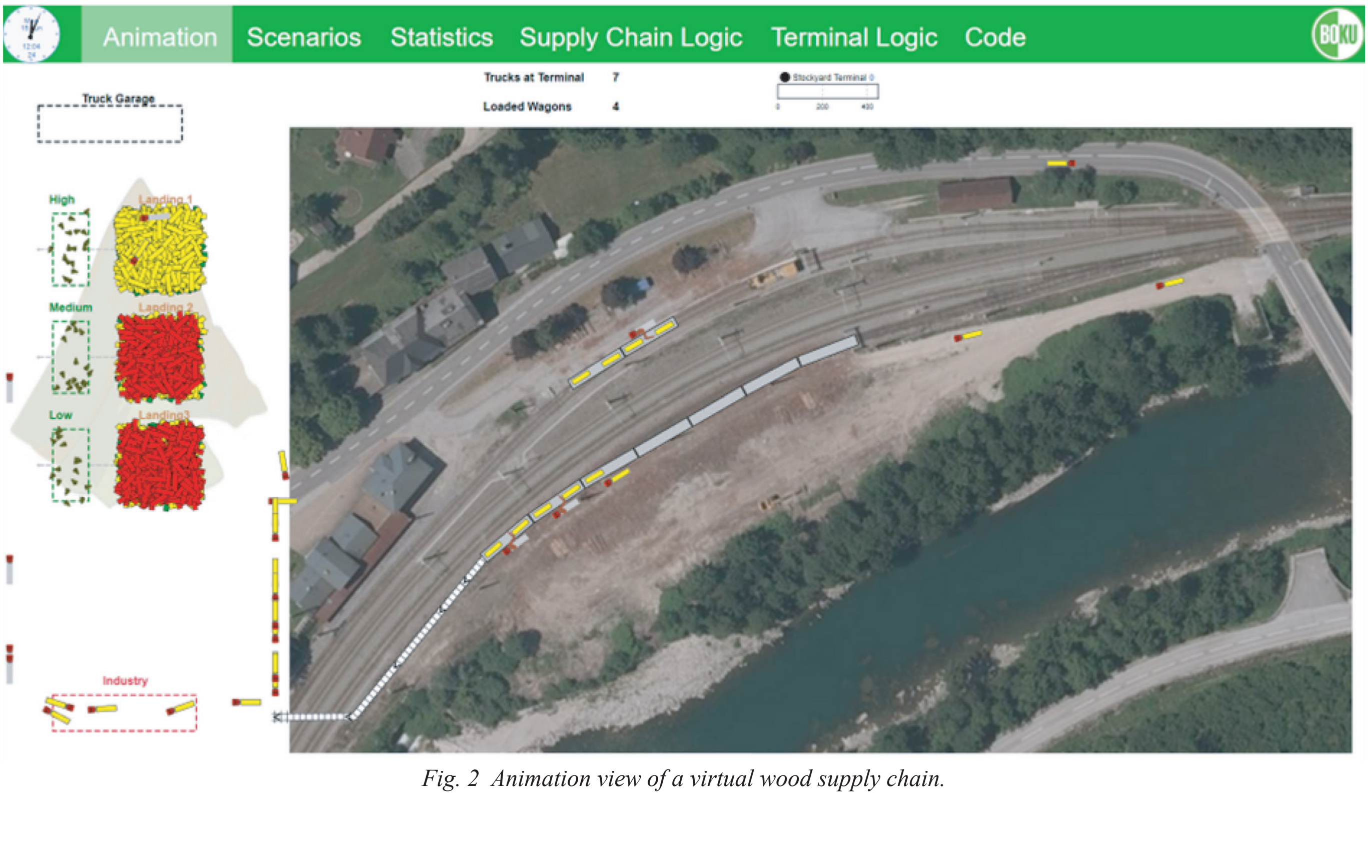


*Fig. 2 Animation view of a virtual wood supply chain.*

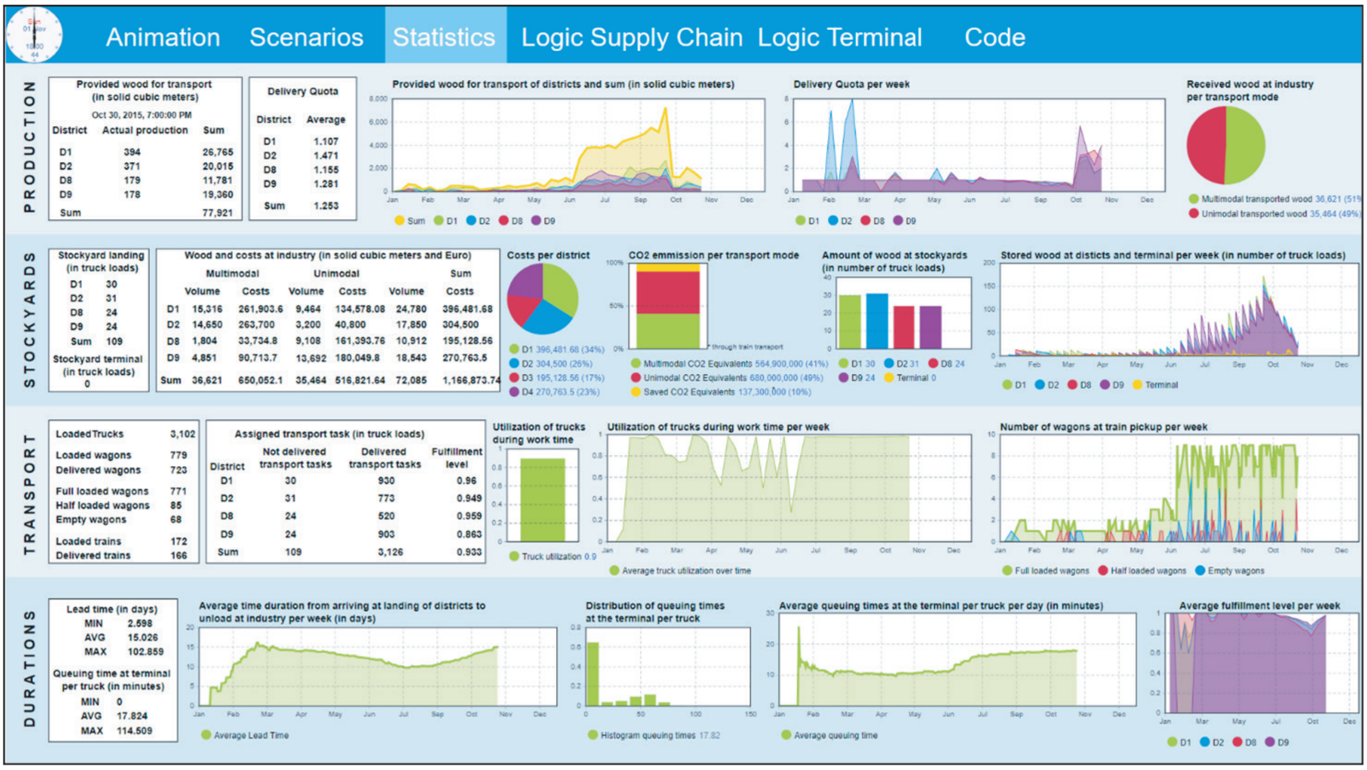


*Fig. 3 Key performance indicator cockpit of a virtual wood supply chain.*

settings were evaluated based on multi-criteria metrics for *e.g.*, the transported volume, delivery quota, queuing time at terminal, stockyard volume, lead time, number of loaded wagons, carbon dioxide equivalents, fulfillment level, truck utilization and transport costs. A detailed description of the covered case study as well as the discrete event simulation model (modules: forest, truck transport, terminal, train transport, industry), views (*i.e.*, animation, parameterization, management cockpit, supply chain processes and logic, terminal processes and logic, statistics) and parameterization for the performed simulation experiments can be found in [8] and [9].

### 2.3 Multi-echelon unimodal transport

Multi-echelon unimodal wood transport strategies are based on short self-loading truck transportation to transshipment terminals. There semitrailers are provided for the subsequent transport with prime mover trucks. The lower tare weight of semitrailers compared to self-loading trucks increases transport efficiently as well as alleviates the drastic self-loading truck driver bottleneck. The multi-echelon unimodal model allows the simultaneous optimization of the fleet as well as handling infrastructure (*i.e.*, number of transshipment slots, self-loading trucks, semitrailers) based on complete enumeration.

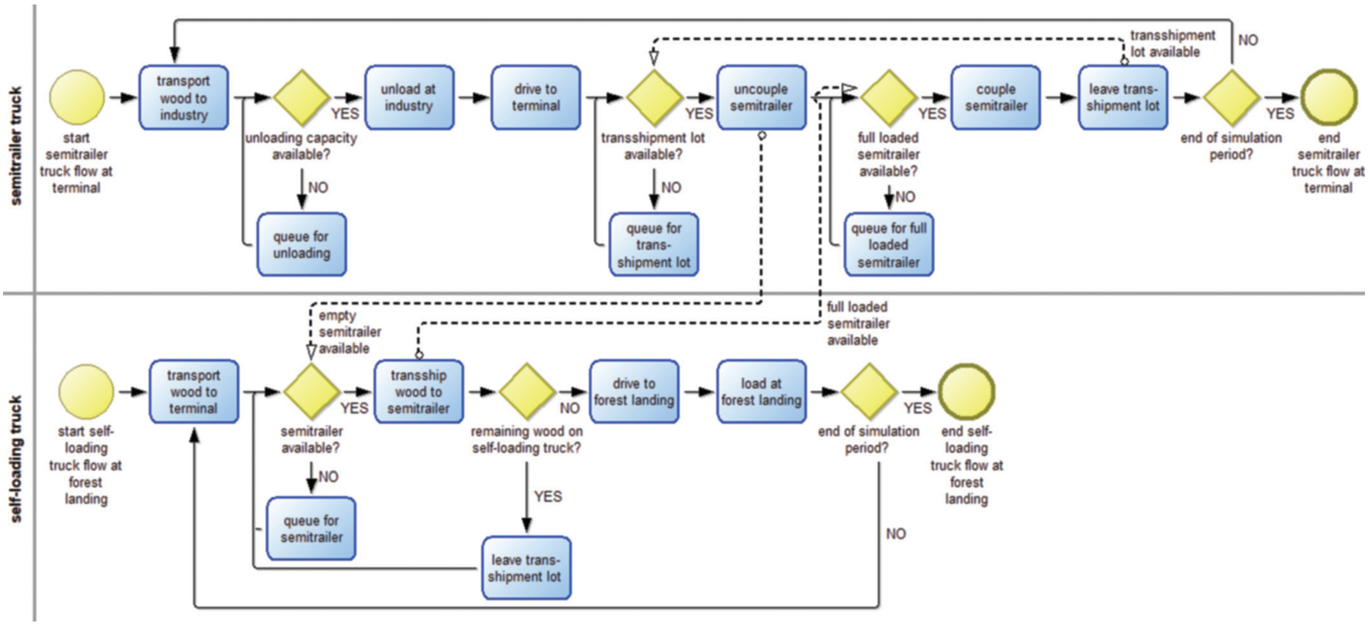


*Fig. 4 Transport processes of self-loading trucks, prime mover trucks and semitrailers.*

Fig. 4 represents the logic and interactions of self-loading trucks, prime mover trucks and semitrailers in a diagram modeld in the open access Bee-Up software environment (available on omilab.org) corresponding the standards of the Business Process Model and Notation (2.0). For further information on the optimal truck fleet configurations and detailed descriptions of the simulation model refer to [10] and [11].

## 3. GAME-BASED STAKEHOLDER WORKSHOPS

In order to enhace the scientific support for today's (managers) and tomorrow's (students) decision makers, state of the art simulation methods were integrated with stakeholder participation in tool development and analyses. The scientific discrete event simulation models for supply chains were further developed with special focus on animation, visualization and intuitive usability in a workshop setting. They proved to facilitate needed decision support for managers and to provide means to train students and sensitize researchers. This enabled a learning process through playing a serious game and analyzing the outcome of decisions according to key performance indicators in group discussions. The collaborative development of supply chain control strategies by means of a participatory simulation environment enhanced the development of advanced risk management and therefore improved supply chain resilience, efficiency, and sustainability.

Fig. 5 shows the workshop control view of a discrete event simulation model with harvesting volumes for each region for the upcoming week (A) as well as the harvesting volumes of the past weeks (B). Furthermore, the transport plan for the upcoming week can be defined by choosing the number of train wagons (1), number of trucks (2), number of train pickups per day (3), transport mode split (4) and transport priority (5). After the current situation of the supply chain was analysed by observing the management cockpit, animation and logic views, the transport strategy for the upcoming week is selected and the simulation for the next week starts (6).

The workshop consists of a input, learning by doing and analysis stage, each with a duration between 30 and 60 minutes.The input stage gives an overview of the workshop agenda, problem setting and goals. Furthermore, the discrete event simulation model is introduced by a live demonstration of process flows, a detailed animation and changes of key performance indicators to observe the behavior of the system. The learning by doing stage starts with a clear scenario definition, before participants get hands-on experience and play the defined simulation scenario in small groups from 3 to 5 people. Week-by-week, every group discusses their strategies and decides on the transport plan for the next week. At the end of the simulation runs in the analysis stage, the key performance indicators are exported, discussed with the participants and transport strategies applicable in practice are developed based on the learnings. Further insights on the didactial concepts and concrete workshop program with feedback of testruns can be found in [12] and [13].

## 4. CONCLUSION

Current and future challenges require innovative, digital and quantitative decision support tools for the stakeholders along wood supply chains. The presented wood transport models demonstrate the high suitability of the discrete event simulation method for contingency planning (*e.g.*, concrete transport planning tables), risk management (*e.g.*, climate crisis-related extreme scenarios, wood quality development) and strategy development (*e.g.*, serious

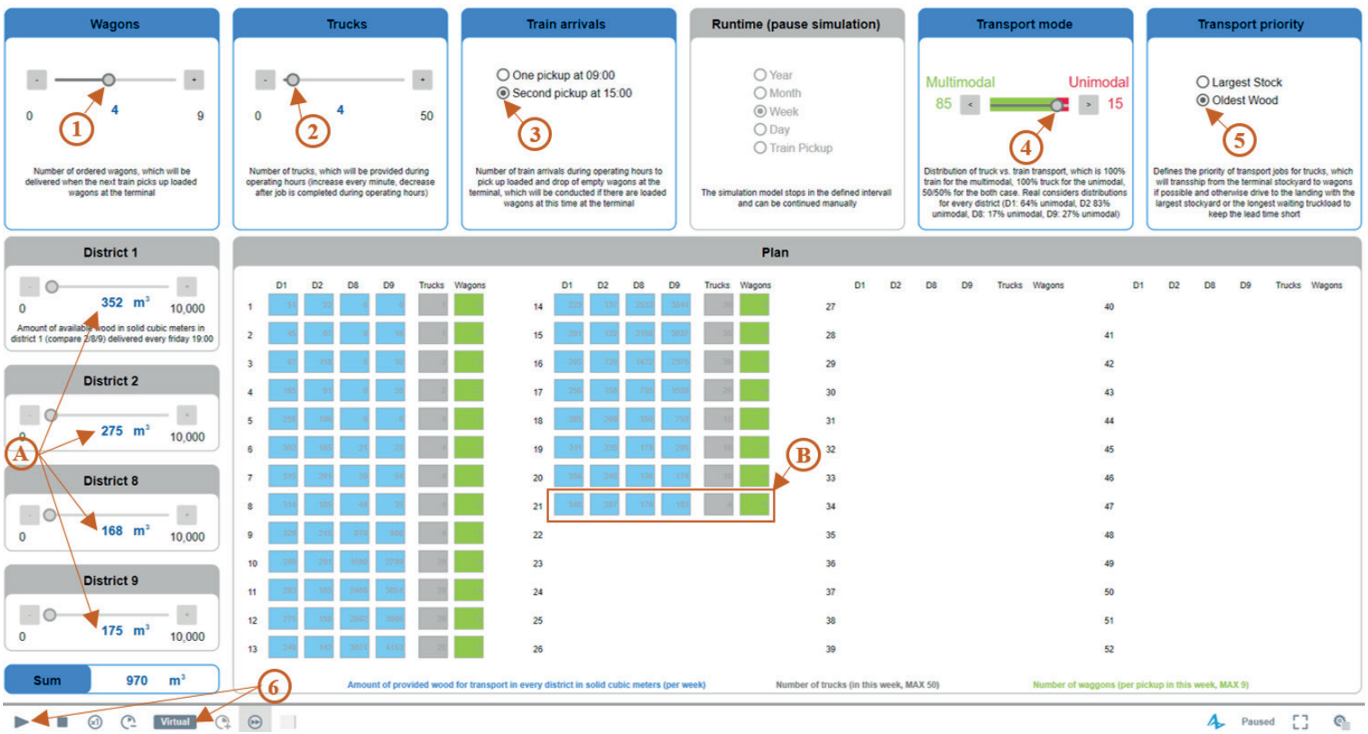


*Fig. 5 Workshop control view of a discrete event simulation model.*

game-based simulation workshops) to improve the efficiency, sustainability and – according to the presented definition – resilience of wood logistics.

The scientific impact of the presented models includes an unique level of detail in the modeling of multimdal wood supply chains combined with the most comprehensive key performance indicator representation, first simultaneous optimization of the multi-echelon unimodal fleet configuration and the handling infrastructure as well as first-time quantification of wood value losses caused by lead times and avoidance of these losses through the development of logistics strategies for proactive risk management. Further development opportunities for wood transport simulation include the integration of real-time data and artificial intelligence [14].

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