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DECISION SUPPORT BY DISCRETE EVENT SIMULATION FOR THE WOOD SUPPLY CHAIN

Dissertation

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Institute of Production and Logistics

Vienna, August 2020

Affidavits

I give my solemn word that I have compiled this work solely and without external help, have not utilized any sources outside those permitted and that the sources used have been given verbatim or quoted textually in the places indicated.

Vienna, 19 August 2020

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Place, Date

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1 PREFACE

The first section emphasizes the importance of companions along the exciting way to a dissertation (1.1) and provides a first glimpse of the dissertation manuscript in the form of an English (1.2) and German (1.3) abstract. Moreover, it gives an overview by listing the comprised publications (1.4) and describes the motivation for this dissertation project and its creation process (1.5).

1.1 ACKNOWLEDGEMENTS

I would like to acknowledge the ideal working environment for my dissertation project provided by the University of Natural Resources and Life Science, Vienna. Here, I was challenged to further develop my scientific, academic and managerial skills, which I first acquired during my business administration studies at the University of Graz and computer science studies at the Upper Secondary Technical and Vocational High School in Leonding.

I thank my supervisor, Peter Rauch, as well as the members of my advisory team, Manfred Gronalt, Dag Fjeld and Marc Reimann. Furthermore, I would like to thank my colleagues at the Institute of Production and Logistics, my scientific project partners of the research projects MultiStrat, THEKLA and GreenLane, which included research groups in Austria, Sweden and Norway, as well as my industrial project partners involving numerous actors along the entire Austrian wood supply chain. In addition, I thank my hosts at the University of California in Berkeley, Jeroen Dewulf and William Stewart, as well as my students at the University of Natural Resources and Life Sciences, Vienna and at the University of Applied Sciences Campus Vienna. Moreover, thanks go to my assessors, coaches, mentors, proof-readers, editors and anonymous reviewers.

It was possible to finance this dissertation project with support from the Institute of Production and Logistics at the University of Natural Resources, Vienna, the European Union, the Austrian Ministry for Transport, Innovation and Technology (BMVIT), the Austrian Research Promotion Agency (FFG), the Austrian Forest-, Wood- and Paper Industry Consortium (FHP), the Austrian Marshall Plan Foundation, the BOKU Vienna Open Access Publishing Fund, the Austrian Research Association (ÖFG), the Special Interest Group (SIG) on Simulation and Modeling (SIM) of the Association for Computing Machinery (ACM) and the Symposium on Systems Analysis in Forest Resources (SSAFR).

I thank my wonderful friends, family and Helena for their backing and support over the years.

Sincerely grateful and delighted,

Christoph

P.S.: “Live as if you were to die tomorrow. Learn as if you were to live forever.”

[Mahatma Gandhi]

1.2 English Abstract

In challenging times of climate crisis, digitalization and globalization, innovative supply chain management is needed for socially, environmentally and economically sustainable wood transport solutions. This cumulative dissertation provides decision support to investigate intensified international competition and further develop wood supply chain management regarding resilience (e.g., handling risks such as increasingly frequent and extreme wind-storms and bark beetle infestations), sustainability (e.g., transshipping wood from trucks to trains at terminals for multimodal wood transport) and efficiency (e.g., using Discrete Event Simulation models to provide key performance indicators).

Kogler and Rauch (2018) provided a first structured review focusing on the wood supply chain, Discrete Event Simulation and multimodal transport. They analysed the development of the research area (first research question = Q1) and derived existing research gaps (Q2).Thereby, they recommended simulating entire supply chain networks, concentrating on timber transport, stimulating knowledge transfer to industry and using opportunities of multimodal transport.

Kogler and Rauch (2019) contributed a virtual wood supply chain simulation environment for a detailed abstraction level and operational planning horizon combination, which previously had not been covered in literature. They developed a Discrete Event Simulation model (Q3) to compare multimodal and unimodal transport strategies based on key performance indicators in risk scenarios (Q4). Results indicate the reduction of carbon dioxide emissions and enhancement of resilience through the integration of multimodal wood transport.

Kogler and Rauch (2020) initiated wood supply chain contingency planning with DES by delivering a toolbox consisting of a Discrete Event Simulation model setup, strategies to cope with challenging business cases as well as transport tables, templates and frameworks. They identify critical parameters (Q5), defined transport plans (Q6) and quantified the impact of decreasing truck trips due to increased transport tonnages on terminal performance (Q7).

The dissertation consisting of one framework paper, one literature review and two research articles contributes innovative knowledge to the scientific (e.g., identifies and closes research gaps), industrial (e.g., supports stakeholders in analyzing outcomes of decision with Discrete Event Simulation before making long-lasting, unsustainable or inefficient changes) and educational communities (e.g., educates students in a game-based learning workshop). Research on wood value tracking, intensified cooperation, digital twins, selvedge wood logistics and combining Simulation with Optimization is promising to further develop wood supply chain management in the future.

1.3 GERMAN ABSTRACT

In herausfordernden Zeiten der Klimakrise, Digitalisierung und Globalisierung ist ein innovatives Lieferkettenmanagement für sozial-, ökologisch- und wirtschaftlich nachhaltige Holztransportlösungen erforderlich. Die vorliegende kumulative Dissertation liefert Entscheidungsunterstützung zur Begegnung des verschärften internationalen Wettbewerbs und Weiterentwicklung des Holzlieferkettenmanagements in Bezug auf Resilienz (z.B. Bewältigung von Risiken, wie immer häufigere und extremere Stürme und Borkenkäferkalamitäten), Nachhaltigkeit (z.B. multimodaler Holztransport durch Holzumschlag von LKWs auf Züge in Terminals) und Effizienz (z.B. diskrete Ereignissimulationsmodelle zur Bereitstellung von Kennzahlen).

Kogler und Rauch (2018) boten eine erste strukturierte Wissenssammlung mit Schwerpunkt auf Holzlieferkette, diskrete Ereignissimulation und multimodalen Transport. Sie analysierten die Entwicklung des Forschungsbereichs (erste Forschungsfrage = Q1) und zeigten bestehende Forschungslücken auf (Q2). Dabei empfahlen sie, komplette Lieferkettennetzwerke zu simulieren, sich auf den Rundholztransport zu konzentrieren, Wissenstransfer zur Industrie zu forcieren und das Potential des multimodalen Transports zu nutzen.

Die virtuelle Holzlieferketten-Simulationsumgebung von Kogler und Rauch (2019) behandelte eine in der Literatur noch nicht betrachtete Kombination aus operativem Planungshorizont und detaillierter Abstraktionsebene. Sie entwickelten ein diskretes Ereignissimulationsmodell (Q3), um multimodale und unimodale Transportstrategien anhand von Kennzahlen in Risikoszenarien zu vergleichen (Q4). Ergebnisse deuten darauf hin, dass die Integration von multimodalen Holztransport Kohlendioxidemissionen verringert und die Resilienz von Lieferketten erhöht.

Kogler und Rauch (2020) initiierten die Notfallplanung für die Holzlieferkette mit Hilfe diskreter Ereignissimulation, indem sie eine Werkzeugpalette bestehend aus einem diskreten Ereignissimulationsmodell-Setup, Strategien zur Bewältigung herausfordernder Geschäftsfälle sowie Transporttabellen, -vorlagen und -rahmenpläne zur Verfügung stellten. Sie identifizierten kritische Parameter (Q5), definierten Transportpläne (Q6) und quantifizieren die Auswirkungen reduzierter LKW-Fahrten aufgrund erhöhter Transporttonnagen auf die Terminalleistung (Q7).

Die aus Rahmenschrift, Literaturübersichts- und zwei Forschungsartikeln bestehende Dissertation bringt innovative Erkenntnisse für Wissenschaft (z.B. identifiziert und schließt Forschungslücken), Wirtschaft (z.B. hilft Stakeholdern Ergebnisse von Entscheidungen mittels diskreter Ereignissimulation zu analysieren, bevor langfristige, nicht nachhaltige oder ineffiziente Änderungen vorgenommen werden) und Bildung (z.B. lernspielbasierte Workshops für Studierende). Zukunftsträchtige Forschungsansätze zur Weiterentwicklung des Holzlieferkettenmanagements sind Holzwertverfolgung, intensivierte Zusammenarbeit, digitale Zwillinge, Schadholzlogistik und Kombination von Simulation und Optimierung.

1.4 LIST OF PUBLICATIONS

Kogler C., Rauch P. 2018: Discrete event simulation of multimodal and unimodal transportation in the wood supply chain: a literature review; Silva Fennica: 52(4), 29p, https://doi.org/10.14214/sf.9984.
Received: 29 March 2018, Accepted: 30 October 2018, Published: 14 November 2018 Citations: 12, Views Journal Webpage: 59133, Views Research Gate: 204 (19 August 2020) Journal (Country): Silva Fennica (Finland) 5-year impact factor: 1.950, Scimago Journal Ranking: 1st Quartile in Forestry "A comprehensive review study conducted by Kogler and Rauch (2018) reviewed using DES for addressing wood SC transportation issues at both tactical and operational levels." *(Al-Hawari et al. 2020)*

Kogler C., Rauch P. 2019: A discrete event simulation model to test multimodal strategies for a greener and more resilient wood supply; Canadian Journal of Forest Research: 49(10), 1298–1310, https://doi.org/10.1139/cjfr-2018-0542.
Received: 19 December 2018, Accepted: 4 July 2019, Published: 16 July 2019 Citations: 4, Views Journal Webpage: 134, Views Research Gate: 197 (19 August 2020) Journal (Country): Canadian Journal of Forest Research (Canada) 5-year impact factor: 2.162, Scimago Journal Ranking: 1st Quartile in Forestry "Kogler et al. used Discrete Event Simulation (DES) in perhaps the most detailed railroad terminal study to date for the wood supply chain." *(Acuna et al. 2019)*

Kogler C., Rauch P. 2020: Contingency plans for the wood supply chain based on bottleneck and queuing time analyses of a discrete event simulation; Forests: 11(4), 23p, https://doi.org/10.3390/f11040396.
Received: 13 March 2020, Accepted: 31 March 2020, Published: 2 April 2020 Citations: 0, Views Journal Webpage: 642, Views Research Gate: 50 (19 August 2020) Journal (Country): Forests (Switzerland) 5-Year impact factor: 2.484, Scimago Journal Ranking: 1st Quartile in Forestry

1.5 Dissertation Project

The dissertation project is motivated by manifold scientific curiosity, the aspiration to further develop wood supply chain management in a sustainable way, and the incentive to provide innovative contributions to the scientific, industrial and educational communities. Consequently, an interdisciplinary research approach combining computer science, operations research, business and forest/wood economy to close existing research gaps, tackle practical challenges and educate students was developed and implemented. Necessary skills and knowledge were achieved primarily through the doctoral studies of social and economic science at the University for Natural Resources and Life Sciences, Vienna. These build on earlier studies of business administration with a specialization in production management and logistics including a master thesis in the wood-based industry as well as computer science studies with a specialization in media informatics.

A comprehensive project management was set up to fulfil required tasks at the University of Natural Resources and Life Sciences, Vienna such as getting a confirmation of assistance from the supervisor and advisory committee, getting admission as a doctoral candidate, registering the doctoral project, writing a synopsis of the dissertation, completing doctoral courses, sending out yearly project reports to the advisory committee, publishing at least two articles as first author in peer-reviewed journals with an impact factor and writing a framework paper. The doctoral studies consisted of 180 ECTS credits including 160 ECTS credits for the dissertation. In the following courses, 20 ECTS credits were achieved with a grade point average of 1.0: Simulation of Business Processes; Simulation 1; Simulation 2; Logistics in the Forest Wood Supply Chain; Principles and Challenges of Research in Socio-Economics, Natural Resources and Life Sciences; Strategical Data Analyses with SPSS and the Dissertation Seminar.

The position as a research assistant for international (MultiStrat, GreenLane) and national (THEKLA) research projects at the Institute of Production and Logistics provided deep insight into scientific work. Experiences included obtaining external funding through project initiation (THEKLA: 200,000 €; SKAT: 89,000 €) and application (THEKLA, GreenLane, SKAT) as well as completion of projects (MultiStrat, THEKLA) including seven interim- and two final reports. In all above-mentioned research projects, industry was involved, which enabled the establishment of close relationships through more than 30 expert interviews, field trips, stakeholder workshops, meetings, presentations, networking events and publications in industry magazines. Scientific articles were reviewed for the journals Annals of Operations Research and Computers & Operation Research. The position as a lecturer for Process Modeling and Simulation in the Master's program Biotechnological Quality Management (University of Applied Sciences Campus Vienna), Business Management 2 in the Master's program Wood Technology and Management as well as Production Management in the Bachelor's program Wood and Fibre Technology (both at the University of Natural Resources and Life Sciences, Vienna) and the initiation and co-supervision of master thesis revealed a passion for educational work. It forced one to develop a deep understanding for theory as well as the applied methods and challenged one to implement research-guided teaching and be able to communicate scientific findings in a straightforward, visual and easily traceable way. This is exemplified especially through the developed game-based wood supply chain simulation workshop, where different teams played in groups to outperform others according to predefined key performance indicators. The knowledge transfer of handling a complex simulation model to manage challenging, close to reality scenario settings (e.g., managing high supply after windstorms, restricted train wagon availability) for multimodal wood supply chains was achieved through a special workshop edition of the Discrete Event Simulation model focusing on animation, visualization and intuitive usability. The workshop edition was well received by students, managers and scientists. Therefore, another research article focussing on knowledge transfer through game-based workshops was accepted for publication in the International Journal of Simulation Modelling.

Highly valuable experiences were received through research meetings, conference participations and a research stay abroad. Project meetings for the international research projects in Norway and Sweden provided insight in the work of other research groups and have deepened relationships with other scientists who previously had been known only from numerous video meetings. Participating at scientific conferences in the USA (Seattle, Washington), Sweden (Gothenburg) and Chile (Puerto Varas) provided wide-ranging experiences such as preparing and reviewing conference papers, presentations, talks and posters as well as presenting, discussing and getting feedback for latest findings. Moreover, moderation and organizational skills were trained as a session chair at the Winter Simulation Conference (WSC) 2018 and the Symposium on Systems Analysis in Forest Resources (SSAFR) 2019 as well as a member of the program committee for introductory tutorials at the WSC 2020. Conference and PhD-colloquium participations were supported by grants (PhD Student Travel Grant for WSC 2018, Student Travel Award for WSC 2019, Student Travel Fellowship Award for SSAFR 2019) and enabled the building of a scientific network abroad. Deep insight of scientific and educational processes at a US university was achieved during a three-month research stay at the University of California in Berkeley funded by the Austrian Marshall Plan Foundation and the Austrian Research Association. The Symposium on Wood Supply Chain Management in Austria and California was organized in cooperation with the inviting hosts at the Institute of European Studies and Berkeley Forests to investigate different challenges of wood supply chains, compare research methods and connect researchers.

All these collected experiences deepened understanding of the wood supply chain as well as improved scientific, industrial and educational skills, which were highly valuable during the dissertation project, publishing of three scientific articles and compiling the framework paper.

2 FRAMEWORK PAPER

The second section introduces the overarching dissertation topic by providing background and relevance (2.1), describing the problem setting (2.2) and giving insights into the methods (2.3) to tackle the raised research questions. It spans a red thread from early comprehensive literature analyses (results of the first article in 2.4) to the intermediate detailed model development (results of the second article in 2.5) until final applications for contingency planning (results of the third article in 2.6). In the discussion (2.7), the articles are classified, categorized and set in relation to each other in order to illustrate their contribution to the research area. The section culminates in the conclusion (2.8), where the overall findings and outlook for further research are presented, highlighting the dissertation's scientific, industrial, and educational impact to further develop wood supply chain management. The last sub section (2.9) lists all references.

2.1 BACKGROUND AND RELEVANCE

Since time immemorial, wood has been harvested, transported, processed, stored and used by generations of humans and, somehow, these processes along the wood supply chain appear to have always been managed. With the progress of knowledge and technology, new approaches to provide decision support have been invented, but also new and more intricate questions have been raised. Nowadays, wood supply chains are complex dynamic networks of information-, material-, financing- and service flows between and within different actors. Consequently, wood supply chain management covers crucial decisions to plan, design, operate, control and monitor the entire wood supply chain. In challenging times of climate crisis, globalization and digitalization, innovative wood supply chain management is needed to contribute to socially-, environmentally- and economically sustainable solutions.

The United Nations highlight the impact of trees, forests and sustainable wood value chains to achieve the Sustainable Development Goals (SDGs). They emphasize that trees and forests contribute to all 17 SDGs and quantify their contributions based on 28 targets in detail (FAO 2018). In their global meeting report (FAO 2017), the United Nations, in cooperation with the Sustainable Wood for a Sustainable World initiative (SWFSW: Food and Agriculture Organization of the United Nations, World Wildlife Fund, World Bank, Center for International Forestry Research, International Tropical Timber Organization, Advisory Committee on Sustainable Forest-based Industries), especially noted the relevance of decent work and economic growth (SDG8), responsible consumption and production (SDG12), climate action (SDG13) and life on land (SDG15).

The contribution of forests and wood value chains to the SDGs can be sensed by the impressive number of 86 million green jobs (FAO and UNEP 2020) provided by forests world-wide as well as the high amount of forest cover on different regional levels. Globally, 31% of the total land area is covered with forests (FAO and UNEP 2020). This value is even higher in the European Union with 43% (Eurostat 2018) and still higher for Austria with a forest cover of 48% (ARCF 2019). According to the trade map of the International Trade Center (joint agency of the World Trade Organization and the United Nations), in the year 2019 Austria had, with almost two billion euros, the 8th highest positive trade balance for wood, articles of wood and wood charcoal worldwide (ITC 2019). Regarding the share in value, Austria covered 4% in the world's exports (6th worldwide after China, Canada, Germany, Russian Federations, USA) and 2.3% in the world's imports (9th worldwide after China, USA, Japan, Germany, UK, France, Italy, Netherlands).

Consequently, the wood supply chain is of high importance for Austria, where wood is the only available sustainable natural resource (BMNT 2018) and 172,000 companies provide work for 300,000 people along the value chain of forestry, wood and paper (FHP 2019). Important actors along the wood supply chain are forest owners, forest entrepreneurs, truck and train carriers, timber traders, joineries, carpenters, energy producers, advocacy groups, public authorities, end customers as well as saw-, pulp-, paper, board, construction, fiber, chemical, clothing, furniture and ski industries. They produce mass products such as wood raw materials, sawn soft- and hardwood, wood chips, wood fuels, pellets, pulp, paper, wood-based panels as well as a variety of value added products including glued structural timber components, wood constructions, prefabricated wooden houses, windows, doors, wooden floors, furniture and skis. For a detailed description of the wood supply chain refer to Gronalt et al. (2005) and Kogler (2016). An overview of the wood flows in Austria is provided by Strimitzer et al. (2019) in the Sankey-Diagram in Figure 1. It shows the flow of wood volumes in million cubic meters from procurement (felling, import, other sources such as waste wood, copse and landscape care) via processing (sawmill, pulp and paper industry, further processing including carpentry, joinery, furniture and veneer mills) to consumption (material and energy). The latest performance indicators can be found in the yearly updated versions of the annual industry reports of the Austrian Paper Industry Association (AP 2019) and Austrian Wood Industry Association (FH 2019), the performance report of the Austrian Association for Forest, Wood and Paper (FHP 2019) as well as the Green Report (2019a) and Austrian Market Report (2019b) of Austria's Federal Ministry for Agriculture, Regions and Tourism.

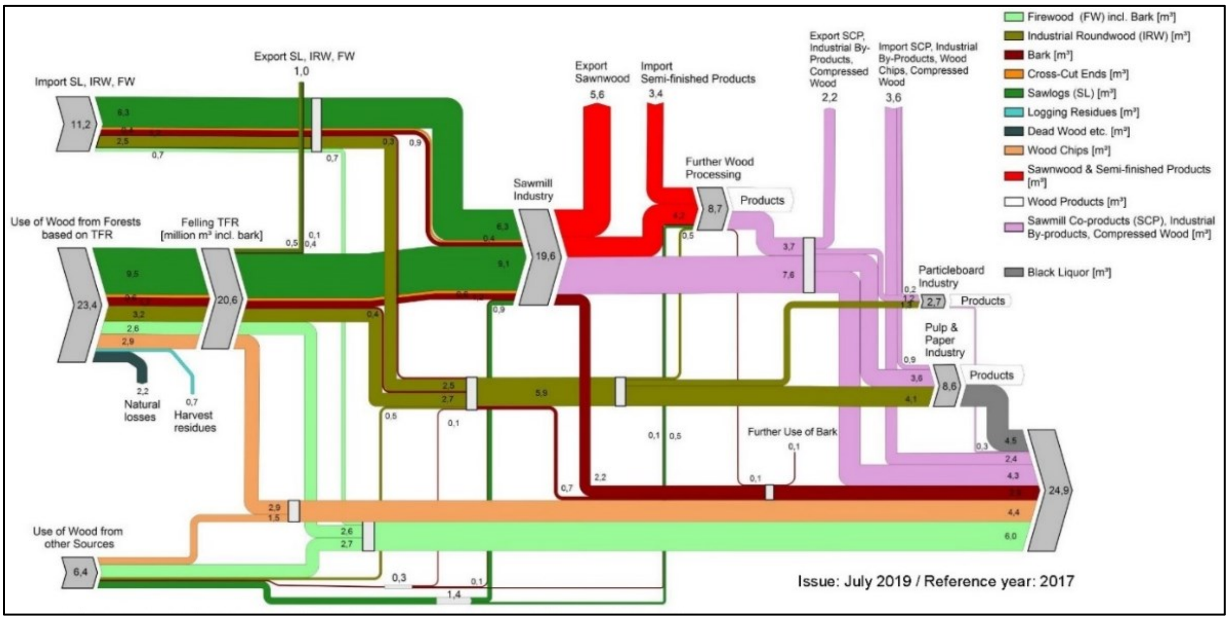

Figure 1: Wood Flows in Austria in million cubic meters (Strimitzer et al. 2019).

The provided background information about wood supply chain management, its impact on the SDGs and its high relevance to the world, the EU and especially Austria serve to introduce the general subject area of this dissertation project. To get an impression of the Austrian wood supply chain, actors and products were listed and complemented with performance indicators, wood flows were illustrated and further reading to the most relevant resources were referenced. This sets the scene for the overarching problem setting of the dissertation project.

2.2 PROBLEM SETTING

For a long time, Austria's worldwide renowned contributions in research, industry and education regarding forests operations (e.g., cable crane logging on steep slope terrain), advanced wood energy systems (e.g., pellets, biomass) and value added wood building products (e.g., cross laminated timber) compensated for high wood procurement costs and inefficient supply chains suffering from risks and natural disturbances. But in modern times of globalization, international competition and rapidly increasing wood demand in emerging markets, the Austrian wood-based industry and its supply chain is under pressure to keep a competitive edge.

Consequently, within this dissertation project, research along the wood supply chain was performed to find opportunities, approaches and potential for further developments. This included comprehensive analyses of strengths, weaknesses, opportunities and threads (SWOT), stakeholder participation through questionnaires and more than 30 expert interviews with actors along the wood supply chain. Moreover, case studies of a train terminal, wood trader and carriers were executed including business process, information flow and data analyses. On the one hand, it revealed weaknesses regarding unfavorable industry characteristics such as market power concentration, cherry picking by individual actors, resistance to innovation as well as absence of data-driven decision support and professional positions for supply chain management. On the other hand, it emphasized the ongoing challenge to ensure resilient, sustainable and efficient wood supply. Areas of concern include long lead times threatening wood quality, a decreasing number of crane-truck drivers causing a bottleneck in transporting wood out of the forests, long queuing times for trucks unloading at industries and location disadvantages such as relatively low maximal weight limits of trucks.

Weaknesses and challenges are further intensified by supply disruptions (e.g., available transport capacity, inclement weather, technical breakdowns), demand disruptions (e.g., delivery stops at mills, rapid market price fluctuations, limited inventory) and natural disturbances (e.g., ice broken treetops, avalanches, heavy rain, high snow cover). However, windstorms are the most influential disturbance. They cause a shock to the market and demand an immediate contingency planning to transport high volumes of salvage wood out of the forest quickly in order to limit further damage, wood value loss and, most importantly, the feared spread of bark beetles. In 2018, more than 50% off the harvested wood in Austria was salvage wood (BMNT 2019a). These risks increase in frequency and impact due to climate crisis and cause long recovery times for again reaching a stable, sustainable and efficient wood flow throughout the chain.

The deep insight into the Austrian wood supply chain has brought to light a lack of professional supply chain management. Particularly noticeable is the limited cooperation between actors, lack of data-driven decision support and the absence of contingency plans for recurring risk events. Firstly, the limited cooperation can be traced back to the switching market power between big forest owners and industry, that shifts after heavy windstorms. This leads to distrust, missing automatized information sharing as well as short term contracts and plans, which also negatively affects smaller actors such as wood contractors and carriers. Here, professional supply chain management would strive for a shift from cherry picking by individual actors to a focus on the overall supply chain performance. Secondly, management is often based on simple Excel spreadsheets or even rule of thumbs and relies massively on experience and patterns established over time. Although companies have started to collect high amounts of data, in most cases, this data has not been used for quantitative decision support and customized software solutions, which would be needed to enable a professional, data driven supply chain management. Thirdly, existing control mechanisms fail if risk events occur. That can lead to break downs of entire supply chains with long, unsustainable, inefficient and expensive recovery times. In such a highly uncertain environment, professional supply chain management is needed for active risk management and advanced contingency planning.

A simulation approach has the potential to tackle potential challenges with practicable solutions and bring systems up to speed regarding professional supply chain management, digitalization and data-driven decision support. Simulation experiments facilitate a better understanding of complex interdependencies along the wood supply chain and allow analyzing strategies based on key performance indicators (KPIs) in different scenario settings. In particular, the Discrete Event Simulation (DES) approach has considerable potential due to its abstraction level, powerful software support and straightforward model structure based on business processes and events. Moreover, it has major strengths to facilitate stakeholder participation in model development, design of experiments, verification, validation, evaluation of results as well as in communicating findings through animation, visualization and what-if analyses.

This method has been well known in science and has had the potential to further develop wood supply chain management, however, it is barely known by today's (i.e., manager) and tomorrow's (i.e., students) decision makers along the Austrian wood supply chain. Consequently, it would be interesting to know *how the DES method can be used to provide decision support for the wood supply chain*. This general problem formulation was broken into highly related, but clearly dividable research questions to be answered in a stepwise manner and each would benefit from building on the other's findings to close research gaps, tackle challenges of the wood-based industry and educate students.

The description of the problem setting based on SWOT analyses, interviews, case studies and data analyses provided insights regarding challenges along the Austrian wood supply chain. The potential of the DES approach was introduced briefly and paves the way for the delimitation of the overall problem formulation. This allows one to dig deeper by solidifying research questions and describing the approaches and methods used to answer them.

2.3 METHODS

The DES method sets the theoretical background to provide decision support for advanced wood supply chain management. Powerful DES software packages enable a realistic representation of the wood flow through supply chain processes. Moreover, they provide basic modeling elements (e.g., flow charts with sources, delays, queues, sinks, entities and resources) to perform experiments (e.g., random number generator, database for input parameters and output data, statistical counters, charts). These allow observing complex interdependencies, bottlenecks, system capacities and various KPIs such as utilizations, queuing- and lead times to analyze effects of management decisions before making real, costly, dangerous, inefficient, long-lasting or unsustainable changes. For a comprehensive explanation of simulation modeling and analysis, refer to Law (2015) and, for an educational guideline how to develop DES models, refer to Mahdavi (2020).

An innovative practical approach to tackle observed challenges and contribute important strategic options for increasing resilience, sustainability and efficiency is multimodal wood transport, where wood is transshipped from trucks to trains at terminals. Advantages include additional transport and storage capacities, reduced carbon dioxide emissions and fewer bottlenecks of forest trucks equipped with cranes. The management of multimodal supply chains is a challenging task, but the DES provides the theoretical method to observe the applicability of this practical approach and gives advanced decision support to manage complex multimodal wood supply chains.

Consequently, in this dissertation project, a stepwise approach was chosen to review existing DES models for multimodal and unimodal wood transport, build a detailed DES model to compare specific multimodal, unimodal and combined transport strategies under risk scenarios and further develop the model to a contingency planning toolbox for multimodal wood transport. This resulted in three publications, which answered research questions (Q1–7) to close existing research gaps (see Figure 2). Firstly, in order to collect, analyze and structure existing knowledge, a meta-analysis of existing reviews as well as systematic and narrative reviews of research articles were performed. Secondly, a detailed DES model was developed and used in stakeholder workshops based on detailed case study research, data collection and mapping of material flow, information flow and risk influences. Finally, the model was further developed through additional expert interviews, data analyses, business process modeling, stakeholder workshops and extensive experiments for various scenarios and parameter settings to enable advance contingency planning for multimodal wood supply chains.

The explanation of the stepwise research path, combining the theoretical DES method with the practical multimodal transport approach provided an overview of the observed topics, research gaps, questions and methods that were answered in the following articles.

Figure 2: Overview of research gaps, questions and methods.

2.4 LITERATURE REVIEW RESULTS

The literature sub-section summarizes the literature review by Kogler and Rauch (2018) and provides an overview of the delivered information and main results (find entire article in 3.1). Both co-authors participated in conceptualization, search strategy development, resources, investigation, verification, validation, review and editing. Christoph Kogler contributed the methodology, data curation, formal analysis, literature selection, article assessment and classification, visualization, writing and original draft preparation. Peter Rauch provided supervision, project administration and funding acquisition.

A meta-analysis of twelve literature reviews (D'Amours et al. 2008, Manuj et al. 2009, Tako and Robinson 2012, Shahi and Pulkki 2013, Seay and Badurdeen 2014, Wolfsmayr and Rauch 2014, Lautala et al. 2015, Atashbar et al. 2016, Borodin et al. 2016, Oliveira et al. 2016, Mirkouei et al. 2017, Opacic and Sowlati 2017) revealed that they covered the topics of DES (10 studies), optimization models (9), biomass (6), wood supply chain (4) and multimodal transport (4), but none focused on DES, the wood supply chain and multimodal transport in one review. To fill this research gap, a specifically designed literature selection strategy led to detailed analyses of 32 research articles and was complemented by additional information from 48 related works in order to show the development of the research area.

Basic information regarding definitions for wood supply chain management, planning horizon (i.e., strategic, tactic, operational) and abstraction level (i.e., high, intermediate, low) was provided. Moreover, transport modes (i.e., single echelon unimodal transport, multi echelon unimodal transport, intermodal transport, multimodal transport) were explained based on Wolfsmayr and Rauch (2014) and compared according to Lautala et al. (2015). DES was differentiated from other simulation methods (i.e. Agent-Based Simulation, System Dynamics and Monte Carlo Simulation) and described in detail.

In order to answer the first research question (Q1), *"To what extent has the DES approach been applied in the wood supply chain, especially with focus on multimodal and unimodal transport?"*, a systematic as well as a narrative review compared 32 research articles in detail. The articles were assigned to thematic groups within the multimodal (i.e., train, vessel, both, general) and unimodal (i.e., forest chips, forest biomass, timber, firewood) transport modes. Moreover, the articles were categorized regarding general (i.e., year, region, journal, abstraction level, planning horizon, assortment, transport mode, software) and specific (i.e., risk consideration, case study inclusion, simulation period, resolution time, supply network, objective) classification criteria. Furthermore, their documentation, validation, statistical analysis, input parameters, structure and data collection were compared in detailed sub-categories. Narrative descriptions included reflections, synthesis, critics and developments.

The research topic and method gained interest during the last decade of the observation period (27 out of 32 publications) and was mainly investigated by Finnish (10), Canadian (6) and Swedish (4) research groups. Popular simulation software such as Witness (7), ExtendSim (6) and AnyLogic (5) were used to simulate periods of one year (10), longer than a year (5), weeks to months (5) and days (4), with minutes as most common resolution time. The majority of the studies concentrated on unimodal transport (22). Different biomass assortments (24) were the dominant transported goods. Multimodal transport was observed in ten studies covering train transport (Saranen and Hilmola 2007, Karttunen et al. 2013, Etlinger et al. 2014, Wolfsmayr et al. 2016, Gronalt and Rauch 2018), vessel transport (Asikainen 2001, Kattunen et al. 2012) or both (Mobini et al. 2013, Mobini et al. 2014). One early study chose a general approach and did not further declared the observed transport mode (De Mol et al. 1997). The 22 unimodal transport studies were categorized by forest chips (Asikainen 1998, Asikainen 2010, Zamora et al. 2013, Eriksson et al. 2014a, Eriksson et al. 2014b, Spinelli et al. 2014, Eliasson et al. 2017, Eriksson et al. 2017, Väätäinen et al. 2017), forest biomass (Mahmoudi et al. 2009, Mobini et al. 2011, Zhang et al. 2012, Windisch et al. 2013a, Windisch et al. 2013b, Windisch et al. 2015, Pinho et al. 2016a, Pinho et al. 2016b, Kishita et al. 2017), timber (Myers and Richards 2003, Beaudoin et al. 2012, Marques et al. 2014) and firewood (Cavalli et al. 2012).

Also, the answer for the second research question (Q2), *“What contradictions, gaps or hot topics have not been addressed thus far?”*, builds on the systematic as well as narrative reviews. The analyses showed the focus in literature on biomass and unimodal transport and pointed out the shortcomings by simulating the supply chain only partly and only rudimentarily considering external risks such as natural disasters in scientific models. Consequently, it was recommended to simulate entire supply chain networks, concentrate on other transport goods such as timber, stimulate knowledge transfer to enhance the applicability of scientific models in industry and use the opportunities of multimodal transport to increase the resilience, sustainability and efficiency of wood supply chains.

The literature review set the stage for the next generation of DES wood supply chain models by highlighting research gaps and providing inspirations to improve the verification and validation as well as documentation of future simulation models. Methods such as expert involvement on a regular basis, structural walkthroughs, visualization, animation, extreme scenarios and comparisons of results with high quality real-life case studies or literature data enhance the credibility of simulation models. Moreover, improved documentation regarding flow/business process diagrams in standardized notation, detailed verbal description of model logic and scenarios, figures and charts, tables with parameters and screen shots of the simulation model in the used software environment contribute to build on existing knowledge and bring scientific models into practical use. Consequently, the review paper provided information for a broad readership including different scientific disciplines, industrial experts and students.

2.5 SIMULATION MODEL RESULTS

The simulation model sub-section briefly recapitulates the research paper by Kogler and Rauch (2019) to give an overview about the DES model and the results of simulation experiments (find entire article in 3.2). Both co-authors were involved in conceptualization, case study research, investigation, resources, data curation, verification, validation, stakeholder workshops, review and editing. Christoph Kogler did methodology, expert interviews, formal analysis, business process modelling, DES model development, software, visualization, writing and original draft preparation. Peter Rauch provided supervision, project administration and funding acquisition.

Based on the detailed literature analyses and highlighted future research directions in Kogler and Rauch (2018), the research gap of a missing virtual environment to compare unimodal and multimodal wood transport based on KPIs in risk scenarios on a detailed abstraction level for an operational planning horizon was detected. In order to close this research gap and enable the development of green and resilient wood transport strategies, a versatile applicable DES model was developed based on an in-depth case study. Therefore, the simulation model provides a proof of concept for multimodal wood transport planning and advanced wood supply chain management based on the DES method. Moreover, a special focus was placed on an intuitively operable graphical user interface to allow a high level of stakeholder involvement in model development, verification and validation. The graphical user interface further enabled one to communicate findings in game-based learning workshops, multi-criteria analyses and strategy development for scientists, industry experts and students. Furthermore, the intuitive operability was enhanced through detailed animations, data import from and export to Excel as well as automatically updating statistics in a clear organized KPI cockpit to observe system characteristics and implications of decision during runtime. The broad functionality of the simulation model can be used further to test, analyze and evaluate a variety of transport plans, strategies and system internals. Its modular design provides a solid foundation to build specific extensions in the future.

The third research question (Q3), *"How to develop a DES model to test multimodal strategies under risk scenarios for a greener and more resilient wood supply?"*, was answered by a detailed description of a newly developed DES model for the wood supply chain. Visual elements such as an edited aerial photograph of a train terminal, screenshots, business process and flow diagrams provided an overview about the case study location, simulation model features and system logic. Comprehensive verbal description of the system logic, scenarios, KPIs (e.g., definitions, ranking process), case study, verification and validation provided deep insight into the simulation model. Moreover, the used elements of the AnyLogic process modeling library as well as the settings for the simulation experiments were listed and detailed information about main inputs, processes, outputs, decision variables and parameters was provided in tables.

The DES model consists of five modules (i.e., forest, truck transport, terminal, train transport, industry) that model the flow of wood through the entire wood supply chain in detail. The forest module generates wood entities in different forest districts and covers processes such as cutting, extracting and storing at forest landings. The truck transport module controls the behavior of trucks within the network to transport wood entities batched to truckloads either directly to the industry module (i.e., unimodal transport) or to the terminal module (i.e., multimodal transport). The terminal module contains the processes for transshipping wood to train wagons or stockyard and models the complex queuing logic of trucks at a terminal. In the train module, the pickup of fully loaded wagons, sorting of wagons according to their loading status, parking empty wagons for loading and train transport to industry was modeled. Finally, the industry module covers the unloading processes of trucks and trains at wood-based industry sites.

In order to answer the fourth research question (Q4), *"How to provide an unbiased comparison of multimodal and unimodal transport with sets of ranked KPIs to support supply chain decisions?"*, simulation experiments were performed to evaluate three transport strategies (i.e., MULTI: only multimodal, UNI: only unimodal, BOTH: 50% unimodal and 50% multimodal) in three scenario settings (BAU: usual production volumes, SNOW: -75% production in first quarter of the year, STORM: +300% production in third quarter of the year) based on ten KPIs. The advantage of combining unimodal transport and multimodal transport was proven through results of 90 simulation runs each covering a one-year simulation period with minutes as resolution time. The resilient strategy BOTH avoided bottlenecks and ill-timed plans, reduced carbon dioxide emissions and performed regarding crucial (transport volume, mean delivery quota, mean queuing time) and second level (stockyard volume, mean lead time, number of half-loaded- and empty wagons) KPIs.

In addition to scientific simulation experiments, the simulation model environment provides different operation concepts to vary decision variables manually during runtime, based on pre-built plans, through Excel import or in a game-based learning workshop setting. This allows one to observe effects of transport plan (i.e., number of trucks, wagons, train pickups) and strategy (i.e., transport mode split, transport priority) decisions in the animation view and management cockpit. These views as well as the built-in supply chain and terminal logic views, where the wood flow can be followed through the system elements, were well-received in scientific presentations as well as at industry and university workshops. Consequently, the DES model provides manifold decision support for the wood supply chain and encourages knowledge transfer between science, industry and education.

2.6 CONTINGENCY PLANNING RESULTS

This sub-section aggregates the main results of the research paper by Kogler and Rauch (2020) and provides an overview regarding the innovative contingency planning toolbox (find entire article in 3.3). Both co-authors participated in conceptualization, validation, investigation, resources, data curation, funding acquisition, review and editing. Christoph Kogler contributed methodology, formal analysis, software, visualization, writing and original draft preparation. Peter Rauch provided supervision and project administration.

As indicated in Kogler and Rauch (2018) and further elaborated in Kogler and Rauch (2019), supply chain performance suffers from risks, especially after more frequent and extreme natural calamities due to climate crisis. Although, no concrete, short-term contingency plans for multimodal wood supply chains are available, nor strategies to cope with challenging planning conditions, neither critical factors for bottleneck and queuing time analyses were identified. Consequently, a contingency planning toolbox to investigate critical parameters, decision variables and KPIs for advanced strategies, transport templates, frameworks and tables was developed to close the existing research gap. The included DES model setup builds on Kogler and Rauch (2019), but delivers extensions regarding a new generic model structure to provide contingency plans for various multimodal wood supply chains, new delivery time, transport tonnage and train pick-up scenarios with refined parameterizations and crucial KPIs for contingency planning. A special focus was set on providing a close-to-reality scenario design and communicating results of comprehensive simulation runs in clear tables and diagrams to provide rapid decision support as well as a straightforward and helpful applicability for contingency planning.

To observe the answer to the fifth research question (Q5), *"Which parameters are critical for multimodal contingency planning?"*, sensitivity analyses of extensive preliminary simulation experiments were performed. They indicated the sensitivity of results regarding delivery time from forest to terminal (i.e., resulting in different number of truck trips per day), transport tonnages (i.e., vary due to exemption clauses) and number of train pick-ups at the terminal (i.e., vary for different railway lines). Consequently, in cooperation with industry experts (i.e., foresters as well as wood, transport and logistics managers), scenarios for short-, medium- and long delivery times, low-, moderate- and high truck tonnages as well as one and two train-pickups were designed. Realistic parameter settings were specified to provide robust results for the majority of Austria's 153 small scale train terminals for wood transshipment. The main decision variables for contingency planners are the numbers of available trucks and wagons. Other critical factors such as the terminal transshipment volume, required terminal stockyard and average and maximal queuing times at the terminal, truck and train utilization, as well as work time coordination were identified to provide useful decision support for a variety of objectives.

For the response to the sixth research question (Q6), *"How many trucks and wagons are needed for short-, medium-, and long delivery times, respectively, with one or two train pick-ups to perform best?"*, 936 simulation runs (consisting of 52 weeks for 18 scenarios) were performed to provide transport plans and develop robust transport strategies for a broad range of logistic cases. The work time was coordinated to provide results for decision variables (i.e., number of trucks and wagons) and KPIs (i.e., terminal transshipment volume, required terminal stockyard, average and maximal queuing times) with high truck utilization (i.e., over 95%) and no empty wagons at the time of train pick-up. In order to follow managerial practice for operational wood transport planning, the results were aggregated to a weekly level and clearly arranged in a framework for beneficial wagon-to-truck ratios for one and two train pick-ups and one to seven train wagons, transport configuration tables and frameworks for every transport strategy as well as transport templates for every scenario, where the KPIs can be observed in detail. In the robust multi-objective transport planning strategy, BEST FIT solutions with up to 10% lower maximal transshipment volumes were considered, which led to saved truck and train resources, high transshipment volume as well as low stockyard and queuing time.

The potential for truck trip reduction business cases (e.g., legislative changes, exemption clauses or other regions) and, therefore the answer to the seventh research question (Q7), *"How many truck trips can be avoided, if the maximal transport tonnage increases and how would this effect the terminal performance?"*, is provided for every truck/wagon combination in the complete transport templates. When net tonnages change from low (mode = 24 t) to moderate (mode = 27 t), the number of truck trips can be reduced on average by 6% for one train pick-up and 10% for two train pick-ups. In case of a change from low to high (mode = 30 t), on average 10% of the truck trips for one train pick-up and 17% for two train pick-ups can be saved.

The contingency planning toolbox provides decision support in challenging business cases such as restricted wagon or truck availability, defined delivery quota, terminal selection, inventory accumulation and queuing time reduction. A detailed guideline for using the transport templates in challenging business cases demonstrates the practical applicability of the contingency planning toolbox. This illustrates its practical relevance for crisis management units, transport planners and supply chain managers.

The findings provide new influencing tools, insights and literature on contingency planning for wood supply chains, which is needed in industry, science and education. This showcases how the DES method can be used to provide decision support for the wood supply chain and points out its potential to further develop and professionalize wood supply chain management.

2.7 Discussion

The dissertation is well integrated in the covered scientific research area and extends the sparsely existing literature on DES models for the multimodal wood supply chain. Consequently, the research articles of the dissertation project were supplemented in the classification framework of multimodal (circles) and unimodal (squares) DES models for the wood supply chain introduced by Kogler and Rauch (2018). Figure 3 shows that the articles of Kogler and Rauch (33, 34) provide much needed decision support for a detailed abstraction level and operation planning horizon combination, which was not covered in literature before. Especially in comparison with other multimodal models (circles), important contributions to fill uncovered space in Figure 3 were added.

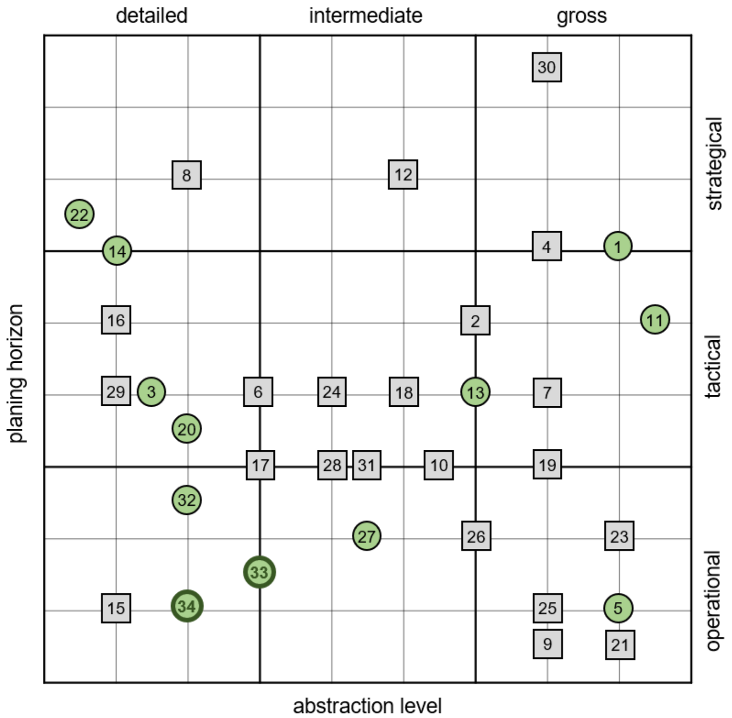

Figure 3: Classification of contributed research articles in the framework of Kogler and Rauch (2018).

Multimodal (circle): 1 De Mol et al. (1997), 3 Asikainen (2001), 5 Saranen and Hilmola (2007), 11 Karttunen et al. (2012), 13 Karttunen et al. (2013), 14 Mobini et al. (2013), 20 Etlinger et al. (2014), 22 Mobini et al. (2014), 27 Wolfsmayr et al. (2016), 32 Gronalt and Rauch (2018), **33 Kogler and Rauch (2019)**, **34 Kogler and Rauch (2020)**.

Unimodal (square): 2 Asikainen (1998), 4 Myers and Richards (2003), 6 Mahmoudi et al. (2009), 7 Asikainen (2010), 8 Mobini et al. (2011), 9 Beaudoin et al. (2012), 10 Cavalli et al. (2012), 12 Zhang et al. (2012), 15 Windisch et al. (2013a), 16 Windisch et al. (2013b), 17 Zamora et al. (2013), 18 Eriksson et al. (2014a), 19 Eriksson et al. (2014b), 21 Marques et al. (2014), 23 Spinelli et al. (2014), 24 Windisch et al. (2015), 25 Pinho et al. (2016a), 26 Pinho et al. (2016b), 28 Eliasson et al. (2017), 29 Eriksson et al. (2017), 30 Kishita et al. (2017), 31 Väätäinen et al. (2017).

In order to provide an overview on how the research articles contributed to further develop the research area, they are categorized and described based on the criteria of Kogler and Rauch (2018). This allows one to observe overall characteristics in Table 1 and Table 2 and compare them with other unimodal and multimodal DES models for the wood supply chain (see Table 2–5 in Kogler and Rauch 2018).

Table 1: Categorization of contributed research articles in the framework of Kogler and Rauch (2018).

Reference (year)	RC	CS	SP (RT)	Region	Journal	Assort-ment	Transport mode	Software
Kogler and Rauch (2019)	X	X	1 year (minutes)	AUT	Canadian Journal of Forest Research	timber	unimodal and multimodal (train)	AnyLogic
Kogler and Rauch (2020)	X	X	1 week (minutes)	AUT	Forests	timber	multimodal (train)	AnyLogic

RC = risk considered, CS = case study included, SP (RT) = simulation period (resolution time)

The objective of Kogler and Rauch 2019 was to compare unimodal and multimodal wood transport based on KPIs in risk scenarios. Therefore, they used a supply network of four harvesting districts, 1-20 trucks, 0-9 train wagons, terminals with storage area and two loading sidings, one train pick-up per day and 15 industrial sites. In Kogler and Rauch 2020, a more universal approach for the supply network was chosen to pave the way to provide decision support for various multimodal supply chains. Consequently, the supply network consisted of three categories of delivery times (short, medium, long) between harvesting districts and terminals, 1-25 trucks with three categories of transport tonnages (low, moderate, high), terminals with and without storage areas and one loading siding for up to seven wagons, one or two train pick-ups per day and industrial sites. Here, the objective was to develop strategies to cope with challenging planning conditions and identify critical factors for bottleneck and queuing time analyses to derive concrete short-term contingency plans for multimodal wood supply chains.

Table 2: Model description of contributed research articles in the framework of Kogler and Rauch (2018).

References	Documentation						Validation						Statistical analyses				Input parameter				Structure						Data collection				
	Screen shots	Distribution descriptions	Equations	Business process diagrams	Decision tree	Flow diagram	Verbal	Expert/Manager involvement	Animation and visualization	Comparing with literature data	Comparing with case study data	Structured walk-through	Statistical tests	Regressions	Confidence intervals	Sensitivity analyses	Diagrams and Tables	Parameter description	Random number generation	Distribution fitting	Warm-up period	Repeated simulation runs	Limitations	Scenario analysis	Assumptions	Modular design	Official statistics	Time study	Interview	Literature	Case study
Kogler and Rauch (2019)	X	X		X		X	X	X	X		X	X				X	X	X	X	X	X	X	X	X	X	X	X		X		X
Kogler and Rauch (2020)		X				X	X	X	X		X	X				X	X	X	X	X	X	X	X	X	X	X	X		X		X

The review article set the stage by identifying open research questions, which was well received and cited by Al-Hawari et al. (2020) as “a comprehensive review study conducted by Kogler and Rauch (2018) reviewed using DES for addressing wood SC transportation issues at both tactical and operational levels”. The closely related research articles of Kogler and Rauch (2019 and 2020) built on this knowledge and answered raised research questions. Furthermore, recommendations were addressed, for example, to provide detailed model descriptions, which was done in Kogler and Rauch (2019) with a special focus on visualization. This allowed Kogler and Rauch (2020) to refer back to those comprehensive descriptions and add important changes and further developments enabling the concentration on detailed scenario analyses, refined multimodal transport plans and concrete applicable results for a variety of real life business cases. Additionally, the suggestion to simulate the entire supply chain network in-depth was picked-up and commented on by Acuna et al. 2019 stating, “Kogler et al. used DES in perhaps the most detailed railroad terminal study to date for the wood supply chain.” The observation of Kogler and Rauch (2018) that risks were only considered rudimentary from half of the analyzed multimodal DES studies led to the integration of external risks such as natural disasters in Kogler and Rauch (2019). In the later work, Kogler and Rauch (2020) do not only focus in detail on those risk impacts, but also provide short-term contingency plans to deal with them. This is the first attempt in literature on wood supply chain management to deliver concrete transport plans, strategies, tables, templates and a simulation model setup for contingency planning.

To address suggestions of Kogler and Rauch (2018) to stimulate knowledge transfer and enhance the applicability of scientific models in industry and education, a game-based learning workshop edition of the DES model and a contingency planning toolbox were delivered. These tools allow one to communicate scientific findings to stakeholders in a straightforward, intuitive and visual way. A discussion promoting serious games and game-based learning can be found in Despeisse 2018. Simulation games teaching supply chain principles were developed (e.g., Miller 1973, Showers 1977, Crookall 1990) and there are valuable contributions for wood supply chains (e.g., D’Amours et al. 2017, Abasian et al. 2020). However, Kogler and Rauch (2019 and 2020) showcase an approach to deliver adapted scientific simulation models and findings through a workshop setting to stakeholders in order to provide close-to-reality decision support for a variety of real-life business cases. Kogler and Rauch (2019) extend the rarely existing comparisons of multimodal and unimodal wood supply chains (e.g., Karttunen et al. 2012, Karttunen et al. 2013) reflecting on a variety of KPIs (i.e., not only transport costs) for an operational planning horizon on a lower abstraction level covering more details as existing literature. Kogler and Rauch (2019 and 2020) add to the sparse literature on multimodal timber transport and contribute the only models which allow one to observe diverse research questions through different operating concepts (i.e., vary decision variables: manually during runtime, based on pre-built plans or Excel import, in a game-based learning workshop setting).

For the overall discussion, the published articles were classified and categorized to illustrate their contribution to the research area of wood supply chain management with the DES method. Moreover, they were discussed and set in context pointing out their close relationship, building on and benefitting from each other. This stepwise approach was conducive to derive learning outcomes and conclusions.

2.8 CONCLUSION

This dissertation shows how to use the DES method to provide decision support for the wood supply chain in order to further develop wood supply chain management. Thereby, it contributes new knowledge to the scientific, industrial and educational world. Firstly, it closes existing scientific research gaps by answering seven research questions (Q1–7) in three published journal articles. Secondly, it tackles challenges of the wood-based industry regarding resilience, sustainability and efficiency by providing a proof of concept for multimodal wood transport planning and advanced wood supply chain management based on the DES method. Lastly, it introduces educational tools such as a game-based learning workshop edition of a DES model and contingency planning toolbox to communicate findings.

Firstly, the added scientific value is based on conclusions of the published research articles, which (1) structured knowledge on wood transport for the first time with a focus on DES, multimodal transport and the wood supply chain; (2) built a DES model to compare multimodal and unimodal transport regarding various KPIs for an abstraction level/planning horizon combination, which had not been covered in literature before; and (3) initiated the development of concrete contingency plans for real life business cases of wood supply chains with DES. The impact of this work can be emphasized by 15 citations (Google Scholar), 60000 views (journal web pages) and a total research interest rating of 30.9 (Research Gate). Moreover, early results and first insights were presented and discussed in five presentations, two poster sessions and one PhD colloquium at four international scientific conferences.

The knowledge collection of Kogler and Rauch (2018) confirms that DES is well-suited to provide decision support for the wood supply chain. Analyses of transport logistics between interconnected actors allow one to observe entire supply chain management considerations in order to build competitive advantages through cooperation and coordination. A detailed description of relevant DES model information (e.g., model logic and modules, scenario designs, experiments) combined with clear visual methods (e.g., business process/flow diagrams, model screen shots, tables with parameter descriptions) as well as reliable validation (e.g., expert involvement, statistical analyses, extreme scenarios) support credibility, trust and integration of DES models. Research on multimodal wood transport and risk impacts contributes to further develop wood supply chain management regarding resilience, sustainability and efficiency.

Kogler and Rauch (2019) build on the knowledge collection and contribute a virtual wood supply chain simulation environment to test, analyze and evaluate unimodal and multimodal transport strategies in different scenario settings. Multimodal transport is crucial to manage, transport and store large amounts of wood since there has been an alarming bottleneck of experienced forest truck drivers who are willing to handle crane transshipment at any weather conditions and navigate on steep mountain roads partly without GPS support. Additional multimodal transport capacities reduce lead times and, subsequently, risks for bark beetle infestations and wood quality loss. Moreover, they reduce queuing time at industry and accompanying costs for compensating truck carriers, who renegotiate transport prices when queuing times at industry sites increase dramatically after windstorms. The low utilization of wagons in the strictly restricted (i.e., enforced by the Austrian law) simulation model indicates that, in reality, carriers sometimes exceed their limit of legal working hours per day or maximal legal payload. Increasing occurrences of natural disturbances and supply chain risks require additional research focusing on contingency planning including refined transport plans for multimodal wood transport.

The contingency planning toolbox of Kogler and Rauch (2020) builds on the virtual wood supply chain simulation environment and the knowledge collection to deliver a DES model setup for analyses on an operational level, strategies to cope with challenging business cases as well as transport tables, templates, and frameworks to analyze outcomes of decisions before real, unsustainable, inefficient, costly, long-lasting or not resilient changes are made. This enables one to develop contingency plans to prepare for and react to increasing risk events and more frequent natural disturbances due to climate crisis. DES covers dynamic and interdependent changes and thus is well-suited for queuing time and bottleneck analyses of complex multimodal wood supply chains. Increased truck transport tonnages reduce truck trips if working times and train pick-ups are coordinated. Contingency plans are influenced by the number of train pick-ups, delivery time from forest to industry and truck net transport tonnage. Moreover, the number of available trucks and wagons, terminal transshipment volume, required terminal stockyard, average and maximal queuing times at the terminal, truck and train utilization, as well as work time coordination are critical for advanced contingency planning.

Secondly, the added practical value was achieved by stakeholder involvement and knowledge transfer to industry. In order to further develop and professionalize wood supply management, existing weaknesses and challenges were observed through more than 30 expert interviews including field trips and company visits as well as data and literature analyses. The semi-structured interviews with experts along Austria’s wood supply chains lasted between two and three hours each and resulted in detailed written reports supplemented by questionnaires to allow comprehensive SWOT analyses. Together with scientific and industrial experts, the potentials for improvement were analyzed to tackle the most urgent challenges and use emerging opportunities. Interim and final results were discussed at stakeholder workshops, industry presentations and research project meetings with industry associations. The close cooperation established trust and credibility, conveyed the practical usability of the DES method and enabled the development of wood supply guidelines, which were broadly disseminated across the Austrian forest-based industry. Preliminary results were discussed in an industry symposium and published in two Austrian industry magazines.

The stakeholder involvement established understanding for complex system interdependencies and the need of intensified cooperation along the Austrian wood supply chain. Moreover, knowledge was transferred to further develop the resilience, sustainability and efficiency of wood supply chains to keep the Austrian wood-based industry competitive. In order to enhance the resilience and guarantee supply security, the delivered knowledge of risk management, multimodal wood transport and advanced contingency planning with DES provide helpful decision support to prepare for and react to risk events in the future. Furthermore, ecological (e.g., multimodal wood transport reduces carbon dioxide emissions and noise pollution), social (e.g., jobs along the wood supply chain and supply security of wood products for end customer) and economical (e.g., stable wood supply, additional transport and buffer capacities) contributions were delivered to increase the sustainability along wood supply chains. The efficiency of the wood supply chain was further developed based on data-driven decision making with the DES method. Innovative and powerful alternatives to simple Excel spreadsheets, managerial experiences and patterns established over time include the virtual wood supply chain simulation environment and contingency planning toolbox. Both were introduced in different workshop settings and well received by experts. These tools focused on an intuitive decision support facilitated by animation, visualization and multiple KPIs. Industry was struggling to identify KPI changes (e.g., lead times, queuing times, utilizations, transport capacities) after risk events such as windstorms because earlier simple contingency plans had never been benchmarked. Here, simulation results of different scenario settings provided first sound values to control the system. Consequently, this thesis contributed by pointing out the need for professional wood supply chain management in industrial practice as well as the potential of decision support by DES to satisfy this need.

Lastly, an educational value was added through integration of scientific and practical findings in university courses for future decision makers of the wood supply chain (i.e., Business Management 2 in the Master's program Wood Technology and Management as well as Production Management in the Bachelor's program Wood and Fibre Technology at the University of Natural Resources and Life Science, Vienna). Moreover, game-based learning workshops were held with students who got hands-on experiences on DES models to handle challenging supply and contingency planning scenarios with their own transport strategies to beat other competing groups regarding predefined KPIs. The preparation of learning goals, theoretical inputs as well as reflective discussions forced a deep understanding of interdependencies within complex systems and learning while “playing a game”.

Research on wood supply chain management applying interdisciplinary research approaches combining elements of computer science, operations research, business and forest/wood economy is promising to deliver greatly needed knowledge to science, industry and education. Consequently, a research article (Kogler and Rauch, accepted) on workshops for the wood supply chain has been accepted for publication in the International Journal of Simulation Modelling. Current working papers include a SWOT analysis of the Austrian wood supply chain as well as a DES model to observe the transshipment of wood from crane trucks to semi-trailer trucks.

Future research comparing wood supply chain management in different countries, observing wood value-tracking and lead times as well as the impact of cooperative planning along the wood supply chain is needed. Furthermore, future works observing the digitalization, cooperation, actors and salvage wood logistics along the Austrian wood supply chain based on questionnaires, expert interviews, literature analyses, business process modeling and reengineering is essential to be conducted. Meta-analyses reviewing existing works on Agent-Based and System Dynamics simulation models, digital twins, simulation games, teaching DES and SWOT analyses for (wood) supply chains are areas of interest. Expanding the initial approaches to combine DES with Agent-Based Simulation, System Dynamics, Meta-Heuristics and Optimization contributes to tackle existing and future challenges as well as opportunities along the wood supply chain.

The climate crisis, globalization and digitalization show that professional wood supply chain management based on advanced decision support is needed. Supply chains of other industries (e.g., car, computer, electronic) paved the way for the wood supply chain, which should and can (prime examples from other regions such as Canada and Scandinavia are indicative) catch up regarding cooperation, integration, digitalization and innovation.

This dissertation contributes influencing novelties to the literature of multimodal wood supply chain management, DES applications and contingency planning. It provides decision support by DES for the wood supply chain and delivers a knowledge collection, virtual wood supply chain simulation environment and contingency planning toolbox. Hence, the manifold contributions for science, industry and education as well as an outlook for further research were presented to highlight the impact of the dissertation regarding the further development of wood supply chain management.

2.9 REFERENCES

Abasian F., Rönnqvist M., Marier P., Fjeld D. 2020: The transportation game; INFORMS Transactions on Education: https://doi.org/10.1287/ited.2019.0223.

Acuna M., Sessions J., Zamora R., Boston K., Brown M., Ghaffariyan M. R. 2019: Methods to manage and optimize forest biomass supply chains: a review; Current Forestry Reports: https://doi.org/10.1007/s40725-019-00093-4.

Al-Hawari T., Qasem A. G., Smadi H., Arauydah H., Al Theeb N. 2020: The effects of pre or post delay variable changes in discrete event simulation and combined DES/system dynamics approaches in modelling supply chain performance; Journal of Simulation: https://doi.org/10.1080/17477778.2020.1764399.

AP (Austrian Paper Industry Association) 2019: Annual Report 2018/19; Available online: https://www.austropapier.at/fileadmin/austropapier.at/dateiliste/Dokumente/Downloads/Jahresberichte/19.04.10__Gesamter_Bericht__9MB_.pdf (accessed on 19 August 2020).

ARCF (Austrian Research Centre for Forests) 2019: Interim report forest inventory 2016/18; Available online: https://bfw.ac.at/cms_stamm/050/PDF/BFW-Praxisinfo50_waldinventur_fertig_web.pdf (accessed on 19 August 2020).

Asikainen A. 1998: Chipping terminal logistics; Scandinavian Journal of Forest Research: https://doi.org/10.1080/02827589809382998.

Asikainen A. 2001: Simulation of logging and barge transport of wood from forests on islands; International Journal of Forest Engineering: https://doi.org/10.1080/14942119.2001.10702445.

Asikainen A. 2010: Simulation of stump crushing and truck transport of chips; Scandinavian Journal of Forest Research: https://doi.org/10.1080/02827581.2010.488656.

Atashbar N. Z., Labadie N., Prins C. 2016: Modeling and optimization of biomass supply chains: a review and a critical look; IFAC-PapersOnLine: https://doi.org/10.1016/j.ifacol.2016.07.742.

BMNT (Federal Ministry for Sustainability and Tourism, Republic of Austria) 2018: Austrian forest strategy 2020+; Available online: https://www.bmlrt.gv.at/forst/oesterreich-wald/waldstrategie-2020/waldstrategie_paper.html (accessed on 19 August 2020).

BMNT (Federal Ministry for Sustainability and Tourism, Republic of Austria) 2019a: Green report; Available online: https://gruenerbericht.at/cm4/jdownload/send/2-gr-bericht-terreich/2007-gb2019 (accessed on 26 July 2020).

BMNT (Federal Ministry for Sustainability and Tourism, Republic of Austria) 2019b: Austrian market report 2019; Available online: http://www.unece.org/fileadmin/DAM/timber/meetings/2019/20191104/Austria2019.pdf (accessed on 19 August 2020).

Beaudoin D., LeBel L., Soussi M. A. 2012: Discrete event simulation to improve log yard operations; Infor: https://doi.org/10.3138/infor.50.4.175.

Borodin V., Bourtembourg J., Hnaien F., Labadie N. 2016: Handling uncertainty in agricultural supply chain management: a state of the art; European Journal of Operational Research: https://doi.org/10.1016/j.ejor.2016.03.057.

Cavalli R., Grigolato S., Pellegrini M. 2012: Determination of the forest road network influence on the supply chain for firewood production by discrete event simulation; Journal of Agricultural Engineering: https://doi.org/10.4081/jae.2011.4.41.

Crookall D. 1990: Fish banks ltd: a microcomputer-assisted simulation that teaches principles for sustainable management of renewable resources; Simulation & Gaming 21(2), 208–211.

D'Amours S., Ronnqvist M., Weintraub A. 2008: Using operational research for supply chain planning in the forest products industry; Information Systems and Operational Research: https://doi.org/10.3138/infor.46.4.265.

D'Amours S., Marier P., Rönnqvist M., Azouzi R., Fjeld D. 2017: The online wood supply game; INFORMS Transactions on Education: https://doi.org/10.1287/ited.2017.0174.

De Mol R. M., Jogems M. A. H., Van Beek P., Gigler J. K. 1997: Simulation and optimization of the logistics of biomass fuel collection; Netherlands Journal of Agricultural Science: https://doi.org/10.18174/njas.v45i1.535.

Despeisse M. 2018: Games and simulations in industrial engineering education: a review of the cognitive and affective learning outcomes; Proceedings of the 2018 Winter Simulation Conference: https://doi.org/10.1109/WSC.2018.8632285.

Eliasson L., Eriksson A., Mohtashami S. 2017: Analysis of factors affecting productivity and costs for a high-performance chip supply system; Applied Energy: https://doi.org/10.1016/j.apenergy.2016.10.136.

Eriksson A., Eliasson L., Hansson P.-A., Jirjis R. 2014a: Effects of supply chain strategy on stump fuel cost: a simulation approach; International Journal of Forestry Research: https://doi.org/10.1155/2014/984395.

Eriksson A., Eliasson L., Jirjis R. 2014b: Simulation-based evaluation of supply chains for stump fuel; International Journal of Forest Engineering: https://doi.org/10.1080/14942119.2014.892293.

Eriksson A., Eliasson L., Sikanen L., Hansson P.-A., Jirjis R. 2017: Evaluation of delivery strategies for forest fuels applying a model for weather-driven analysis of forest fuel systems (WAFFS); Applied Energy: https://doi.org/10.1016/j.apenergy.2016.12.018.

Etlinger K., Rauch P., Gronalt M. 2014: Improving rail road terminal operations in the forest wood supply chain – a simulation based approach; Available online: http://www.msc-les.org/proceedings/hms/2014/HMS2014_199.pdf (accessed on 19 August 2020).

Eurostat 2018: Agriculture, forestry and fishery statistics; Available online: https://doi.org/10.2785/340432 (accessed on 19 August 2020).

FAO (Food and Agriculture Organization of the United Nations) 2017: Sustainable wood for a sustainable world - global meeting report; Available online: http://www.fao.org/forestry/46700-0a274f69ab292a75be6ef89e8c4aa7566.pdf (accessed on 19 August 2020).

FAO (Food and Agriculture Organization of the United Nations) 2018: The state of the world's forests 2018 - forest pathways to sustainable development; Available online: https://doi.org/10.18356/18a7cf8d-en (accessed on 19 August 2020).

FAO (Food and Agriculture Organization of the United Nations) and UNEP (United Nations Environmental Programme) 2020: The state of the world's forests 2020 - Forests, biodiversity and people; Available online: https://doi.org/10.4060/ca8642en (accessed on 19 August 2020).

FH (Austrian Wood Industry Association) 2019: Annual report 2018/19; Available online: https://www.wko.at/branchen/industrie/holzindustrie/branchenbericht-2018-2019.pdf (accessed on 19 August 2020).

FHP (Austrian Forest-Wood-Paper Association) 2019: Performance report value chain wood; Available online: https://www.forstholzpapier.at/images/Leistungsbericht_kompakt_2019_Ansicht_FINAL.pdf (accessed on 19 August 2020).

Gronalt M., Chloupek A., Greigeritsch T., Häuslmayer H. 2005: WoodLog – Perspektiven der Holzlogistik Supply Chain – Optimierungspotentiale durch ein Logistikleitzentrum Holz – Österreich; Lignovisionen Band 11, University of Natural Resources and Life Sciences, Vienna.

Gronalt M., Rauch P. 2018: Analyzing railroad terminal performance in the timber industry supply chain – a simulation study; International Journal of Forest Engineering: https://doi.org/10.1080/14942119.2018.1488913.

ITC (International Trade Center) 2019: Trade map; Available online: https://www.trade-map.org/Country_SelProduct_TS.aspx?nvpm=1%7c%7c%7c%7c%7c44%7c%7c%7c2%7c1%7c1%7c3%7c2%7c1%7c2%7c1%7c1%7c1 (accessed on 19 August 2020).

Karttunen K., Väätäinen K., Asikainen A., Ranta T. 2012: The operational efficiency of water-way transport of forest chips on Finland's lake Saimaa; Silva Fennica: https://doi.org/10.14214/sf.49.

Karttunen K., Lättilä L., Korpinen O.-J., Ranta T. 2013: Cost-efficiency of intermodal container supply chain for forest chips. Silva Fennica: https://doi.org/10.14214/sf.1047.

Kishita Y., Nakatsuka N., Akamatsu F. 2017: Scenario analysis for sustainable woody biomass energy businesses: the case study of a Japanese rural community; Journal of Cleaner Production: https://doi.org/10.1016/j.jclepro.2016.11.161.

Kogler C. 2016: Optimization of timber-flow logistics at the Papierholz Austria GmbH. Available online: https://resolver.obvsg.at/urn:nbn:at:at-ubg:1-104175 (accessed on 19 August 2020).

Kogler C., Rauch P. 2018: Discrete event simulation of multimodal and unimodal transportation in the wood supply chain: a literature review, Silva Fennica: https://doi.org/10.14214/sf.9984.

Kogler C., Rauch P. 2019: A discrete event simulation model to test multimodal strategies for a greener and more resilient wood supply, Canadian Journal of Forest Research: https://doi.org/10.1139/cjfr-2018-0542.

Kogler C., Rauch P. 2020: Contingency plans for the wood supply chain based on bottleneck and queuing time analyses of a discrete event simulation; Forests: https://doi.org/10.3390/f11040396.

Kogler C., Rauch P. Accepted for publication: Game-based workshops for the wood supply chain to facilitate knowledge transfer; International Journal of Simulation Modelling: 12p.

Lautala P. T., Hilliard M. R., Webb E., Busch I., Hess J. R., Roni M. S., Hilbert J., Handler R. M., Bittencourt R., Valente A., Laitinen T. 2015: Opportunities and challenges in the design and analysis of biomass supply chains; Environmental Management: https://doi.org/10.1007/s00267-015-0565-2.

Law A. M. 2015: Simulation modeling and analysis; 5th edition, McGraw-Hill, New York.

Mahdavi A. 2020: The art of process-centric modeling with AnyLogic; Available online: http://www.anylogic.com/resources/books/the-art-of-process-centric-modeling-with-anylogic (accessed on 19 August 2020).

Mahmoudi M., Sowlati T., Sokhansanj S. 2009: Logistics of supplying biomass from a mountain pine beetle-infested forest to a power plant in British Columbia; Scandinavian Journal of Forest Research: https://doi.org/10.1080/02827580802660397.

Manuj I., Mentzer J. T., Bowers M. R. 2009: Improving the rigor of discrete-event simulation in logistics and supply chain research; International Journal of Physical Distribution & Logistics: https://doi.org/10.1108/09600030910951692.

Marques A. F., De Sousa J. P., Rönnqvist M., Jafe R. 2014: Combining optimization and simulation tools for short-term planning of forest operations; Scandinavian Journal of Forest Research: https://doi.org/10.1080/02827581.2013.856937.

Miller J. 1973: Instructions for group session on the hand simulation game; Memo D-1867, MIT System Dynamics Group, Cambridge.

Mirkouei A., Haapala K. R., Sessions J., Murthy G. S. 2017: A review and future directions in techno-economic modeling and optimization of upstream forest biomass to bio-oil supply chains; Renewable & Sustainable Energy Reviews: https://doi.org/10.1016/j.rser.2016.08.053.

Mobini M., Sowlati T., Sokhansanj S. 2011: Forest biomass supply logistics for a power plant using the discrete-event simulation approach; Applied Energy: https://doi.org/10.1016/j.apenergy.2010.10.016.

Mobini M., Sowlati T., Sokhansanj S. 2013: A simulation model for the design and analysis of wood pellet supply chains; Applied Energy: https://doi.org/10.1016/j.apenergy.2013.06.026.

Mobini M., Meyer J. C., Trippe F., Sowlati T., Frohling M., Schultmann F. 2014: Assessing the integration of torrefaction into wood pellet production; Journal of Cleaner Production: https://doi.org/10.1016/j.jclepro.2014.04.071.

Myers J., Richards E. W. 2003: Supporting wood supply chain decisions with simulation for a mill in northwestern BC; Infor: https://doi.org/10.1080/03155986.2003.11732677.

Oliveira J. B., Lima R. S., Montevechi J. A. B. 2016: Perspectives and relationships in supply chain simulation: a systematic literature review; Simulation Modelling Practice and Theory: https://doi.org/10.1016/j.simpat.2016.02.001.

Opacic L., Sowlati T. 2017: Applications of discrete-event simulation in the forest products sector: a review; Forest Products Journal: https://doi.org/10.13073/fpj-d-16-00015.

Pinho T. M., Coelho J. P., Boaventura-Cunha J. 2016a: Forest-based supply chain modelling using the SimPy simulation framework; IFAC-PapersOnLine: https://doi.org/10.1016/j.ifacol.2016.03.016.

Pinho T. M., Coelho J. P., Moreira A. P., Boaventura-Cunha J. 2016b: Modelling a biomass supply chain through discrete-event simulation; IFAC-PapersOnLine: https://doi.org/10.1016/j.ifacol.2016.03.015.

Saranen J., Hilmola O.-P. 2007: Evaluating the competitiveness of railways in timber transports with discrete-event simulation; World Review of Intermodal Transportation Research: https://doi.org/10.1504/writr.2007.017097.

Seay J. R., Badurdeen F. F. 2014: Current trends and directions in achieving sustainability in the biofuel and bioenergy supply chain; Current Opinion in Chemical Engineering: https://doi.org/10.1016/j.coche.2014.09.006.

Shahi S., Pulkki R. 2013: Supply chain network optimization of the Canadian forest products industry: a critical review. American Journal of Industrial and Business Management: https://doi.org/10.4236/ajibm.2013.37073.

Showers J. L. 1977: An inventory management simulation game; Proceedings of the 1977 Winter Simulation Conference: 278–284.

Spinelli R., Di Gironimo G., Esposito G., Magagnotti N. 2014: Alternative supply chains for logging residues under access constraints; Scandinavian Journal of Forest Research: https://doi.org/10.1080/02827581.2014.896939.

Strimitzer L., Höher M., Nemestothy, K. 2019: Wood Flows in Austria; Available online: https://www.klimaaktiv.at/erneuerbare/energieholz/holzstr_oesterr.html (accessed on 19 August 2020).

Tako A. A., Robinson S. 2012: The application of discrete event simulation and system dynamics in the logistics and supply chain context; Decision Support Systems: https://doi.org/10.1016/j.dss.2011.11.015.

Väätäinen K., Prinz R., Malinen J., Laitila J., Sikanen L. 2017: Alternative operation models for using a feed-in terminal as a part of the forest chip supply system for a CHP plant; Global Change Biology Bioenergy: https://doi.org/10.1111/gcbb.12463.

Windisch J., Röser D., Mola-Yudego B., Sikanen L., Asikainen A. 2013a: Business process mapping and discrete-event simulation of two forest biomass supply chains; Biomass & Bioenergy: https://doi.org/10.1016/j.biombioe.2013.05.022.

Windisch J., Röser D., Sikanen L., Routa J. 2013b: Reengineering business processes to improve an integrated industrial roundwood and energywood procurement chain; International Journal of Forest Engineering: https://doi.org/10.1080/14942119.2013.857833.

Windisch J., Vaatainen K., Anttila P., Nivala M., Laitila J., Asikainen A., Sikanen L. 2015: Discrete-event simulation of an information-based raw material allocation process for increasing the efficiency of an energy wood supply chain; Applied Energy: https://doi.org/10.1016/j.apenergy.2015.03.122.

Wolfsmayr U. J., Rauch P. 2014: The primary forest fuel supply chain: a literature review; Biomass & Bioenergy: https://doi.org/10.1016/j.biombioe.2013.10.025.

Wolfsmayr U. J., Merenda R., Rauch P., Longo F., Gronalt M. 2016: Evaluating primary forest fuel rail terminals with discrete event simulation: a case study from Austria; Annals of Forest Research: https://doi.org/10.15287/afr.2015.428.

Zamora-Cristales R., Boston K., Sessions J., Murphy G. 2013: Stochastic simulation and optimization of mobile chipping economics in processing and transport of forest biomass from residues; Silva Fennica: https://doi.org/10.14214/sf.937.

Zhang F., Johnson D. M., Johnson M. A. 2012: Development of a simulation model of biomass supply chain for biofuel production; Renewable Energy: https://doi.org/10.1016/j.renene.2012.02.006.

3 Journal Publications

The third section presents the three published articles. The first (3.1, CC BY-SA 4.0) and the third (3.3, CC BY 4.0) paper were published in open access journals enabling the presentation of the final and freely available versions. The Canadian Science Publishing permitted to freely share and post the accepted version of the manuscript for the second paper (3.2), which is presented in this dissertation. The final version of the second paper, which passed professional proof reading, copy editing and was extended by a French abstract, is available under the following DOI Link: https://doi.org/10.1139/cjfr-2018-0542. The headers and footers were adjusted to the design of this dissertation. The cover pages of the journals were provided by the publishing institutions and permission was granted to edit them. Thanks to Dr. Pekka Nygren for designing the cover for the Silva Fennica Journal specially for this dissertation.

3.1 Discrete Event Simulation of Multimodal and Unimodal Transportation in the Wood Supply Chain: a Literature Review

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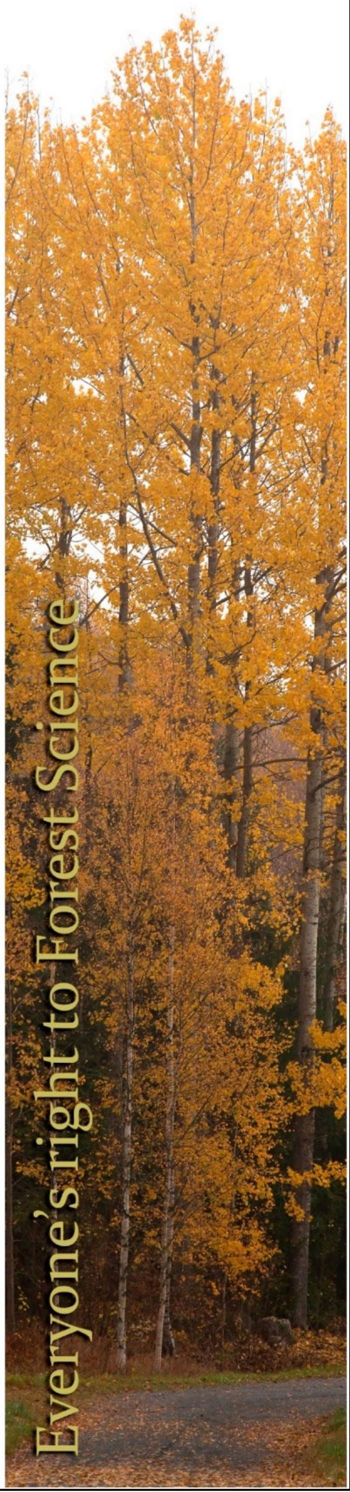

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Christoph Kogler and Peter Rauch

Discrete event simulation of multimodal and unimodal transportation in the wood supply chain: a literature review

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Highlights

- Focus on discrete event simulation, wood supply chain and multimodal transport.
- Analyses of 12 review articles and a core of 32 research papers, complemented by 48 related ones.
- Research focus from unimodal to multimodal transport to build efficient, resilient, green and socially sustainable supply chains.
- Development of robust risk management considering supply risks, demand risks and external risks is needed.

Abstract

This review systematically analyses and classifies research and review papers focusing on discrete event simulation applied to wood transport, and therefore illustrates the development of the research area from 1997 until 2017. Discrete event simulation allows complex supply chain models to be mapped in a straightforward manner to study supply chain dynamics, test alternative strategies, communicate findings and facilitate understanding of various stakeholders. The presented analyses confirm that discrete event simulation is well-suited for analyzing interconnected wood supply chain transportation issues on an operational and tactical level. Transport is the connective link between interrelated system components of the forest products industry. Therefore, a survey on transport logistics allows to analyze the significance of entire supply chain management considerations to improve the overall performance and not only one part in isolation. Thus far, research focuses mainly on biomass, unimodal truck transport and terminal operations. Common shortcomings identified include rough explanations of simulation models and sparse details provided about the verification and validation processes. Research gaps exist concerning simulations of entire, resilient and multimodal wood supply chains as well as supply and demand risks. Further studies should expand upon the few initial attempts to combine various simulation methods with optimization.

Keywords supply chain management; logistics; forest products industry; decision support systems; validation and verification of simulation models; resilient risk management
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1 Introduction

The use of operations research methods in wood supply chain research created a wide range of strategic, tactical and operational decision support systems (Vacik and Lexer 2014). In general, related scientific literature can be separated in two main research categories. The first focuses on single processes like harvesting, forwarding, transportation, or mill operations, whereas the second highlights integrated issues along these processes considering supply chain management principles (D'Amours et al. 2008; Larsson et al. 2016). Furthermore, driven by a growing bioeconomy and a rising biomass demand, an increasing number of articles widen the focus of (biomass) supply chain studies on sustainability and feasibility issues (Lewandowski 2015; How and Lam 2018). A fundamental supply chain management principle is to emphasize the overall performance of the supply chain in order to compete with other supply chains (Haartveit et al. 2004; Westlund and Furness-Lindén 2010) rather than "trench warfare" or "cherry picking" of individual actors (Gueimonde-Canto et al. 2011), which harms total efficiency. Accordingly, this review article focuses on the wood supply chain connecting forest owners and forest based industries including energy production as part of the wood value chain. Transport is the connective link between dependent system components, and therefore a survey on transport is considered suitable to analyze the significance of supply chain management considerations.

As the wood supply chain is a complex and highly dynamic network due to unpredictable simultaneous interactions, it hardly can be solved optimally. In practice, coordinated processes are applied to cope with this complexity, but fail frequently when unexpected risks occur or changes have to be implemented. This leads to an inefficient supply chain. Although there are optimization as well as simulation models, and even a variety of mixes of both for isolated considerations, simulation models dominate when it comes to wood supply chain management. In contrast, plenty of articles and reviews exists on optimization applied in the forest supply chain (Malladi and Sowlati 2018), however, examples for connecting optimization with simulation are still rare.

In order to deal with such challenges, in addition to Monte Carlo Simulation (MCS), System Dynamics (SD) and Agent-Based Simulation (ABS), the Discrete Event Simulation (DES) approaches are gaining growing importance. Even though all these simulation approaches allow one to include stochastic elements (i.e., randomness of observations is considered), are stepwise converging and software packages (e.g., AnyLogic) support combining them, each method has still its specific field of application. SD describes continuous systems (i.e., infinitesimal time steps), whereas DES and ABS models are discrete (i.e., finite time steps). Unlike SD models with basic stock and flow structure typically covering less details, ABS concentrates on the individual behavior of agents usually providing a complex decision logic and including various details. Due to their abstraction level, both are suitable to only a limited degree for supply chains. In contrast, the intermediate abstraction level (i.e., a medium level of included details) of DES in combination with a straightforward model structure and powerful software enables the mapping of business processes and controlling the system by events. This is appropriate to model a supply chain closer to reality. These advantages led to a broad acceptance of DES among scientists and managers as indicated by the high number of recently published research articles and implemented decision support systems.

Several scientific review articles motivate this combined review, related by either the method (i.e., DES) or research area (i.e., wood supply chain). Oliveira et al. (2016) contribute a detailed meta-analysis and systematic literature review on simulation methods in supply chains, highlighting the suitability of DES for modelling real-world supply chains to support decision makers by analyzing various scenarios, selecting appropriate solutions, and improving both understanding of interactions and performance. They provide a guideline to support implementation of simulation models for supply chains and highlight the trend of combining simulation with optimization methods. Tako and Robinson (2012) compare SD and DES in terms of planning horizon (i.e., strategic and tactical/operational) and conclude that DES is used more frequently with exception of the bullwhip effect where SD is dominant. An eight-step guideline for designing, implementing and evaluating a DES supply chain model is provided by Manuj et al. (2009). They recommend management involvement to review the model in an early stage as it considerably improves trust in gained results.

Focusing on the wood supply chain, D'Amours et al. (2008) explain related strategic, tactical and operational operation research applications and problems. They highlight various difficulties companies face implementing closer supply chain collaborations (e.g., integrating various business units such as forest entrepreneurs, carriers, sawmills, pulp and paper mills). Shashi and Pulkki (2013) comprehensively review literature for supply chain modelling and simulation in general as well as focus on the forest products industry and explain straightforward basics and differences in planning horizon (i.e., strategic, tactic, operative) and simulation models (i.e., DES, SD, ABS and MCS). Moreover, they highlight opportunities of uncertainty considerations and integrated simulation-based optimization models.

A comprehensive overview on the biomass supply chain is provided in Wolfsmayr and Rauch (2014). They describe truck, train and vessel transport, focusing on multimodal transport for different terminal types. Optimization and simulation models are analyzed with regard to decision support for supply chain management. Therefore, they highlight the lack of considerations of stochastic supply disruptions due to environmental impacts or technical defects.

Seay and Badurdeen (2014) track current trends within the biomass supply chain and recommend an integrated approach including process simulation, DES, supply chain optimization and risk assessment to overcome the major challenge of complex and interconnected stakeholder decisions. They refer to DES models that identify possible improvements in different scenarios instead of optimizing supply chain configuration. According to the authors, most models are limited in the integration of sustainability dimensions, risk analysis, long term outcomes or the ability to assess system performance.

Lautala et al. (2015) mention the processes of the biomass supply chain, specialized equipment for biomass transportation and examples of related modelling and simulating applications (i.e., IBSAL, WISDOM, LabTrans, PrevFretes, SIGTrans, BILT). They recognize transportation as a key component in literature and the dominance of truck as primary transport mode. Focusing on multimodal transport, they compare transportation modes (i.e., truck, train and vessel) and recommend to use each transport mode at its best operational scale. Furthermore, they illustrate multi-modal chain cost efficiency of a combined truck and train transportation in comparison with a single-mode truck transportation.

Borodin et al. (2016) focus on uncertainties in agri-supply chain management and provide a historic overview of the development of simulation methods. Mostly the same operations research methods are used to tackle challenges similar to those of the wood supply chain. Atashbar et al. (2016) provide an overview of basic activities and definitions along the biomass supply chain as well as a classification of applied optimization methods in terms of objective function (i.e., minimize costs, maximize profits, maximize net present value, multiple objectives), decision level (i.e., strategic, tactical, operational) and solution method (i.e., optimization, heuristics, simulation). They conclude that future research should concentrate on optimizing the entire supply chain including multimodal transport.

Mirkouei et al. (2017) concentrate on techno-economic modelling and optimization in the biomass supply chain and provide a broad technical background showing that simulation models are not appropriate for calculating optimal solutions, but provide modelling flexibility and improve supply chain understanding. In this narrative review, they chronologically identify purposes, key concepts, challenges, links and solutions and conclude that most studies focus on single topics, especially on harvesting, logistics or storage.

Finally, Opacic and Sowlati (2017) list a selection of DES applications in the forest product sector focusing on fragmented considerations such as the comparison of forest management techniques and harvesting systems, or the evaluation of transportation, logistics and supply chains.

Table 1 summarizes the above mentioned reviews and varying focuses. No review focuses on DES, the wood supply chain and multimodal transport, indicating the need for deeper analyses in this area. The motivation for this work is the suitability of the DES method to contribute to a better understanding of the wood supply chain. DES allows complex supply chain models to be mapped in a straightforward manner to study supply chain dynamics, test alternative strategies, communicate findings and facilitate understanding of various stakeholders. This establishes trust and enables decision makers to gain confidence to implement study results. Therefore, this study illustrates the development of the research area from 1997 until 2017 and pave the way for future applications.

Scientific literature was reviewed to determine to what extent the DES approach has been applied in the wood supply chain, especially with focus on multimodal and unimodal transport, and what contradictions, gaps or hot topics have not been addressed thus far. The remainder of the paper is structured as follows: Section 2 states the applied approach; and Section 3 briefly describes the structure of the wood supply chain and basics of DES. Section 4 contains quantitative analysis in a systematic review with charts and classifying tables; and Section 5 aggregates general characteristics as well as contradictions in DES research articles of multimodal and unimodal transportation in the wood supply chain, based on narrative comparisons. Conclusions and future research directions are provided in Section 6.

Table 1. Categorization of related review papers.

Researcher (year)	Region	Journal	DES	OM	WSC	B	MT
D'Amours et al. (2008)	CAN	Information Systems and Operational Research		X	X		
Manuj et al. (2009)	USA	International Journal of Physical Distribution & Logistics Management	X				
Tako and Robinson (2012)	GBR	Decision Support Systems	X				
Shashi and Pulkki (2013)	CAN	American Journal of Industrial and Business Management	X	X	X		
Seay and Badurdeen (2014)	USA	Current Opinion in Chemical Engineering	X	X		X	
Wolfsmayr and Rauch (2014)	AUT	Biomass & Bioenergy	X	X		X	X
Lautala et al. (2015)	USA	Environmental Management	X	X		X	X
Atashbar et al. (2016)	FRA	IFAC-PapersOnLine		X		X	X
Borodin et al. (2016)	FRA	European Journal of Operational Research	X	X		X	
Oliveira et al. (2016)	BRA	Simulation Modelling Practice and Theory	X	X			
Mirkouei et al. (2017)	USA	Renewable & Sustainable Energy Reviews		X		X	
Opacic and Sowlati (2017)	CAN	Forest Products Journal	X		X		
Kogler and Rauch (2018)	AUT	Silva Fennica	X		X		X

DES = Discrete Event Simulation, OM = Optimization Models, WSC = Wood Supply Chain, B = Biomass, MT = Multimodal Transportation

2 Methodology

This review combines narrative and systematic elements to merge the benefits of both in terms of comprehensive analyses and standardization. Literature research included the following databases and library services: BokuLitSearch, Crossref, Directory of Open Access Journals, Emerald Insight, Google Scholar, IEEE Xplore, Sage, ScienceDirect, Scopus, Springer Link and Web of Science. The search query was set as follows: *(discrete event simulation OR simulation) AND (wood OR timber OR forest OR biomass) AND supply chain.* In addition, a modified search vocabulary was considered including the terms *multimodal, unimodal, train, railway, vessel, waterway, truck, transport, shipping, hauling, procurement, logistics, decision support systems* and *simulation modelling*. These terms and phrases were mostly found in titles, keywords and abstracts, but also in the full text of articles. Moreover, the reference sections were scanned and papers cited in these articles were investigated. Approximately 150 articles were shortlisted, organized in EndNote X8 and studied in detail. For the majority of cases, articles exclusively dealing with optimization methods were excluded, as well as very old articles, as the focus of this review is on contemporary DES approaches. Moreover, articles not dealing with supply chain issues, but rather single process analysis were rejected as their approach mainly improves profit of a single actor, resulting in costs elsewhere and harming the competitiveness of an entire chain. The selection process resulted in 12 review articles and a core of 32 research papers, complemented by 48 related books, papers published in peer-reviewed journals as well as a handful relevant conference papers. To analyze selected articles, the following classifying parameters were defined: reference (year), risk considered, case study included, simulation period, resolution time, supply network, objective, region, journal, abstraction level, planning horizon, assortment, transport mode, software, data collection, structure, input parameter, statistical analyses, validation and documentation. After assessing each article according to the classifying parameters, a qualitative analysis was conducted prior to compilation. Fig. 1 summarizes the described methodology and the applied working process.

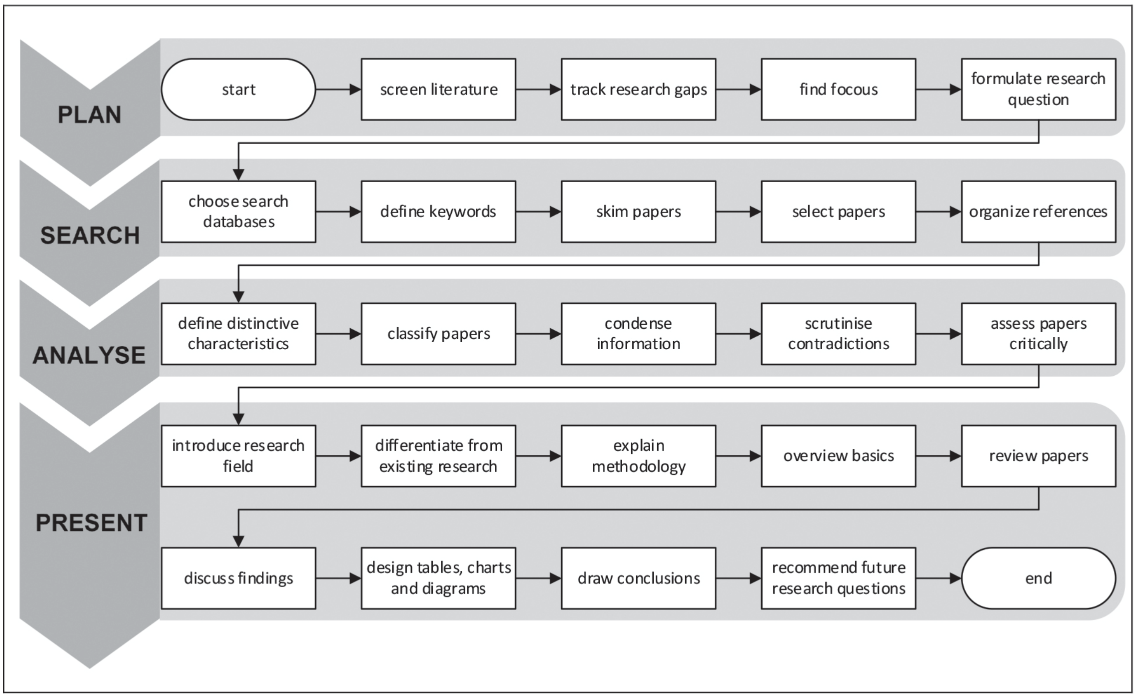


Fig. 1. Methodology of the literature research (cf. Oliveira et al. (2016)).

3 Simulate the wood supply chain by discrete events

The wood supply chain is a complex dynamic network consisting of various actors and material-, service-, financing- and information flows within and between them. The wood passes through different levels of suppliers and customers and is, due to unpredictable and simultaneous interdependencies, not easily controllable. Wood supply chain management deals with relevant decisions to plan, design, operate, control and monitor the wood supply chain to improve efficiency and resilience from an economic, ecologic and social point of view. Wood supply chain research focuses mainly on planning and design to improve the real world wood supply chain by operations research methods. Simulation, especially DES, is an appropriate method to tackle the outstanding issues where analytic calculations fail (Borshchev and Filippov 2004) or a straightforward model structure to communicate findings to stakeholders by animation is required.

The wood supply chain comprises growing, harvesting, extraction, transporting, storing, (pre-)processing, (re-)using and recycling of wood. Specific planning aspects of the supply chain relating to strategic, tactical and operational horizons are comprehensively described for the forest products industry by D'Amours et al. (2008) and, for biomass supply chains, by Atashbar et al. (2016). Strategic planning (e.g., forest growth, new industry locations, management strategies) considers several years or even decades in advance, while tactical planning (e.g., resource allocation, production, inventory policies) considers months to a year and operational planning (e.g., harvesting, scheduling, transportation) hours, days and weeks (Weintraub 2007; Rauch 2013; Shahi and Pulkki 2013). This planning horizon definition was used for the classification of the 32 research papers in Table 4, Fig. 3 and the related explanations presented. Moreover, the abstraction level is evaluated in this context. Therefore, the term abstraction level is defined as the complexity of a simulation model. The abstraction level assesses the level of detail in the included components, decisions and processes. In this regard, few details only covering part of the supply chain indicate high abstraction level, while many details covering the entire supply chain indicate low abstraction level.

3.1 Transport in the wood supply chain

Wolfsmayr and Rauch (2014) define four different transport means for wood including single echelon unimodal transport (i.e., exclusive truck, train or vessel transport), multi echelon unimodal transport (i.e., transhipment, unchanged transport mode), intermodal transport (i.e., one loading unit on different transport modes) and multimodal transport (i.e., change of transport mode). They indicate that there is a clear dominance of truck transport in research as well as in practice. In case of multimodal transport, transhipments mainly take place at terminals where wood is loaded from trucks to trains (Mahmudi and Flynn 2006; Etlinger et al. 2014; Wolfsmayr et al. 2016; Gronalt and Rauch 2018) or vessels (Karttunen et al. 2012).

Lautala et al. (2015) compare transport modes and conclude that truck transport offers good performance in terms of network coverage, accessibility, speed and flexibility, but has low energy efficiency and capacity per unit. While train transport performs intermediate in all categories, water transport has low network coverage, accessibility, speed and flexibility, but high energy efficiency and capacity per unit.

3.2 Simulation approaches

Abstract mathematical modelling is frequently applied to provide decision support and solve real world problems, if experiments with real objects are difficult or not possible due to expense, danger, inefficiency, duration or other doubts. Particularly, when analytic calculations are complex or simply not possible, simulation offers appropriate means for problem solving (Lehtonen and Holmström 1999; Almeder et al. 2009; Webb et al. 2014). To build a simulation model, both details and less relevant issues are abstracted to focus on important questions with lower complexity. Simulation experiments facilitate both a better understanding of the part of reality modelled and evaluating strategies in various scenarios to support decision making.

Important simulation approaches beside DES are MCS, SD and ABS. The different simulation approaches were developed separately, but move closer together and can be combined (e.g., ABS in DES: forklift drives on a log yard and makes own decisions, SD in ABS: budget for decisions of an individual, SD in DES: an event gets executed shortly before a dam brakes). MCS is often applied to run random sample experiments within other simulation approaches (Borshchev and Filippov 2004). SD fits well for continuous systems with a high abstraction level, whereas DES and ABS models are discrete (Tako and Robinson 2012). DES focuses on events on an intermediate abstraction level compared to the concentration on individual behavior on a low abstraction level in ABS models. Law (2015) provides insight into the above mentioned simulation approaches and the required statistics. Borshchev (2013) and Grigoryev (2015) concentrate on the simulation software AnyLogic and both provide practical guidelines to develop simulation models. A comprehensive evaluation of simulation software can be found in Albrecht (2010).

3.3 Decision support in the wood supply chain by DES

DES with its intermediate abstraction level, universal extendibility with regard to other simulation and optimization approaches, and powerful potential to treat complex, dynamic (i.e., changing variables according to the simulation time) and stochastic (i.e., randomness of observations is considered) systems is a suitable tool to provide decision support for the wood supply chain (Cavalli et al. 2012; Shahi and Pulkki 2013; Opacic and Sowlati 2017; Gronalt and Rauch 2018). The wood supply chain can be represented by queues and activities, where state changes (events) occur at discrete points in time. Specific attributes (e.g., weight restriction, speed, lead time) are assigned to each entity (e.g., people, objects) that uses resources (e.g., personal, machines, vehicles) to determine what happens during the simulation (Tako and Robinson 2012). In DES models, every value above the level of abstraction can be tracked and statistically analyzed at any time (Borshchev 2013). Complex interdependencies of the wood supply chain can be straightforwardly modelled and visually illustrated in an animation to demonstrate model internals to stakeholders. Therefore, results for different model configurations and what-if analyses can be computed and compared providing managers with valuable decision support. For example, the complex interdependencies of the wood supply chain can be visualized in the Wood Supply Game by Fjeld (2001), simulating information and material flows.

According to Manuj et al. (2009), limitations for simulation include the generalization of a population of interest, cases where analytical solutions are possible (i.e., DES compares alternatives, but provides no optimal solutions), and difficulty with interpretation. Banks and Gibson (1997) list ten situations where simulations are not appropriate and Banks et al. (2005) state that simulation models will rarely be the same even when they are constructed by skilled experts.

4 Systematic literature review

Thirty-two selected research papers were classified to determine the extent to which DES was applied to transport in the wood supply chain, the majority (27) of which were published in the last ten years (Table 4). Unimodal transport (21) is the predominant transport mode and different biomass assortments (24), the greatest transported good. Fig. 2 shows a rising interest in the analyzed research topic in the last years, indicated by an increasing publication level and a spreading to more countries. The majority of the analyzed papers were published by Finnish (10), Canadian (6), and Swedish (4) research groups and the most popular software used were Witness (7), ExtendSim (6) and AnyLogic (5). All Thirty-two papers were already published in one of 16 different journals, with most publications in the Scandinavian Journal of Forest Research (5), Applied Energy (5), International Journal of Forest Engineering (4) and Silva Fennica (3). Case studies (27) and risk considerations (22) were included in many papers and simulation periods used were one year (10), longer than a year (5), weeks to months (5) and days (4) with minutes (11) as most common resolution time (Table 2, Table 3). Multimodal DES models are summarized in Table 2, illustrating the different research approaches. Table 3 summarizes unimodal DES models by comparing the different research approaches.

In Table 4 and Fig. 3, the analyzed research papers are classified based on abstraction level and planning horizon. The planning horizon rates the duration of the planning period. Strategical planning horizons are long-term decisions (e.g., location decision), while tactical planning horizons are medium-term decisions (e.g., resource allocation, production, inventory policies), and operational planning horizons are short-term decision (e.g., loading/unloading, scheduling). Due to sparse descriptions and absent clarifications in some papers, Fig. 3 provides a basic assessment for further investigations. DES is mainly used for tactical (14) and operational (13) planning horizons, evenly distributed over all levels of abstraction.

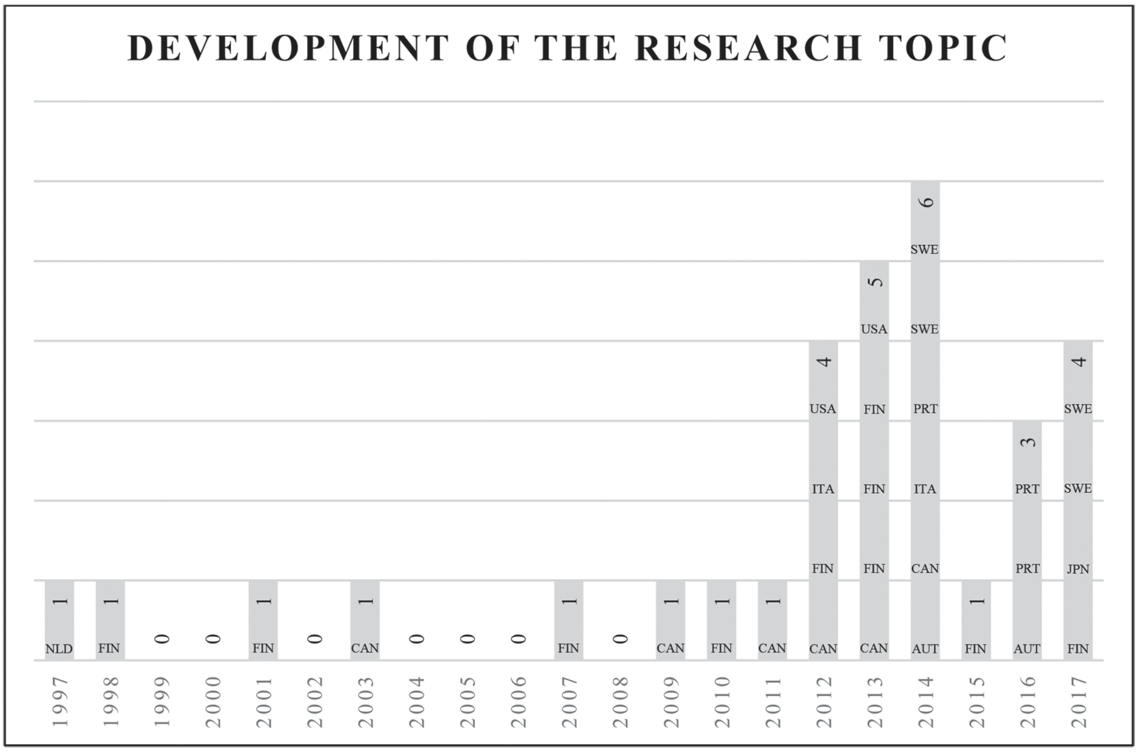


Fig. 2. Amount of analyzed papers per year and country.

Table 2. Multimodal DES models.

Reference (year)	RC	CS	Simulation period (resolution time)	Supply network	Objective
De Mol et al. (1997)		(X)	1 year	source, collection, pre-treatment, transhipment, energy plant	gain insight into the costs and energy consumption of logistics
Asikainen (2001)		X	1 month	harvesting, forwarding, 15 vessel terminals, powered barge / push barge, mill	cost comparison of push barge systems to a powered barge system for waterway transport
Saranen and Hilmola (2007)		X	2 weeks	28 rail terminals, railway network, 2 mills	evaluate the competitiveness of a unit train concept by cost considerations
Karttunen et al. (2012)	X	X	9 months	3 fuel terminals at harbors, waterway network, 3 bio-power plants	determine the efficiency of waterway transport and compare the costs to truck transport of forest chips for Lake Saimaa
Karttunen et al. (2013)		X	1 year	roadside storage, chipping, container truck transport, terminal, railway transportation, combined heat and power plant	compare the cost-efficiency of a multimodal supply chain with an intermodal container supply chain for long-distance transportation of wood chips by road and rail with a combined simulation and GIS model
Mobini et al. (2013)	X	X	1 year	5 suppliers, transportation (10 trucks, railcar, ocean vessel), raw material handling and storage, 1 pellet mill (drying, size reduction, pelletization, cooling, storage, packing, distribution), end customer	estimate delivery cost to customer and CO_2 emissions along the wood pellet supply system in scenarios with different fuel types and different raw material mixtures for pellets
Etlinger et al. (2014)	X	X	1 year (minutes)	forest and prehaulage, 4 rail terminals, railway network, 2 saw mills, 2 paper mills	improve efficiency of supply chain and determine transhipment time / cycle time, stock levels at terminals over time, utilization of terminal infrastructure, network capacity and terminal size
Mobini et al. (2014)	X	X	1 year	5 suppliers, truck transport, export port for incoming rail and outgoing vessels, raw material handling and storage, 1 pellet mill (drying, torrefaction, pelletization, cooling, storage, packing, distribution), end customer in north western Europe, Japan, Korea or China	extend a wood pellets simulation model by developing a torrefaction process module to compare the delivered cost to markets, distribution costs, energy consumption and carbon dioxide emission with those of regular pellets
Wolfsmayr et al. (2016)		X	1 year (minutes)	3 rail terminals	investigate potentials of existing transhipment infrastructure (rail sidings, storage areas, access roads) for biomass
Gronalt and Rauch (2018)	X	X	1 year (minutes)	forest and prehaulage, 4 rail terminals, railway network, 2 saw mills, 2 paper mills	compare scenarios for different railway operation schedules (shuttle train vs. single wagon traffic)

RC = Risk Considered, CS = Case Study include

In only one paper dealing with multimodal transport (Saranen and Hilmola 2007) and six papers handling unimodal transport (Myers and Richards 2003; Beaudoin et al. 2012; Cavalli et al. 2012; Zamora-Cristales et al. 2013; Eriksson et al. 2014b; Eliasson et al. 2017) the validation method is presented as a separate section. In one other multimodal paper (Mobini et al. 2013) and five unimodal papers (Asikainen 1998; Windisch et al. 2013a; Windisch et al. 2013b; Eriksson et al. 2014a; Windisch 2015), validation methods were at least mentioned.

Table 3. Unimodal DES models.

Reference (year)	RC	CS	Simulation period (resolution time)	Supply network	Objective
Asikainen (1998)	X		(minutes)	residue storage, terminal, truck with draw bar trailer/semitrailer/ interchangeable container, crusher, tub grinder, wheel loader, power plant	compare chipping into truck, chipping onto ground and loading using a wheeled loader, long-distance transport by truck with draw-bar trailer, by truck with a semitrailer and by a truck with interchangeable platforms to quantify the impact of machine interactions in monetary terms
Myers and Richards (2003)		X	5 years (weeks)	standing inventory, ground-based harvesting, cable based harvesting, transportation, mill yard operations, mill operations	evaluate central tire inflation and cable-based harvesting systems to reduce inventory, handling and holding costs of a mill
Mahmoudi et al. (2009)	X	X	1 year	forest, felling, skidding, processing, moving, chipping, extracting, power plant gate	develop a simulation model for forest biomass logistics and apply it to the case study of supplying a potential power plant with roadside residues from a mountain pine beetle-infested forest
Asikainen (2010)	X		1 week (minutes)	50 stump storages, crusher, 1–4 semi-trailer trucks, heat plant	find the optimal number of trucks for different road transport distances of at the landing crushed wood chips and compare the findings of static as well as dynamic simulation approaches
Mobini et al. (2011)	X	X	20 years	forest, felling, skidding, loading, transportation, delimbing, processing, moving, chipping, extracting, gate of the power plant	use full tree chipping, conventional harvesting and satellite harvesting to simulate forest biomass logistics over the service life of a power plant to measure delivery cost, carbon emissions and moisture content
Beaudoin et al. (2012)		X	1 day (minutes)	loaded trucks with different trailers, 3 mobile loader, stockyard, slasher, wave, scale, stocks	reduce average truck cycle times and loaders driving distances by advantageous loader to truck allocation strategies
Cavalli et al. (2012)	X	X	(minutes)	stump extraction: tractor with forest winch, landing and cross cut operation: tractor with loader, offroad transport: tractor with trailer, on-road transport: truck and trailer, terminal	compare in different scenarios the productivity of a firewood supply chain to evaluate the influence of a forest road network extension, supported by a GIS network analyses of the transportation network
Zhang et al. (2012)		X	20 years (days)	harvest/process, forward to landing, load at landing, transport, unload and store at biorefinery	evaluate a biofuel supply chain by delivered feedstock cost, GHG emissions and energy consumption for different locations and plant size under consideration of low value pulpwood and spring break up in a GIS network
Windisch et al. (2013a)	X	X	not mentioned	finding stands, stand evaluation, negotiation and completion of contract, logging, measurements, chipping, accounting, payment	provide a method for structural analysis of forest fuel supply chains including the measurement of processes and work time expenditure in different operational environments
Windisch et al. (2013b)	X	X	not mentioned	finding stands, stand evaluation, negotiation and completion of contract, logging, measurements, chipping, accounting, payment	improve logistics of an integrated round wood and energy wood supply chain by business process reengineering and calculate cost saving potential of new business processes
Zamora et al. (2013)	X	X	(minutes)	chipper, truck with single or double trailer, chipping, dumping, transporting, loading/unloading, drop/hook trailers, chipping site, bioenergy facility	minimize mobile chipping processing and transportation costs under uncertainty to improve the efficiency of the forest biomass supply chain in steep slope terrain

Table 3 continued.

Reference (year)	RC	CS	Simulation period (resolution time)	Supply network	Objective
Eriksson et al. (2014a)	X		not mentioned	10 harvesting areas, harvesting, forwarding, storage, transport and comminution, fuel delivery, excavator with stump lifter, mobile truck or trailer-mounted grinder, self-loading chip truck with crane and bucket, loose residue stump truck, stationary crusher	evaluate the impact of site characteristics, fuel quality, biomass losses, machine performance on fuel costs to deliver stump fuel at a competitive price
Eriksson et al. (2014b)	X		not mentioned	20 landings, mobile crusher, 1–3 self-loading chip truck/hook-lift trucks/chip trucks, loose-stump truck, large scale crusher, end user (terminal or heating plant)	model systems for stump comminution and transport from landing to the end user to enhance resource efficiency by quantifying and reducing process costs
Marques et al. (2014)	X	X	1 day (minutes)	stockyard, trucks, trailers, arrival, queuing, unloading	compute performance metrics, provide visualization and identify bottlenecks in deterministic harvesting and transportation plans generated by optimization techniques, when stochastic events occur
Spinelli et al. (2014)	X	X	not mentioned	chipper on the trailer of a farm tractor, farm tractors with trailer bins, loader, forwarder, buffer pile, heavy road trucks	examine the interaction delays between individual units along the logging resides supply chain and criteria for the right chipping location
Windisch et al. (2015)	X	X	1 year	328 storages, truck-mounted mobile chipper, two truck trailer combinations, CHP plant	compare productivity, transportation distance, moisture content and storage volume of a current supply chain and an information based approach for a forest biomass supply chain
Pinho et al. (2016a)	X	(X)	1 day	depot, 4 wood piles, 2 chippers, 4 trucks, 4 power plants	measure the impact of deterministic behavior, machine delay and stochastic behavior in a daily working plan of a biomass supply chain
Pinho et al. (2016b)	X	(X)	1 day	depot, 4 wood piles, 2 chippers, 4 trucks, 6 power plants	estimate dynamic system behavior of a biomass supply chain to predict deadlocks and impact of disturbances on scheduling
Eliasson et al. (2017)			1 week (minutes)	logging residues, chipper, landing, 3/6 buffer containers, forwarder, 2/3/4 trucks for three containers, heating plant	reduce supply costs for forest chips and increase chipper efficiency, forwarder and container trucks interaction by taking into account the effect of shunting distance, buffer size, truck scheduling and number of trucks available
Eriksson et al. (2017)	X	(X)	5 years (minutes)	harvest, store in heaps, forwarding, store at road site, transport and comminute, store at CHP plant, 4 forwarders, 6 chipper trucks	assess delivery strategies due to storage time, fuel quality, transport distance, machine utilization and delivery quality to create benefits for supply company and end user
Kishita et al. (2017)	(X)	X	20 years	import, collecting, chipping, land transportation, timber production, landfill, pelletizing, selling	compare scenarios to examine conditions for a sustainable forest biomass energy life cycle based on CO_2 emissions and economic profit
Väätäinen et al. (2017)		X	1 year (minutes)	roadside storages of forest biomass, four forest chip suppliers operating with one truck-mounted chipper and two chip trucks, terminal, wheeled loader, shuttle truck with higher capacity truck and trailer unit, combined heat and power plant	examine the impact of terminal location and investment costs, truck utilization and quality changes in stored forest chips for cost comparisons of direct forest chip supply to the integration of feed-in terminals

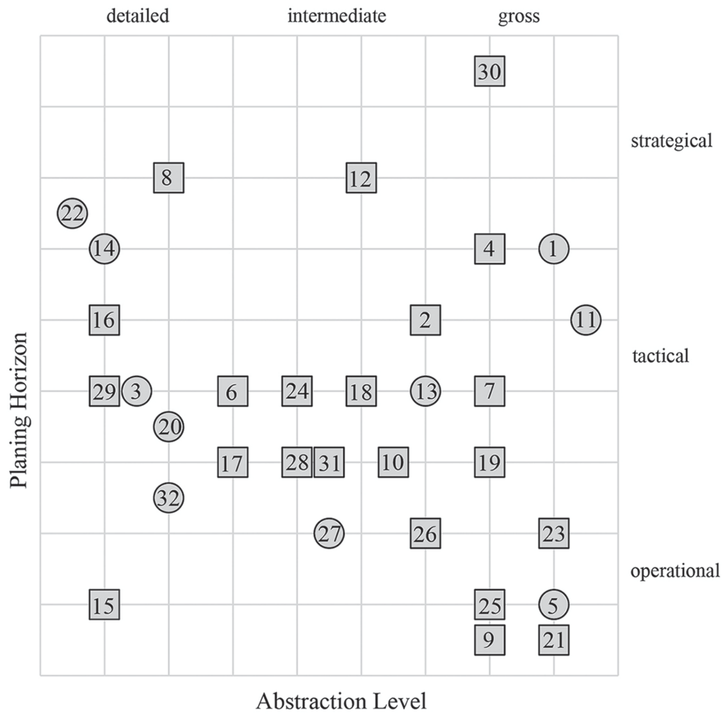
RC = Risk Considered, CS = Case Study included

Table 4. Classification of the research articles.

Reference (year)	Region	Journal	Abstraction level	Planning horizon	Assortment	Transport mode	Software
De Mol et al. (1997)	NLD	Netherlands Journal of Agricultural Science	abstract	tactical	forest biomass	multimodal	ProSim
Asikainen (1998)	FIN	Scandinavian Journal of Forest Research	intermediate	tactical	forest chips	unimodal	Witness
Asikainen (2001)	FIN	International Journal of Forest Engineering	detailed	tactical	timber	multimodal (vessel)	Witness
Myers and Richards (2003)	CAN	Information Systems and Operational Research	abstract	tactical	timber	unimodal	AWESIM
Saranen and Hilmola (2007)	FIN	World Review of Inter-modal Transportation Research	abstract	operational	timber	multimodal (train)	Quest
Mahmoudi et al. (2009)	CAN	Scandinavian Journal of Forest Research	detailed	tactical	forest biomass	unimodal	EXTEND
Asikainen (2010)	FIN	Scandinavian Journal of Forest Research	abstract	tactical	forest chips	unimodal	Witness
Mobini et al. (2011)	CAN	Applied Energy	detailed	strategical	forest biomass	unimodal	ExtendSim
Beaudoin et al. (2012)	CAN	Information Systems and Operational Research	abstract	operational	timber	unimodal	AnyLogic
Cavalli et al. (2012)	ITA	Journal of Agricultural Engineering	intermediate	operational	firewood	unimodal	Witness
Karttunen et al. (2012)	FIN	Silva Fennica	abstract	tactical	forest chips	multimodal (vessel)	Witness
Zhang et al. (2012)	USA	Renewable Energy	intermediate	strategical	forest biomass	unimodal	Arena
Karttunen et al. (2013)	FIN	Silva Fennica	intermediate	tactical	forest chips	multimodal (train)	AnyLogic
Mobini et al. (2013)	CAN	Applied Energy	detailed	strategical	forest pel-lets	multimodal (train, ocean vessels)	ExtendSim
Windisch et al. (2013a)	FIN	Biomass and Bio-energy	detailed	operational	forest biomass	unimodal	SigmaFlow
Windisch et al. (2013b)	FIN	International Journal of Forest Engineering	detailed	tactical	forest biomass	unimodal	SigmaFlow
Zamora et al. (2013)	USA	Silva Fennica	detailed	operational	forest chips	unimodal	Arena
Eriksson et al. (2014a)	SWE	International Journal of Forestry Research	intermediate	tactical	forest chips	unimodal	ExtendSim
Eriksson et al. (2014b)	SWE	International Journal of Forest Engineering	abstract	tactical	forest chips	unimodal	ExtendSim
Etlinger et al. (2014)	AUT	HMS Conference Paper	detailed	tactical	saw logs, pulp wood	multimodal (train)	AnyLogic
Marques et al. (2014)	PRT	Scandinavian Journal of Forest Research	abstract	operational	timber	unimodal	Simio
Mobini et al. (2014)	CAN	Journal of Cleaner Production	detailed	strategical	forest pel-lets	multimodal (train, ocean vessels)	ExtendSim
Spinelli et al. (2014)	ITA	Scandinavian Journal of Forest Research	abstract	operational	forest chips	unimodal	Arena
Windisch et al. (2015)	FIN	Applied Energy	intermediate	tactical	forest biomass	not men-tioned	Witness
Pinho et al. (2016a)	PRT	International Fed-eration of Automatic Control Conference Paper online	abstract	operational	forest biomass	unimodal	SimPy

Table 4 continued.

Reference (year)	Region	Journal	Abstraction level	Planning horizon	Assortment	Transport mode	Software
Pinho et al. (2016b)	PRT	International Federation of Automatic Control Conference Paper online	intermediate	operational	forest biomass	unimodal	SimEvents
Wolfsmayr et al. (2016)	AUT	Annals of Forest Research	intermediate	operational	timber, forest chips	multimodal (train)	AnyLogic
Eliasson et al. (2017)	SWE	Applied Energy	intermediate	operational	forest chips	unimodal	not mentioned
Eriksson et al. (2017)	SWE	Applied Energy	detailed	tactical	forest chips	unimodal	ExtendSim
Kishita et al. (2017)	JPN	Journal of Cleaner Production	abstract	strategical	forest biomass	unimodal	not mentioned
Väätäinen et al. (2017)	FIN	Global Change Biology Bioenergy	intermediate	operational	forest chips	unimodal	Witness
Gronalt and Rauch (2018)	AUT	International Journal of Forest Engineering	detailed	operational	timber, forest biomass	multimodal (train)	AnyLogic



Multimodal (circle)

1 De Mol et al. (1997)
3 Asikainen (2001)
5 Saranen and Hilmola (2007)
11 Karttunen et al. (2012)
13 Karttunen et al. (2013)
14 Mobini et al. (2013)
20 Etlinger et al. (2014)
22 Mobini et al. (2014)
27 Wolfsmayr et al. (2016)
32 Gronalt and Rauch (2018)

Unimodal (square)

2 Asikainen (1998)
4 Myers and Richards (2003)
6 Mahmoudi et al. (2009)
7 Asikainen (2010)
8 Mobini et al. (2011)
9 Beaudoin et al. (2012)
10 Cavalli et al. (2012)
12 Zhang et al. (2012)
15 Windisch et al. (2013a)
16 Windisch et al. (2013b)
17 Zamora et al. (2013)
18 Eriksson et al. (2014a)
19 Eriksson et al. (2014b)
21 Marques et al. (2014)
23 Spinelli et al. (2014)
24 Windisch et al. (2015)
25 Pinho et al. (2016a)
26 Pinho et al. (2016b)
28 Eliasson et al. (2017)
29 Eriksson et al. (2017)
30 Kishita et al. (2017)
31 Väätäinen et al (2017)

Fig. 3. Categorization according to abstraction level and planning horizon.

All other papers did not report on validation, therefore estimations based on method descriptions were used to classify them in Table 5. In De Mol et al. (1997), the model description is very rough and provides no method descriptions. Business process diagrams are an appropriate way to describe a complex model logic, as in Wolfsmayr et al. (2016). Mobini et al. (2013) and (2014) provide clarity and detail in their model descriptions, however, additional information about the verification, validation and establishing credibility process describing the process and outcomes would also enhance these works. Eriksson et al. (2017) and Beaudoin et al. (2012) are good examples of study design, but even here the model documentation could be enhanced by visualizations (i.g., business process diagrams, screenshots, histograms for distribution fitting). Good examples of business process diagrams describing model logic can be found in the works of Windisch et al. (2013a; 2013b; 2015). Zhang (2012) provides good activity and model flow charts and is the only paper where the model is available to the general public online. The only papers in which the applied distribution fitting and testing methods were extensively described were Cavalli et al. (2012), Spinelli et al. (2014) (both used Kolmogorov-Smirnov tests) and Myers and Richards (2003), Zamora-Cristales et al. (2013) and Beaudoin et al. (2012) (all used chi squared goodness of fit tests).

5 Narrative literature review

In wood supply chain research, the attention is shifting from optimization models focusing on one single or few processes to modelling the entire supply chain. Little research exists on wood supply chains topics before the 1990s, but, driven by technological and commercial changes (Larsson et al. 2016), a considerable increase is observed for other industries and supply chains such as agriculture (Manuj et al. 2009; Tako and Robinson 2012; Borodin et al. 2016; Oliveira et al. 2016). For forest-based industries, DES models were predominantly developed for wood supply chains with multimodal transport (Table 2) or unimodal transport (Table 3).

The following narrative reflections in this section are supplemented by structural comparisons (Table 4) showing that for example the predominant abstraction level/planning horizon combination are abstract/tactical (5), detailed/tactical (5), abstract/operational (5) and intermediate/operational (5) whereas abstract/strategical (1) and interim/strategical (1) rarely arise. Moreover, within an abstraction level/planning horizon combination similarities and differences can be observed. For example, in the abstract/tactical combination, there are two multimodal transport modes, of which one focuses on vessels as well as forest chips and was developed in Witness (Karttunen et al. 2012). The other has a general focus and was developed with ProSim (De Mol et al. 1997).

5.1 Multimodal transportation

The transport mode of wood can either change (i.e., multimodal transport) through transhipments at a terminal or stay the same (i.e., unimodal transport), mainly in the form of trucks (Wolfsmayr and Rauch 2014). Multimodal transport is beneficial for long distance or high volume transports (Etlinger et al. 2014) and increases the supply security against supply risks as well as contributes to green logistics by increasing rail transport share. In case of wood supply chain disturbances (e.g., due to more frequently occurring natural disasters), robustness of the wood supply chain is of high importance. Robustness (or resilience) is defined as resistant against changes or to have the ability to return quickly to a previously good condition or state after disturbances. This can be achieved by supply chain management including contingency planning and the use of multimodal terminals to provide buffer storage.

Table 5. Reported model descriptions in the papers.

	Data collection					Structure						Input parameter				Statistical analyses				Validation					Documentation						
Reference (year)	Case study	Literature	Interview	Time study	Official statistics	Modular design	Assumptions	Scenario analysis	Limitations	Repeated simulation runs	Warm-up period	Distribution fitting	Random number generation	Parameter description	Diagrams and Tables	Sensitivity analyses	Confidence intervals	Regressions	Statistical tests	Structured walk through	Comparing case study[1]	Comparing literature[2]	Animation and visualization	Expert/Manager involvement	Verbal	Flow diagram	Decision tree	Business process diagrams	Equations	Distribution descriptions	Screen shots
De Mol et al. (1997)	X							X															X		X	X					
Asikainen (1998)		X					X			X	X	X	X							X			X		X	X					
Asikainen (2001)	X									X		X	X	X											X				X	X	
Myers and Richards (2003)	X	X					X	X	X	X	X	X		X	X		X		X		X				X	X	X			X	
Saranen and Hilmola (2007)							X	X						X						X			X	X	X	X					
Mahmoudi et al. (2009)	X	X			X	X		X		X				X								X			X	X			X		
Asikainen (2010)		X					X	X		X		X	X	X											X						
Mobini et al. (2011)	X	X			X		X			X		X	X	X											X	X			X		
Beaudoin et al. (2012)	X		X	X			X	X		X		X	X	X	X	X	X		X		X		X	X	X	X	X			X	
Cavalli et al. (2012)				X						X	X	X	X	X			X	X	X	X			X		X			X		X	
Karttunen et al. (2012)	X	X	X							X		X	X	X			X					X	X		X				X	X	X
Zhang et al. (2012)	X				X	X	X		X					X									X		X	X		X	X		X
Karttunen et al. (2013)	X	X			X		X	X	X			X		X	X	X					X		X	X	X	X				X	X
Mobini et al. (2013)	X	X				X		X		X		X		X	X		X			X	X				X	X		X	X		
Windisch et al. (2013a)	X	X	X							X		X	X								X	X		X	X	X		X			
Windisch et al. (2013b)		X	X							X		X	X	X								X		X	X	X		X	X	X	
Zamora et al. (2013)				X				X				X		X	X				X						X	X		X	X	X	
Eriksson et al. (2014a)		X				X	X	X					X	X		X				X		X	X		X	X			X		
Eriksson et al. (2014b)		X	X	X		X	X	X		X		X	X	X		X				X		X	X	X	X	X		X	X	X	
Etlinger et al. (2014)	X					X	X	X				X											X		X	X					X
Marques et al. (2014)	X		X				X	X					X	X									X	X	X	X					X
Mobini et al. (2014)	X	X				X		X		X		X		X	X	X	X					X			X	X			X		
Spinelli et al. (2014)		X		X			X			X		X	X	X	X	X			X		X	X			X					X	
Windisch et al. (2015)	X	X	X		X			X		X		X	X	X							X	X		X	X			X	X		
Pinho et al. (2016a)	X							X				X													X	X					
Pinho et al. (2016b)	X					X	X	X		X		X													X	X					
Wolfsmayr et al. (2016)	X						X	X		X		X		X		X					X				X			X			
Eliasson et al. (2017)		X					X	X		X				X			X								X	X	X				
Eriksson et al. (2017)	X	X			X	X	X	X		X		X	X	X						X	X		X		X	X			X		
Kishita et al. (2017)	X	X	X				X	X	X					X		X									X	X			X		
Väätäinen et al. (2017)	X	X					X	X	X	X		X	X	X	X	X	X				X	X			X	X				X	
Gronalt and Rauch (2018)	X					X	X	X				X		X									X		X	X					X

[1] Comparing simulation model results with real world case study data, [2] Comparing simulation model results with literature data

Table 2 allows structural analyses of multimodal papers and shows that most multimodal research papers provide information about their case studies, except a few concerns about De Mol et al. (1997), and their simulation period, however, only half of them consider risks. Furthermore, the objectives and supply networks can be compared and provide an overview (e.g., how Mobini et al. developed their model from 2013 to 2014) or reflect the numbers of included rail terminals (e.g., 28 (Saranen and Hilmola 2007), 4 (Etlinger et al. 2014; Gronalt and Rauch 2018), 3 (Wolfsmayr et al. 2016)). The multimodal transportation papers are further categorized by transport mode and follow the structure (1) train, (2) vessel, (3) train and vessel and (4) general.

Firstly, Saranen and Hilmola (2007), Karttunen et al. (2013), Etlinger et al. (2014), Wolfsmayr et al. (2016) and Gronalt and Rauch (2018) solely focus on train transport. Saranen and Hilmola (2007) show the competitiveness of a unit train railway transportation concept (i.e., permanent locomotive equipped with a timber loader) for long distance with competitive prospect even for short distances. Additionally, they defer considerations of risk factors such as disturbances, breakdowns and fluctuations in demand to future studies, similar to Wolfsmayr et al. (2016). Karttunen et al. (2013) combine a GIS with a simulation model to find cost-efficient alternatives for long-distance transportation of forest chips. Therefore, they link multimodal truck and railway transportation and show that total costs of traditional supply chains are 5–19% higher than the corresponding container supply chain. Due to increased maximum road transport limits in Finland, analyses of 9-axle trucks with up to 76 tons would give further insights compared to the used 7-axle trucks with 64 tons in this study. Nonetheless they indicate the advantageousness of intermodal container logistics and train transport to traditional solid-frame transportation for long distances. Etlinger et al. (2014) show in their DES model for multimodal truck-train transport a way to nearly double the amount of round wood transport. Essentially, the numerical experiments with various scenarios result in the recommendation to change the railway operation system from a single wagonload to a shuttle system. Stochastic effects are implemented in the forest and precarriage module to take into account operating conditions (e.g., seasonality, weather conditions). Gronalt and Rauch (2018) analyze and add to the work of Etlinger et al. (2014) through complementary simulation experiments including bottleneck analysis and scenarios for appropriate train schedules. The importance of capacity matches between railway tracks and storage is indicated as well as the fact that throughput of terminals with high utilization can be increased by redesign, ensuring that trucks can be unloaded without hindrances. Similar to Saranen and Hilmola (2007), Gronalt and Rauch (2018) focus on a railway transportation concept, but with a higher level of abstraction regarding supply stations and mills, and a deeper focus on train scheduling. In contrast, Wolfsmayr et al. (2016) only focus on one module for terminal operations and aggregate the upstream and downstream components of the supply chain by in- and outgoing flows. The authors investigate multimodal biomass transport utilizing the same simulation software (i.e., AnyLogic) and case study area (i.e., Austria). Based on two scenarios, where the regular scenario covers a normal supply and the disturbance scenario an oversupply resulting from a storm or bark beetle infestation, daily and yearly transhipment capacities are simulated considering terminal layout bottlenecks and are statistically analyzed with ANOVA. The importance of risk consideration (i.e., stochastic events) along the wood supply in future research is highlighted.

Secondly, Asikainen (2001) and Kattunen et al. (2012) solely concentrate on vessel transport. Asikainen (2001) investigates waterway transport with barge systems from islands to a mill, including logging, loading and unloading modules. The model simulates the supply chain from forest stands to the unloading of the vessels at the mill. For the case study region, a push boat and three barges are more competitive than the powered barge system currently in use. Further improvements can be achieved by loading directly onto the barge by a forwarder over a suitable ramp. In contrast to the multimodal railway transport models, Asikainen (2001) provides insights into logging operations through productivity functions and highlights the benefit of simulation considering machine interactions (e.g., queuing and waiting) for a multimodal waterway supply chain. Kattunen et al. (2012) compare waterway transport of forest chips with truck transport and find benefits in case of loading capacity and bulk density, resulting in a cost advantage of waterway transport to road transport if transportation distance is more than 100 to 150 km. Stochastic effects of speed correction of the vessel-barge combination, loading/unloading events and loading size were handled by random occurring events, where every experiment was repeated five times. Waterway transport can only be cost competitive to supply the south of Finland if harbour and barge logistics are managed efficiently due to high competition in truck transport compared to tugboats and barges given the limited fleet size. The authors aggregate upstream and downstream logistics and interactions before and after terminal operations, as also seen in Saranen and Hilmola (2007). In addition, Kattunen et al. (2012) exclude queuing time and consider only one-way transport, which can be reasonable for truck transport, but not for barge transport systems. Winter months are excluded as waterways are closed due to ice cover in the Lake Saimaa region.

Thirdly, Mobini et al. (2013) and Mobini et al. (2014) cover both train and vessel transport. The entire wood pellets supply chain starting at the source over procurement, truck transportation, storage, pellet production and distribution to customer by truck or for export by train and vessel is modelled by Mobini et al. (2013). The model includes modules for transportation, supplier, pellet mill and customer, while incorporating uncertainties and measuring time, cost and emission. For the included case study, average costs of delivered pellets are shown, which consist of 29% raw material transportation costs and of 30% distribution costs, where a cost reduction potential of about 5% was reported. In a subsequent work, Mobini et al. (2014) indicate with an extended simulation model that torrefaction of biomass prior to densification leads to 9% cheaper pellets, 3% lower energy consumption and 3 kg less carbon dioxide emission per GJ of delivered energy content when transported to Europe. Including a torrefaction process, this pellets supply chain demonstrates the trade-offs between reduced transport costs, higher capital and operating cost and is, therefore, particularly attractive for long transportation distances with ocean vessels.

Lastly, De Mol et al. (1997) do not further declare the observed multimodal transport mode. They design an early simulation model for biomass and respond to network structure and biomass mixture decisions with a mixed-integer linear programming model. Results show higher costs for pre-treatments, multimodal transport and recommend chipping at the energy plant. The authors link strategic and tactical optimization models, but information regarding the simulation model and case study is not provided.

5.2 Unimodal transportation

Unimodal truck transport is advantageous for short transportation distances because no additional transhipment costs and time durations occur, resulting in lower administrative effort compared to multimodal transport. Scientific literature focuses on unimodal transportation with an increase on biomass assortments and, to some extent, firewood and wood pellets over the last years. Another important issue in unimodal transportation is chipping or bundling that increase the energy density of the material. Finally, logistics at wood yards of saw and pulp mills (e.g., truck queuing) define the last analyzed research focus since DES is rarely used to simulate transportation in other supply chain areas (e.g., harvesting or furniture manufacturing).

Structural comparisons of unimodal papers (Table 3) supplement the following narrative analyses and indicate a high number of papers considering risks (17) and including information about case studies (17). Simulation periods of unimodal papers are more heterogeneous than multimodal ones and many (7) authors do not report the simulation period at all. The objective column provides a starting point for further comparisons according to the focal point of the studies (e.g., which papers focus mainly on costs or include a GIS network or emission analyses). The unimodal transportation papers are further categorized by assortment following the structure (1) forest chips, (2) forest biomass, (3) timber and (4) firewood.

Firstly Asikainen (1998), Asikainen (2010), Eriksson et al. (2014b), Eriksson et al. (2014a), Eliasson et al. (2017), Eriksson et al. (2017), Väätäinen et al. (2017), Spinelli et al. (2014) and Zamora et al. (2013) focus on forest chips. Asikainen (1998) indicates the importance of interaction between chipping and transportation of chips for supply systems with direct chipping onto trucks (i.e., hot system) by quantifying their costs. A step-by-step run of a model and observation of graphic animation as verification methods is mentioned, as also seen in Cavalli et al. (2012). Asikainen (1998) compares the outcomes to the results of related studies for validation, but does not include information about a related case study. In a later work, Asikainen (2010) focuses particularly on crushing of stumps and a suitable number of trucks for different road transport distances. It is one of the few studies where static spreadsheet modelling is directly compared to a dynamic DES model and the impact of interactions and random elements are shown. The static model underestimates interaction impacts and provides more optimistic results because random impacts are not considered. Eriksson et al. (2014b) also investigate stump fuel supply chains, but focus more on different comminution techniques and transport distances of one to three trucks. The authors indicate that using a self-loading truck for crushed stumps on the ground is most cost-effective, irrespective of transport distance. Moreover, the balance between the number of trucks, transport distance and the productivity of the crusher is highlighted. The range of the total costs for chip trucks reported by Eriksson et al. (2014b) are comparable to that of Asikainen (2010) and can be used in specific conditions to avoid unfavorable systems. Eriksson et al. (2014a) further improve this ExtendSim-based simulation model by implementing site generation, fuel delivery, harvesting, forwarding and storage modules. The authors highlight the high costs of material losses in later stages compared to earlier ones, resulting in higher handling investments in the material over time. Eriksson and Eliasson (2015) indicate that transporting bulky, uncomminuted stumps, especially for more than 50 km, should be avoided. In addition, direct loading of trucks by crushers reduces machine utilization, which significantly raises supply costs due to the high cost of crushing. In contrast to the common practice of optimizing chipping and transport separately, Eliasson et al. (2017) promote optimization of the entire supply system. By evaluating the main influencing parameters (i.e. transport distance, number of trucks, shift form and chip buffers), the authors favor a system configuration with a buffer of six containers and staggered shifts as well as four trucks for longer (i.e., greater than 50 km) and three trucks for shorter (i.e., 30–50 km) transport distances. Great insight into the behavior of high-performance chip supply systems is provided and shift scheduling was indicated as a main cause of queuing time. The authors suggest that this can be avoided by staggered instead of simultaneous working shift start times of truck drivers. Eriksson et al. (2017) also build on former studies and weather-driven analysis is the center of their work. The authors put great effort on building a comprehensive model explanation including notes on verification and validation, which is rarely found in other simulation studies. The model enables weather driven analyses and results indicate a favorable strategy of supplying dry material during winter and moister biomass during summer. The findings of Väätäinen et al. (2017) show similarities to Windisch et al. (2015) by considering detailed time spans of daily operations in the simulations, but differ in the integration of a terminal system. The terminal system in Väätäinen et al. (2017) indicates the potential of terminals as balancing elements. Low additional costs of 1.4% arise compared to direct supply, even though capacity utilization for mobile chippers in this study is low. In Spinelli et al. (2014), supply costs are shown as a function of extraction distance, operation type and number of chip shuttles. Therefore, chipping at the landing with a chipper and with two shuttles is recommended as an appropriate system configuration, resulting in both low supply costs and low fuel consumption. The authors add a detailed case study of a small scale chip supply chain, which emphasizes, as does Cavalli et al. (2012), the special characteristics of the chipping supply chain in the Italian mountains, where farm tractors and cable cars are used due to steep terrain. The case study of Spinelli et al. (2014) allows the authors to validate their simulation findings with collected real data. It shows a difference of less than 2% and enables the generation of functions by distribution fitting and statistical test, where, in contrast to other studies, normal distribution was avoided due to potentially negative values during simulation runs. Likewise, Zamora et al. (2013) concentrate on steep terrain conditions with limited available space for adding buffer containers or single passage roads. The authors put even more emphasis on detailed data collection applying tracking analysis by manually timing, video recording and spatial-temporal tracking analysis of machine and truck movements, distribution fitting and parameter estimation. This is the only paper that combines optimization, discrete event simulation and GIS methods and explicitly mentions abstraction level. Furthermore, the authors include a comprehensive validation process and statistical analyses to declare the robustness of the model.

Secondly Mahmoudi et al. (2009), Mobini et al. (2011), Zhang et al. (2012), Windisch et al. (2013a), Windisch et al. (2013b), Windisch et al. (2015), Pinho et al. (2016a), Pinho et al. (2016b) and Kishita et al. (2017) cover forest biomass. Mahmoudi et al. (2009) simulate the wood supply chain from a mountain pine beetle-infested forest to a potential power plant, including seasonal fluctuations due to weather conditions. Twenty simulation runs of a one-year period each run are performed. The authors conclude that only about 30% of the annual feedstock demand can be fulfilled unless other harvesting systems and/or feedstock sources are used or a smaller power plant is considered. Sensitivity analyses show that increasing the number of rainy days will increase the average cost of biomass, where forwarding (4%), chipping (40%) and transportation (56%) contribute to the supply cost and transport is accountable to over 60% of the carbon emissions. Moreover, the authors include risk considerations with weather delays, describe the applied method in detail and illustrate the physical flow via flowcharts. They encourage readers to reapply their model to other case studies and provide accurate estimations of relevant variables like the size of power plants, including longer runtimes to simulate the operating life of the power plant. Some of the suggested extensions are later implemented Mobini et al. (2011), who demonstrate the valuable process of further development of existing models based on detailed descriptions. Based on the investigation, the authors enhance the simulation model by adding full-tree chipping for stands with more than 95% fuel wood and a satellite harvesting method for stands between 50% and 95%, while the remaining part is harvested conventionally. Moreover, the simulation runtime is expanded to a 20 year-long service life of a potential power plant by integrating an external shelf-life model. The results of 10 iteration runs show that even though supply has been considerably increased, demand of the power plant still cannot be met during the years 1–3 and 6–9, which require either timber supply from other areas, the use of stored timber from periods of overproduction, incorporating other agricultural biomass or a reduction of the power plant size. The simulation model of Zhang et al. (2012) shows similarities to De Mol et al. (1997) as it also is based on a pull supply chain system, neglects backhaul and risk considerations, and provides decision support for facility location and chipping at the facility. Three submodels cover reading model inputs, supply activities and daily biomass processing, and evaluate greenhouse gas (GHG) emissions, energy use and delivery cost in order to find the best facility location. The study provides detailed descriptions of numerous assumptions and extra effort is made to describe the model functionality supported by maps, diagrams, screenshots, tables and charts. Windisch et al. (2013a) analyze and compare forest biomass supply chains in Germany and Finland by business process mapping with data from expert interviews and panels as a basis for simulation models. They observe that the number of processes in the supply chain is lower in Finland (213) than in Germany (268), in contrast to the work time expenditure on managerial tasks, which is lower in Germany (1381 min 100 m^{-3}) than in Finland (1483 min 100 m^{-3}) and justify this among other reasons by the higher involvement of forest owners and greater independence of contractors in Finland. The importance of business process mapping as a basis for simulation models is underlined and they provide a high level of detail in the case studies. The cost reduction potential (20–39%) of the German wood supply chain organization and management through business process reengineering is addressed in Windisch et al. (2013b). In the first approach, the existing processes are slightly revised by digitalization of data exchange, standardization of data collection, contact reduction, numerical involvement, task elimination and empowerment. The second approach develops two new business processes for sourcing biomass from precommercial thinnings. Windisch et al. (2015) take it one step further and develop a simulation model with seven scenarios based on expert interviews to enhance productivity of a forest wood supply chain during the peak period from December to February. They expand the focus on risk considerations and interrelated simulation aspects through the use of a more powerful simulation environment compared to their earlier works. In contrast to the usage of software packages with graphical user interface based on drag and drop objects, Pinho et al. (2016a) choose an semantic intensive approach with Python`s simulation package SimPy. The model simulates the daily schedule for synchronous chipper and truck combination including chipping, loading, transporting, unloading at power plants and returning to a depot and includes deterministic and stochastic behavior of processing and driving times. In contrast to software systems that provide built-in elements like AnyLogic, Arena and Witness, a clean coding approach for simulation of SimPy is highlighted by Pinho et al. (2015). This expands the capability of a simulation model to the ones of the scripting language Python, but it is more complex and, therefore, extensive programming knowledge is required. Pinho et al. (2016b) revisit former considerations by implementing a similar simulation model in the MATLAB platform SimEvents. The authors focus on chipping as well as transportation and include stochastic failures and breakdowns to measure performance variations initiated by unfinished tasks and increased waiting times. The authors stay in the same problem environment, but change the simulation software and increase the number of nodes slightly to provide concrete output on driving, chipping and idle times as a percentage of executed workload for more profound comparisons of stochastic simulation scenarios. A life-cycle of a Japanese forest biomass energy process is simulated by Kishita et al. (2017) to enhance sustainability and address uncertainty with a scenario-based approach. Carbon dioxide emissions as well as economic profit are measured and a sensitivity analyses identifies electricity selling price and feedstock supply as most critical uncertainties. This case study of a Japanese rural community is a valuable supplement to literature, which is dominated by mainly European and North-American research. It focuses on wood supply chains and takes into account critical factors such as collecting a sufficient amount of wood residues for electricity generation and keeping a high and stable selling price of electricity from wood, which are not considered by other authors as this is less relevant in western countries.

Thirdly, Myers and Richards (2003), Beaudoin et al. (2012) and Marques et al. (2014) concentrate on timber. Myers and Richards (2003) provide considerations of particular relevance to mills. According to the authors, inventories at the mill yard should be reduced by minimizing seasonal shutdowns for harvesting by using cable-based or central tire inflation systems. Beaudoin et al. (2012) address high raw material inventory levels due to seasonal fluctuation and expand the focus to include transport both to and at the mill. By examining unloading operations at the mill stockyard, insights are gained into a rarely considered part of the wood supply chain, which is of importance due to high interrelations. The authors show that the strategy to empty the queue first decreases the average truck cycle time by 14% and the average total travel distances of the loaders by 18%, outperforming first in-first out and longest queue first strategies. Not considered is an upper limit of waiting time for trucks and upstream activities of the wood supply chain is not integrated in the simulation. Nevertheless, their work focus on unloading strategies inspires other authors to refine their simulation models. Similar to Zamora et al. (2013) or De Mol et al. (1997), Marques et al. (2014) combine simulation with optimization, but, like Beaudoin et al. (2012), for designing and managing truck arrival and unloading at a mill. In a three stage approach, the authors generate alternative scenarios in Excel where uncertainty of arrival times is taken into account, solve a truck scheduling optimization problem and simulate the dynamic behavior to measure performance metrics. Their results show that queuing can be reduced when time slots are used and trucks arrive on time. There is potential for improvement, which can be addressed by integrating scenario generation and optimization directly into the simulation software and by covering the entire wood supply chain.

Lastly, Cavalli et al. (2012) quantify in a simulation of a firewood supply chain in Italy a productivity increase by up to 2% if the forest road network is expanded by 5 m ha^{-1}. Due to the enormous task of road network expansion, the productivity increase seems to be too low to justify implementation in practice. Based on a GIS network analysis, the authors model the interrelation between stump extraction, off-road and on-road transportation from forest site to the processing terminal. The results are analyzed graphically as well as by comparing the outcome with case study data. It is mentioned that outcomes are limited to medium gentle terrain, whereas modelling steep terrain is more complex due to cable logging.

6 Conclusion and outlook

First simulations of wood supply chains in the mid-1970s by Aune (1973) and (1974) already indicated the usability of this method to model interactions and random effects. Within the last two decades, increasing computing capacity enabled international research groups to apply the DES method for transport in the wood supply chain. Accordingly, more and more scientists use this method to develop complex simulation models by means of constantly improvement of simulation software. The results of the reviewed studies indicate that DES is well-suited for analyzing interconnected transportation issues on an operational and tactical level. In line with Tako and Robinson (2012), SD can be an appropriate alternative for strategic planning horizons with a low level of detail. Further studies can expand the few initial approaches to combine DES, ABS and SD with optimization. Furthermore, there are other valuable considerations to investigate multimodal (Lindholm and Berg 2005; Mahmudi and Flynn 2006; Rumpu and Vilko 2011; Chesneau et al. 2012; Lautala et al. 2012; Zhang et al. 2016a; Zhang 2016b) or unimodal transport for biomass (Gallis 1996; Hall et al. 2001; Hamelinck et al. 2005; Windisch et al. 2010; Pinho et al. 2015; Sukumara et al. 2015; Devlin et al. 2016; Laitila et al. 2016), chipping (Johnson and Biller 1974; Belbo and Talbot 2014; Zamora-Cristales et al. 2015) and mills (Aune 1973, 1974; Randhawa et al. 1993; Carlsson and Rönnqvist 2005) in wood supply chains, but with less focus on transport or supply chain management as presented in this review.

Although great amounts of research exist concerning biomass transport, due to intensive funding during the last years, it is important to expand knowledge and research into other transport assortments of the entire wood supply chain. Moreover, greater focus from unimodal to multimodal transport considerations in the future could help build efficient, resilient, green and socially sustainable supply chains. Firstly, multimodal transport supports bigger mills, larger catchment areas and longer transport distances because costs can be saved compared to unimodal transport. Secondly, multimodal terminals also improve resilience as storage capacity expands the strategic options for contingency planning to manage risks and disturbances in order to maintain wood supply to mills and prevent costly shut downs. Lastly, as wood procurement managers will be confronted with stricter regulations and social pressure to make transports more ecologically and socially beneficial in the future, multimodal transport can contribute to reduce CO_2 emissions and noise pollution. DES can be a useful tool to provide decision support and answer what-if questions during this transition period. In addition, DES allows complex models to be mapped in a straightforward manner to facilitate understanding of stakeholders, especially when no analytic solution exist or will be accepted due to traceability, plausibility or comprehensibility concerns of stakeholders.

Within multimodal wood supply chain studies, a focus on terminal operations was found as a common feature in literature. While research usually concentrates more on finding general solutions, implementation and practical application is more a managerial and consultancy consideration. Therefore, simulation knowledge should be shared between science and practice in order to stimulate implementation of simulation tools for general operational planning (e.g., in ERP systems) of companies. Research gaps exist concerning detailed simulation modules for upstream processes of terminals, which allow a more realistic consideration of relevant supply risks. These risks, as well as demand risks, should be observed in comprehensive case studies and stochastic simulation and optimization studies. Currently, risk is considered rudimentary, mainly as internal transport risks such as machine breakdowns or transport delays and short simulation horizons (i.e., up to one year). Nevertheless, great external risks, uncertainties, disruptions and variations exist such as natural disasters (e.g., windstorm, bark beetle infestation), weather (e.g., rain, ice) and delivery stops of mills. These risks play a major role in supply chain performance and should be proactively managed by robust risk management. Simulation of different risk scenarios in a long-term setting (i.e., up to 10 years) can provide valuable decision support in such scenarios.

Proving if a model is a sound basis for decision making is the main task of the verification and validation process (Sterman 2000). Therefore, verification and validation play a significant role in simulation models and should be improved in the next generation of wood supply chain DES models. Methods such as structural (i.e., step-by-step) walkthroughs, visualization and animation, expert (e.g., professionals and scientists) involvement on a regular basis, extreme scenarios (e.g., use of very high/low parameters) and comparisons of the results with high quality real life case studies or literature data have to be considered. Moreover, statistical analysis of input and output data including maximum likelihood estimates, hypothesis testing (e.g., chi-squared goodness of fit or Kolmogorov-Smirnov test), confidence intervals, distribution fitting, sensitivity and correlation and graphical plots (e.g., histograms, distribution functions, boxplots, Q-Q, P-P and spider web plots) are required as well. Furthermore, also frequent reruns of experiments, inclusion of warming up periods and usage of the same seeds for random generators, a written assumption document, modular design, trace driven debugging, component testing and code review by different people are state of the art and have to be applied, described and further developed. In depth analyses and explanations of validation and verification methods in simulation models can be found in Sargent (2013), Aboud et al. (2009) and Kleijnen (1995).

A common shortcoming of many DES research papers covering the wood supply chain is the rough explanation and documentation of the simulation model. Documentation should include flow- and business process diagrams in standardized notation, detailed verbal descriptions of the model logic divided into different modules, figures and charts, entity relationship diagrams, equations, functions, tables with parameter descriptions, screen shots of the simulation model in the used software environment, detailed and easy-to-read scenario descriptions and detailed descriptions of the distribution fitting process including histograms and boxplots. Since findings are only valid for the specific simulation design and cannot be transferred to other cases, it is important to include detailed information about risk consideration, case study, simulation period, resolution time and spatial resolution, supply network (i.e., model structure), quantitative objective formulation (in contrast to increasing the efficiency or competitiveness), justification for the chosen abstraction level, planning horizon, assortment, transport mode, software validation and model documentation to classify the results. The model documentation as well as the model validation (including verification and establishing credibility) should ideally be split into separate sections to enhance readability and clarity.

Given the numerous case studies investigated by this active research community in different parts of the world, surveys and simulation models that compare wood supply chains of different countries could contribute to a better understanding and knowledge transfer between the research groups. Non-transparency inhibits the integration of former findings in the development of next level wood supply chain simulation models. This is observed by absent differentiation and discussion of similar research papers and a lack of acceptance as managers or scientists cannot sufficiently validate the simulation model. Moreover, this is supported by more complex simulation models, which is in contrast to the purpose of simulation models to give straight forward answers. Articles providing the most relevant information (i.e., business process diagrams, model screen shots, case study descriptions) in a descriptive way and applying adequate validation methods (i.e., structural walkthroughs, expert involvement, visualization, statistical analyses, assumption document) support integration and trust in simulation models. Finally, journals and researcher can further improve documentation and understanding of models by providing access to the simulation models itself, however, some burdens such as IPR issues have to be overcome.

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References

Aboud S.J., Al Fayoumi M., Alnuaimi M. (2009). Verification and validation of simulation models. In: Abu-Taieh E.M.O., El-Sheikh A.A. (eds.). Handbook of research on discrete event simulation environments: technologies and applications. Information Science Reference, Hershey, New York. p. 1–19. https://doi.org/10.4018/978-1-60566-774-4.ch004.

Albrecht M.C. (2010). Introduction to discrete event simulation. http://www.albrechts.com/mike/DES/Introduction%20to%20DES.pdf. [Cited 20 March 2018].

Almeder C., Preusser M., Hartl R.F. (2009). Simulation and optimization of supply chains: alternative or complementary approaches? OR spectrum 31(1): 95–119. https://doi.org/10.1007/s00291-007-0118-z.

Asikainen A. (1998). Chipping terminal logistics. Scandinavian Journal of Forest Research 13(3): 386–392. https://doi.org/10.1080/02827589809382998.

Asikainen A. (2001). Simulation of logging and barge transport of wood from forests on islands. International Journal of Forest Engineering 12(2): 43–50. https://doi.org/10.1080/14942119.2001.10702445.

Asikainen A. (2010). Simulation of stump crushing and truck transport of chips. Scandinavian Journal of Forest Research 25(3): 245–250. https://doi.org/10.1080/02827581.2010.488656.

Atashbar N.Z., Labadie N., Prins C. (2016). Modeling and optimization of biomass supply chains: a review and a critical look. IFAC-PapersOnLine 49(12): 604–615. https://doi.org/10.1016/j.ifacol.2016.07.742.

Aune J.E. (1973). Application of simulation technique in the study of sawmill productivity. Master Thesis. Department of Forestry, University of British Columbia, Vancouver, Canada. https://open.library.ubc.ca/cIRcle/collections/ubctheses/831/items/1.0101215. [Cited 20 March 2018].

Aune J.E. (1974). System simulation – a technique for sawmill productivity analyses and designs. The Forestry Chronicle 50(2): 66–69. https://doi.org/10.5558/tfc50066-2.

Banks J., Carson II J.S., Nelson B.L., Nicol D.M. (2005). Discrete-event system simulation. 4th ed. Pearson Education, United States. 528 p. ISBN-13 9780131446793.

Banks J., Gibson R. (1997). Don't simulate when... 10 rules for determining when simulation is not appropriate. IIE solutions 29(9): 30–33.

Beaudoin D., LeBel L., Soussi M.A. (2012). Discrete event simulation to improve log yard operations. Infor 50(4): 175–185. https://doi.org/10.3138/infor.50.4.175.

Belbo H., Talbot B. (2014). Systems analysis of ten supply chains for whole tree chips. Forests 5(9): 2084–2105. https://doi.org/10.3390/f5092084.

Borodin V., Bourtembourg J., Hnaien F., Labadie N. (2016). Handling uncertainty in agricultural supply chain management: a state of the art. European Journal of Operational Research 254(2): 348–359. https://doi.org/10.1016/j.ejor.2016.03.057.

Borshchev A. (2013). The big book of simulation modeling: multimethod modeling with AnyLogic 6. Anylogic, North America. 612 p. ISBN-10 0989573176.

Borshchev A., Filippov A. (2004). From system dynamics and discrete event to practical agent based modeling: reasons, techniques, tools. Conference Paper presented at 22nd international conference of the system dynamics society, Oxford, England.

Carlsson D., Rönnqvist M. (2005). Supply chain management in forestry – case studies at Södra Cell AB. European Journal of Operational Research 163(3): 589–616. https://doi.org/10.1016/j.ejor.2004.02.001.

Cavalli R., Grigolato S., Pellegrini M. (2012). Determination of the forest road network influence on the supply chain for firewood production by discrete event simulation. Journal of Agricultural Engineering 42(4): 41–48. https://doi.org/10.4081/jae.2011.4.41.

Chesneau J.B., Le Net E., Berg S. (2012). A transport tool to evaluate sustainability impacts of transport processes within the forest wood chain. European Journal of Forest Research 131(1): 73–80. https://doi.org/10.1007/s10342-011-0530-4.

D'Amours S., Ronnqvist M., Weintraub A. (2008). Using operational research for supply chain planning in the forest products industry. Infor 46(4): 265–281. https://doi.org/10.3138/infor.46.4.265.

De Mol R.M., Jogems M.A.H., Van Beek P., Gigler J.K. (1997). Simulation and optimization of the logistics of biomass fuel collection. Netherlands Journal of Agricultural Science 45(1): 217–228.

Devlin G., Sosa A., Acuna M. (2016). Solving the woody supply chain for Ireland's expanding biomass sector: a case study. In: Holm-Nielsen J.B., Ehimen E.A. (eds.). Biomass supply chains for bioenergy and biorefining. Elsevier Woodhead. p. 333–355. https://doi.org/10.1016/B978-1-78242-366-9.00015-0.

Eliasson L., Eriksson A., Mohtashami S. (2017). Analysis of factors affecting productivity and costs for a high-performance chip supply system. Applied Energy 185(p1): 497–505. https://doi.org/10.1016/j.apenergy.2016.10.136.

Eriksson A., Eliasson L. (2015). Analyzing machine concepts and delivery strategies to cut delivery costs for forest fuels using a discrete-event simulation model. Conference Paper presented at Winter Simulation Conference (WSC), 6–9 Dec. 2015, Huntington Beach, CA. p. 3194–3195. https://doi.org/10.1109/WSC.2015.7408466.

Eriksson A., Eliasson L., Hansson P.-A., Jirjis R. (2014a). Effects of supply chain strategy on stump fuel cost: a simulation approach. International Journal of Forestry Research 2014: 1–11. https://doi.org/10.1155/2014/984395.

Eriksson A., Eliasson L., Jirjis R. (2014b). Simulation-based evaluation of supply chains for stump fuel. International Journal of Forest Engineering 25(1): 23–36. https://doi.org/10.1080/14942119.2014.892293.

Eriksson A., Eliasson L., Sikanen L., Hansson P.-A., Jirjis R. (2017). Evaluation of delivery strategies for forest fuels applying a model for weather-driven analysis of forest fuel systems (WAFFS). Applied Energy 188: 420–430. https://doi.org/10.1016/j.apenergy.2016.12.018.

Etlinger K., Rauch P., Gronalt M. (2014). Improving rail road terminal operations in the forest wood supply chain – a simulation based approach. Conference Paper presented at 16th International Conference on Harbor, Maritime and Multimodal Logistics Modelling and Simulation, HMS 2014. p. 199–206.

Fjeld D.E. (2001). The wood supply game as an educational application for simulating dynamics in the forest sector. Conference Paper presented at: World symposium Logistics in forest sector: Supply chain management for paper and timber industries. Vaxjo, Sweden. 241–251. ISBN 9176363023.

Gallis C.T. (1996). Activity oriented stochastic computer simulation of forest biomass logistics in Greece. Biomass & Bioenergy 10(5–6): 377–382. https://doi.org/10.1016/0961-9534(96)00002-5.

Grigoryev I. (2015). AnyLogic 7 in three days: a quick course in simulation modeling. Vol. 2nd. 256 p. ISBN-13 978-1508933748.

Gronalt M., Rauch P. (2018). Analyzing railroad terminal performance in the timber industry supply chain – a simulation study. International Journal of Forest Engineering 29(3): 162–170. https://doi.org/10.1080/14942119.2018.1488913.

Gueimonde-Canto A., González-Benito J., García-Vázquez J.M. (2011). Competitive effects of co-operation with suppliers and buyers in the sawmill industry. Journal of Business & Industrial Marketing 26(1): 58–69. https://doi.org/10.1108/08858621111097210.

Haartveit E.Y., Kozak R.A., Maness T.C. (2004). Supply chain management mapping for the forest products industry: three cases from western Canada. Journal of Forest Products Business Research 1(5): 1–30.

Hall P., Gigler J.K., Sims R.E.H. (2001). Delivery systems of forest arisings for energy production in New Zealand. Biomass and Bioenergy 21(6): 391–399. https://doi.org/10.1016/S0961-9534(01)00047-2.

Hamelinck C.N., Suurs R.A.A., Faaij A.P.C. (2005). International bioenergy transport costs and energy balance. Biomass & Bioenergy 29(2): 114–134. https://doi.org/10.1016/j.biombioe.2005.04.002.

How B.S., Lam H.L. (2018). Sustainability evaluation for biomass supply chain synthesis: novel principal component analysis (PCA) aided optimisation approach. Journal of Cleaner Production 189: 941–961. https://doi.org/10.1016/j.jclepro.2018.03.104.

Johnson L.R., Biller C.J. (1974). Wood-chipping and a balanced logging system simulation can check the combinations. Transactions of the ASAE (USA) 17(4): 651–655. https://doi.org/10.13031/2013.36929.

Karttunen K., Väätäinen K., Asikainen A., Ranta T. (2012). The operational efficiency of waterway transport of forest chips on Finland's lake Saimaa. Silva Fennica 46(3): 395–413. https://doi.org/10.14214/sf.49.

Karttunen K., Lättilä L., Korpinen O.-J., Ranta T. (2013). Cost-efficiency of intermodal container supply chain for forest chips. Silva Fennica 47(4) article 1047. https://doi.org/10.14214/sf.1047.

Kishita Y., Nakatsuka N., Akamatsu F. (2017). Scenario analysis for sustainable woody biomass energy businesses: the case study of a Japanese rural community. Journal of Cleaner Production 142: 1471–1485. https://doi.org/10.1016/j.jclepro.2016.11.161.

Kleijnen J.P. (1995). Verification and validation of simulation models. European Journal of Operational Research 82(1): 145–162. https://doi.org/10.1016/0377-2217(94)00016-6.

Laitila J., Asikainen A., Ranta T. (2016). Cost analysis of transporting forest chips and forest industry by-products with large truck-trailers in Finland. Biomass & Bioenergy 90: 252–261. https://doi.org/10.1016/j.biombioe.2016.04.011.

Larsson M., Stendahl M., Roos A. (2016). Supply chain management in the Swedish wood products industry – a need analysis. Scandinavian Journal of Forest Research 31(8): 777–787. https://doi.org/10.1080/02827581.2016.1170874.

Lautala P.T., Pouryousef H., Handler R., Chartier S. (2012). The role of railroads in multimodal woody biomass transportation in michigan. Conference Paper presented at ASME/ASCE/IEEE Joint Rail Conference, Philadelphia, Pennsylvania, USA. p. 465–473.

Lautala P.T., Hilliard M.R., Webb E., Busch I., Hess J.R., Roni M.S., Hilbert J., Handler R.M., Bittencourt R., Valente A., Laitinen T. (2015). Opportunities and challenges in the design and analysis of biomass supply chains. Environmental Management 56(6): 1397–1415. https://doi.org/10.1007/s00267-015-0565-2.

Law A.M. (2015). Simulation modeling and analysis. 5th ed. Industrial Engineering and Management. McGraw-Hill, New York. 776 p. ISBN 978-1-259-25438-3.

Lehtonen J.-M., Holmström J. (1999). How can simulation help in supply chain development? In: Mertins K., Krause O., Schallock B. (eds.). Global production management. IFIP – the international federation for information processing. Springer US, Boston, MA. p. 292–299. https://doi.org/10.1007/978-0-387-35569-6_36.

Lewandowski I. (2015). Securing a sustainable biomass supply in a growing bioeconomy. Global Food Security 6: 34–42. https://doi.org/10.1016/j.gfs.2015.10.001.

Lindholm E.L., Berg S. (2005). Energy requirement and environmental impact in timber transport. Scandinavian Journal of Forest Research 20(2): 184–191. https://doi.org/10.1080/02827580510008329.

Mahmoudi M., Sowlati T., Sokhansanj S. (2009). Logistics of supplying biomass from a mountain pine beetle-infested forest to a power plant in British Columbia. Scandinavian Journal of Forest Research 24(1): 76–86. https://doi.org/10.1080/02827580802660397.

Mahmudi H., Flynn P.C. (2006). Rail vs truck transport of biomass. Applied Biochemistry and Biotechnology 129–132(1): 88–103. https://doi.org/10.1385/abab:129:1:88.

Malladi K.T., Sowlati T. (2018). Biomass logistics: a review of important features, optimization modeling and the new trends. Renewable and Sustainable Energy Reviews 94: 587–599. https://doi.org/10.1016/j.rser.2018.06.052.

Manuj I., Mentzer J.T., Bowers M.R. (2009). Improving the rigor of discrete-event simulation in logistics and supply chain research. International Journal of Physical Distribution & Logistics Management 39(3): 172–201. https://doi.org/10.1108/09600030910951692.

Marques A.F., De Sousa J.P., Rönnqvist M., Jafe R. (2014). Combining optimization and simulation tools for short-term planning of forest operations. Scandinavian Journal of Forest Research 29(sup1): 166–177. https://doi.org/10.1080/02827581.2013.856937.

Mirkouei A., Haapala K.R., Sessions J., Murthy G.S. (2017). A review and future directions in techno-economic modeling and optimization of upstream forest biomass to bio-oil supply chains. Renewable & Sustainable Energy Reviews 67: 15–35. https://doi.org/10.1016/j.rser.2016.08.053.

Mobini M., Sowlati T., Sokhansanj S. (2011). Forest biomass supply logistics for a power plant using the discrete-event simulation approach. Applied Energy 88(4): 1241–1250. https://doi.org/10.1016/j.apenergy.2010.10.016.

Mobini M., Sowlati T., Sokhansanj S. (2013). A simulation model for the design and analysis of wood pellet supply chains. Applied Energy 111: 1239–1249. https://doi.org/10.1016/j.apenergy.2013.06.026.

Mobini M., Meyer J.C., Trippe F., Sowlati T., Frohling M., Schultmann F. (2014). Assessing the integration of torrefaction into wood pellet production. Journal of Cleaner Production 78: 216–225. https://doi.org/10.1016/j.jclepro.2014.04.071.

Myers J., Richards E.W. (2003). Supporting wood supply chain decisions with simulation for a mill in northwestern BC. Infor 41(3): 213–234. https://doi.org/10.1080/03155986.2003.11732677.

Oliveira J.B., Lima R.S., Montevechi J.A.B. (2016). Perspectives and relationships in supply chain simulation: a systematic literature review. Simulation Modelling Practice and Theory 62: 166–191. https://doi.org/10.1016/j.simpat.2016.02.001.

Opacic L., Sowlati T. (2017). Applications of discrete-event simulation in the forest products sector: a review. Forest Products Journal 67(3–4): 219–229. https://doi.org/10.13073/fpj-d-16-00015.

Pinho T.M., Moreira A.P., Veiga G., Boaventura-Cunha J. (2015). Overview of MPC applications in supply chains: potential use and benefits in the management of forest-based supply chains. Forest Systems 24(3): e039. 15 p. https://doi.org/10.5424/fs/2015243-08148.

Pinho T.M., Coelho J.P., Boaventura-Cunha J. (2016a). Forest-based supply chain modelling using the SimPy simulation framework. IFAC-PapersOnLine 49(2): 90–95. https://doi.org/10.1016/j.ifacol.2016.03.016.

Pinho T.M., Coelho J.P., Moreira A.P., Boaventura-Cunha J. (2016b). Modelling a biomass supply chain through discrete-event simulation. IFAC-PapersOnLine 49(2): 84–89. https://doi.org/10.1016/j.ifacol.2016.03.015.

Randhawa S.U., Brunner C.C., Funck J.W., Zhang G.C. (1993). An object-oriented modeling framework for sawmill simulation. Computers & Industrial Engineering 25(1–4): 565–568. https://doi.org/10.1016/0360-8352(93)90345-X.

Rauch P. (2013). Improving the primary forest fuel supply chain. Bulletin of the Transilvania University of Brasov Series II 6(55): 1–8.

Rumpu A., Vilko J. (2011). Assessing information-exchange risks and disruptions in supply chains. International Journal of Intercultural Information Management 2(4): 317–332. https://doi.org/10.1504/ijiim.2011.041750.

Saranen J., Hilmola O.-P. (2007). Evaluating the competitiveness of railways in timber transports with discrete-event simulation. World Review of Intermodal Transportation Research 1(4): 445–458. https://doi.org/10.1504/writr.2007.017097.

Sargent R.G. (2013). Verification and validation of simulation models. Journal of simulation 7(1): 12–24. https://doi.org/10.1057/jos.2012.20.

Seay J.R., Badurdeen F.F. (2014). Current trends and directions in achieving sustainability in the biofuel and bioenergy supply chain. Current Opinion in Chemical Engineering 6: 55–60. https://doi.org/10.1016/j.coche.2014.09.006.

Shahi S., Pulkki R. (2013). Supply chain network optimization of the Canadian forest products industry: a critical review. American Journal of Industrial and Business Management 3: 631–643. https://doi.org/10.4236/ajibm.2013.37073.

Spinelli R., Di Gironimo G., Esposito G., Magagnotti N. (2014). Alternative supply chains for logging residues under access constraints. Scandinavian Journal of Forest Research 29(3): 266–274. https://doi.org/10.1080/02827581.2014.896939.

Sterman J.D. (2000). Business dynamics: systems thinking and modeling for a complex world. McGraw-Hill, Boston.

Sukumara S., Amundson J., Badurdeen F., Seay J. (2015). A comprehensive techno-economic analysis tool to validate long-term viability of emerging biorefining processes. Clean Technologies and Environmental Policy 17(7): 1793–1806. https://doi.org/10.1007/s10098-015-0945-6.

Tako A.A., Robinson S. (2012). The application of discrete event simulation and system dynamics in the logistics and supply chain context. Decision Support Systems 52(4): 802–815. https://doi.org/10.1016/j.dss.2011.11.015.

Väätäinen K., Prinz R., Malinen J., Laitila J., Sikanen L. (2017). Alternative operation models for using a feed-in terminal as a part of the forest chip supply system for a CHP plant. Global Change Biology Bioenergy 9: 1657–1673. https://doi.org/10.1111/gcbb.12463.

Vacik H., Lexer M.J. (2014). Past, current and future drivers for the development of decision support systems in forest management. Scandinavian Journal of Forest Research 29(1): 2–19. https://doi.org/10.1080/02827581.2013.830768.

Webb G.S., Thomas S.P., Liao-Troth S. (2014). Teaching supply chain management complexities: a SCOR model based classroom simulation. Decision Sciences Journal of Innovative Education 12(3): 181–198. https://doi.org/10.1111/dsji.12038.

Weintraub A., Romero C., Bjørndal T., Epstein R. (2007). Handbook of operations research in natural resources. Vol. 99. Springer, New York. 614 p. ISBN-13 9780387718149.

Westlund K., Furness-Lindén A. (2010). Scrutinizing the wood supply chain – reporting from work in progress. Conference Paper presented at FORMEC 2010, Forestry Mechanisation: Forest Engineering: Meeting the Needs of the Society and the Environment, July 11–14, 2010, Padova, Italy. 6 p.

Windisch J. (2015). Process redesign in development of forest biomass supply for energy. Doctoral Thesis. University of Eastern Finland.

Windisch J., Sikanen L., Roser D., Gritten D. (2010). Supply chain management applications for forest fuel procurement – cost or benefit? Silva Fennica 44(5): 845–858. https://doi.org/10.14214/sf.124.

Windisch J., Röser D., Mola-Yudego B., Sikanen L., Asikainen A. (2013a). Business process mapping and discrete-event simulation of two forest biomass supply chains. Biomass & Bioenergy 56: 370–381. https://doi.org/10.1016/j.biombioe.2013.05.022.

Windisch J., Röser D., Sikanen L., Routa J. (2013b). Reengineering business processes to improve an integrated industrial roundwood and energywood procurement chain. International Journal of Forest Engineering 24(3): 233–248. https://doi.org/10.1080/14942119.2013.857833.

Windisch J., Vaatainen K., Anttila P., Nivala M., Laitila J., Asikainen A., Sikanen L. (2015). Discrete-event simulation of an information-based raw material allocation process for increasing the efficiency of an energy wood supply chain. Applied Energy 149: 315–325. https://doi.org/10.1016/j.apenergy.2015.03.122.

Wolfsmayr U.J., Rauch P. (2014). The primary forest fuel supply chain: a literature review. Biomass & Bioenergy 60: 203–221. https://doi.org/10.1016/j.biombioe.2013.10.025.

Wolfsmayr U.J., Merenda R., Rauch P., Longo F., Gronalt M. (2016). Evaluating primary forest fuel rail terminals with discrete event simulation: a case study from Austria. Annals of Forest Research 59(1): 145–164. https://doi.org/10.15287/afr.2015.428.

Zamora-Cristales R., Boston K., Sessions J., Murphy G. (2013). Stochastic simulation and optimization of mobile chipping economics in processing and transport of forest biomass from residues. Silva Fennica 47(5) article 937. https://doi.org/10.14214/sf.937.

Zamora-Cristales R., Sessions J., Boston K., Murphy G. (2015). Economic optimization of forest biomass processing and transport in the Pacific Northwest USA. Forest Science 61(2): 220–234. https://doi.org/10.5849/forsci.13-158.

Zhang F., Johnson D.M., Johnson M.A. (2012). Development of a simulation model of biomass supply chain for biofuel production. Renewable Energy 44: 380–391. https://doi.org/10.1016/j.renene.2012.02.006.

Zhang F., Johnson D., Johnson M., Watkins D., Froese R., Wang J. (2016a). Decision support system integrating GIS with simulation and optimisation for a biofuel supply chain. Renewable Energy 85: 740–748. https://doi.org/10.1016/j.renene.2015.07.041.

Zhang F., Johnson D.M., Wang J. (2016b). Integrating multimodal transport into forest-delivered biofuel supply chain design. Renewable Energy 93: 58–67. https://doi.org/10.1016/j.renene.2016.02.047.

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3.2 A Discrete Event Simulation Model to Test Multimodal Strategies for a Greener and more Resilient Wood Supply

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A discrete event simulation model to test multimodal strategies for a greener and more resilient wood supply

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Abstract

Increasing occurrences of natural disturbances such as windstorms and high snow cover as well as supply chain risks lead to severe irregularities in wood harvest and transport. In order to overcome resulting supply difficulties, innovative multimodal systems via rail terminals are promising options offering potential to increase buffer capacity, improve supply chain resilience and reduce greenhouse gas emissions. Therefore, a train terminal is included in a virtual simulation environment spanning the whole wood supply chain from forest to industry in order to test, analyze and evaluate a complex multimodal system in different scenario settings. Furthermore, the simulation model provides intuitive decision support through animation and a KPI-cockpit, facilitating hands-on workshops with supply chain managers. Results show the advantage of a combination of unimodal and multimodal transport in the wood supply chain of the observed case study region as it proves to be resilient and outperforms other tested supply chain strategies by avoiding both bottlenecks and ill-timed plans as well as reducing CO_2 emissions. Furthermore, workshops conducted with industry experts indicate that adapting collaborative supply chain control strategies by means of a participatory simulation environment enhances the development of advanced risk management and, therefore improves supply chain resilience, efficiency and sustainability.

Keywords

logistics, supply chain management, multimodal and unimodal transport, forest products industry, decision support systems

1. Introduction

Sustainable management of Austrian forests fulfills an important ecological, social and economic function. More than four million hectares, representing nearly half of the state´s land, is covered with forest. Around 300,000 people work in the value chain of forestry, wood and paper in 172,000 companies, generating an annual production value of 12 billion euros and an export surplus of over 3.5 billion euros (FHP 2017). In order to guarantee supply security and competitiveness in the future, innovative research along the wood supply chain is required. Recent interviews with managers of the Austrian Federal Forests (AFF) indicate sustainability and resilience of the wood supply chain as areas with high potentials for improvement.

The Austrian wood supply chain is based mainly on unimodal truck transport, which avoids more complex multimodal planning and keeps costs low. This concept works well under normal business conditions, however, working processes applied in practice and implemented control mechanisms fail frequently when unexpected events occur and inefficient ad hoc contingency plans dominate. Increasing occurrences of natural disturbances and supply chain risks lead to irregularities in wood harvest and transport. Common natural disturbances in Austria are windstorms, avalanches, high snow covers and bark beetle infestations. Supply chain risks involve machine breakdowns, capacity changes or delivery stops of mills as well as uncertainty according to queuing, lead times, logistic capacity bottlenecks, stock level and wagon/truck availability. These disturbances lead to inefficient supply chains as well as cause high additional wood procurement costs and a long recovery time to return to normal business conditions.

To manage these challenges, multimodal strategies offer the potential for greener supply chains including reduced emissions. Selected terminals provide buffer opportunities to overcome risks and to enhance resilience of the whole wood supply chain. Nevertheless, supply chain managers find it often hard to make right decisions because an improvement in one part can result in downgrades elsewhere. Furthermore, network capacity, queuing times and lead times are difficult to estimate. Therefore, an integrated framework for modeling and testing multimodal strategies is useful to provide valuable decision support to managers and show system capacities as well as bottlenecks to contribute to further development of the wood supply chain.

In forest-based industries, decision support with operations research methods focus on single processes (e.g., harvesting, forwarding, transportation) or integrated issues along these processes (e.g., wood supply chain management, total chain efficiency). Optimization is commonly used for single processes, but it is difficult to apply to complex, highly dynamic networks with unpredictable, simultaneous interaction. In such settings, the use of simulation methods is promising. Examples with combined methods are rare for integrated issues along the wood supply chain and only available for isolated considerations (Rahman et al. 2014; Shahi and Pulkki 2015). Discrete event simulation is preferable to realistically model the wood supply chain compared to agent based simulation and system dynamics due to its intermediate abstraction level and straightforward model structure enabling mapping business processes and controlling the system by events (Kogler and Rauch 2018).

For a review of literature on operations research methods in the wood supply chain with a focus on optimization, refer to D'Amours et al. (2008). Opacic and Sowlati (2017) focus on discrete event simulation and Shashi and Pulkki (2013) include both methods. Moreover, Kogler and Rauch (2018) review the literature of discrete event simulation models in the wood supply chains and emphasize transport as the connecting link of dependent system components. They differentiate between unimodal (i.e., only one transport mode used, mainly truck) and multimodal transport (i.e., transshipment from truck to train or vessel) and conclude that unimodal transport, biomass and terminal operations dominate in literature. The majority of multimodal research with discrete event simulation solely focus on train transport (Etlinger et al. 2014; Gronalt and Rauch 2018; Karttunen et al. 2013; Saranen and Hilmola 2007; Wolfsmayr et al. 2016), vessel transport (Asikainen 2001; Karttunen et al. 2012) or studies that cover both (Mobini et al. 2014; Mobini et al. 2013). For future studies, the simulation of entire, resilient and multimodal wood supply chains was encouraged as well as the consideration of risks (Atashbar et al. 2016; Kogler and Rauch 2018; Lautala et al. 2015; Seay and Badurdeen 2014; Shahi and Pulkki 2013; Wolfsmayr and Rauch 2014).

Therefore, the aim of this study is to develop a discrete event simulation model to test multimodal strategies under risk scenarios for a greener and more resilient wood supply and to provide an unbiased comparison of multimodal and unimodal transport with sets of ranked key performance indicators (KPIs) in order to support supply chain decisions. Moreover, managers are lacking key information when estimating both supply chain lead times and queuing times at terminals. Therefore, a comprehensive case study was conducted and is discussed in section 2. The model with modules and views is described in section 3. In section 4, the parameterization and validation are presented and three strategy options for three scenario settings are presented in section 5. Information on KPIs and simulation runs is given in Section 6. Results including different applications are provided in section 7 and conclusions and proposals for further research are given in section 8.

2. Case Study

From 2016 to 2018, a comprehensive case study investigated the challenges of the Austrian wood supply chain and mapped business processes as well as risk events. This allowed for the development of a simulation model based on a real life case. The case study concentrated on a region in the center of Austria around the train terminal Großreifling. This train terminal was selected out of about 150 Austrian wood terminals because it well represents the standard train terminal in Austria and facilitates observing sustainability and resilience. In the past, this terminal was of high importance due to its ability to handle high amounts of wood, especially after windstorms, which frequently occurred in one of the four supplying districts. Moreover, the AFF operate their own loading siding and stockyard at the terminal. The restrictions for this terminal layout (e.g., maximum number of wagons and trucks, stockyard capacity, two loading sidings) and location (e.g., four supplying districts, maximum number of train pickups per day) define the upper bound for wood terminals in Austria. Therefore, a simulation model based on those can be adapted by parameterization to similar and smaller terminals.

The case study was supported by the AFF by providing data and helping to organize field inspections and expert interviews. The AFF are property of the Austrian state and are administered as a stock company. Their 1,100 employees are responsible for 15% of Austrian forests and deliver a supply volume of about 1.5 million cubic meters, from which about a quarter is transported multimodal. Four forest districts directly supply the train terminal in the small Styrian village Großreifling. Three regional carriers transport regularly about 2,000 cubic meters wood per month to the terminal. Once per day (or twice after windstorms) a locomotive picks up two to four wagons (up to nine wagons after windstorms) and leaves empty wagons until the next day at one of the loading tracks. After natural disturbances like windstorms, up to 30,000 cubic meters per month pass through the terminal. In this case, up to 10,000 cubic meters can be stored directly at the terminal.

Supply chain processes were captured for deeper analyses in process maps in different abstraction levels using the software Adonis. Figure 1 shows an abstract process map providing an overview of the supply chain. The actors in the described supply chain are the AFF, logging companies, carriers, Railcargo Austria (the main cargo operator on Austrian railways) and mills. After the planning is concluded, logging is assigned and executed the relevant simulation processes start. Transport has to be initiated and the decision on multimodal or unimodal transport has to be made. In case of multimodal transport, there is a higher managing effort necessary, which can be detected by a longer process chain. This is the main reason why truck transport is favored by regional management, even for cases where costs for truck and train are similar.

(Figure 1: Process map of wood supply chain)

The train terminal Großreifling consists of four 200-meter-long rail tracks (Figure 2). The upper one is privately owned and the lowest one is the loading siding of the AFF. The 175-meter-long and 30-meter-wide stockyard provides areas for round timber and biomass.

(Figure 2: Aerial photograph of the terminal in Großreifling)

After a truck drives to the forest landing, loaded wood and transported it to the terminal, it accesses the terminal at point 1. In point 2, the driver removes safety belts and loads the wagon at point 3 before securing the wagon load on point 4. In 5, he/she cleans the truck loading platform and, in 6, completes the electronic delivery ticket. Queuing and scheduling problems mainly occur after windstorms when many trucks need to be unloaded onto wagons at the same time.

3. Model Description

According to the case study, the goal is to design an easily adaptable and executable discrete event simulation with scenario and parameter selection in order to gain insight into the Austrian wood supply chain. Moreover, a standard system configuration (BAU = business as usual) should to be compared with a scenario with reduced production due to a high snow cover (SNOW: -75% production in the first quarter of the year) and one with an increased production after a windstorm (STORM: +300% production in the third quarter of the year). To allow a high level of management involvement, the simulation model should be intuitively operable by a graphical user interface including a detailed animation view and provide the possibility to parameterize the model via Excel.

The stochastic simulation model consists of five modules (A) Forest, (B) Truck Transport, (C) Terminal, (D) Train Transport and (E) Industry, which can be observed in six different views (1) Animation, (2) Scenarios, (3) Statistics, (4) Logic Supply Chain, (5) Logic Terminal and (6) Code. The logic modules of the simulation model consist of 305 elements of the AnyLogic process modeling library, which are enriched by a detailed control logic coded with Java to boost the functionality of these basic elements. In addition, 35 functions, 80 global variables and statistical counters, 9 variable collections, 5 schedules and 6 events control the simulation model based of 39 input parameters to store information in 33 datasets. Table 1 provides an overview of the transition of inputs to outputs based on the main interrelated simulation processes, stochastic effects and other model components.

(Table 1: Main inputs, processes and outputs of the simulation model)

As Figure 3 shows, the agents generated in the Forest Module flow to the Truck Transport Module, where they either go directly to the Industry Module (unimodal) or first to the Terminal Module and then to the Train Transport Module (multimodal) before they end at the Industry Module.

(Figure 3: Wood Supply Chain with multimodal and unimodal transport)

The Forest Module (A) generates wood agents (= 1 m^3 of wood) in four different sources representing district 1 and 2 of the forest region in Styria and district 8 and 9 in the forest region in Lower Austria, which supply the terminal Großreifling. After the wood is cut and forwarded, it is batched in a truckload (according to the parameterization settings, for Austria 20–30 m^3) and stored at a forest landing (Figure 4).

(Figure 4: Wood flow)

In the Truck Transport Module (B), trucks are generated, queued and controlled by transport jobs. Within their working times, unloaded trucks are sent to the landing (according to the scenario settings: oldest wood or largest stockyard) to pick up one truckload or to do a transshipment job at the terminal. To complete a multimodal (unimodal) transport, trucks have to leave the landings before 13:00 (12:00), otherwise they are sent back to the truck garage as preloaded trucks and finish their tour on the next day. If they were not able to enter the terminal before 17:00, they are sent back to the truck garage. If a truck completed a tour before 15:00, it picks up another truckload at the landing or starts another transhipment job, otherwise it returns to the truck garage (Figure 5).

(Figure 5: Truck flow)

The Terminal Module (C) contains a complex logic to control the truck queuing at the terminal and the transhipment process from truck-respective stockyard (storage capacity 450 truckloads) to train wagon (cargo capacity 2 truckloads). A maximum number of nine trucks can enter the terminal simultaneously. Additional trucks have to queue at a parking space in front of the terminal. The terminal is divided in two loading sidings. Loading siding one provides room for up to seven train wagons and a stockyard, whereas loading siding two provides only up to two wagons. If more than 7 wagons are ordered, the eighth and ninth are received at the second platform. After a truck enters the terminal, it gets routed to the allocated wagon at the right loading siding and queues through according to the processes (Figure 2). Only one truck can unload at one wagon at the same time and it is not possible for trucks to pass each other due to space constraints. Therefore, queuing problems result at the terminal and scale up with the number of trucks. After a truck leaves the terminal, it either returns to the truck garage, queues for the next transhipment job at the terminal or directly drives to the landing to load wood again.

The Train Module (D) generates trains to pick up fully loaded wagons at the terminal in order to transport them to industry, forwards empty wagons at the terminal as well as sorts wagons according to their loading status at the terminal. Since one wagon has a cargo capacity of two truckloads, a wagon can either be fully loaded, half-loaded or empty. Depending on the scenario, a train arrives at the terminal at 09:00 and again at 15:00 if fully loaded wagons are available or empty wagons were ordered. The train picks up fully loaded wagons, moves half-loaded wagons to the front of the chain and leaves empty wagons for loading. After train transport is complete, the loads are unloaded at the industry.

The Industry Module (E) controls the unimodal and multimodal unloading process at the forest-based industry plants and releases the truck and train agents, which enables them to leave the Industry Module and return to the Truck Transport or Train Module.

The entire simulated wood supply chain can be observed in six different views. The Animation View (Figure 6) graphically shows the flow of agents. Wood is harvested at the forests and Forwarded to the landings of the respective district. Trucks start at the truck garage and transport wood batched to truckloads from the landings either to the terminal or directly to the industry. At the terminal, truckloads are transhipped into the waiting wagon(s) or to the stockyard and a train transports them further to the industry.

(Figure 6: Animation view with truck garage, forests, landings, industry, terminal)

The *Statistics View* provides the management cockpit consisting of automatically updated KPIs (Figure 7). The presentation of tables, numbers and diagrams for production, stockyards, transport and duration changes during runtime and gives an interactive feedback overview of the actual and past performance of the entire wood supply chain.

(Figure 7: Statistic view (management cockpit))

The Parameterization View allows one to adapt the simulation model to different case study settings and to define scenarios through changing input parameters (e.g., process duration parameters, truck and stockyard capacity parameters, weekly production amounts per district) or restrictions for decision variables. Moreover, decision variables can be varied as a whole set by different control options (i.e., manually, plans, Excel, workshop) and runtime (i.e., year, month, week, day, train pickup) or as single variable for the number of wagons, trucks and train pickups as well as for transport mode split and transport priority (Table 2).

(Table 2: Decision Variables)

Firstly, the manual control method enables the adjustment of decision variables and production amounts per district on a weekly basis. This option is designed to stop the simulation once a week and adjust the parameter iteratively according to the actual situation and limitations. Secondly, the plan control method enables the selection of four built-in standard scenarios with fixed decision variables enabling a fast demonstration of different simulation runs. Thirdly, the Excel control method activates three additional scenarios, which read parameters and decision variables directly from standardized Excel documents. Therefore, this control method allows the storage of scenario settings for direct comparisons and analyses. Finally, the workshop control method is helpful for practical usage by wood supply chain managers to gain insights about interdependencies of the chain and to see effects of decisions before costly changes are made in reality. Therefore, this option is highly suitable for workshops to give a step-by-step (minute, hour, day, week) explanation of the simulation model (Figure 8).

(Figure 8: Parameterization view)

After selecting the Logic Supply Chain View, the flow of agents through the system elements of the wood supply chain can be observed. Four modules show a clear arrangement of AnyLogic process modelling library elements. The flow of agents through the terminal is visible in the Logic Terminal View, which is directly connected to the logic of the supply chain, but is too complex to visualize both in one window. The Code View provides all implemented functions, variables, data sets, parameter, schedules and events and they appear in a structured overview.

4. Parameterization and Validation

The input data for the model configuration is based on production and truck transport data of the AFF (datasets for 2015 and 2016), train transport data of Railcago Austria (dataset 2007–2016) as well as expert estimations and observations from interviews with managers, foresters and carriers conducted during 2016 and 2017. Triangular distributions were used to integrate expert estimates due to absent or incorrect process duration data. Datasets were further used for model development, initial parameterization and final validation of the model. The process flow, working times and process durations as well as other logic sequences were either directly observed or documented in interview reports and displayed in business process diagrams to initialize the implementation of the agent flow through the supply chain.

On the one hand, stochastic effects induced by natural disturbances such as windstorms and high snow cover are considered through respective scenarios with different production volumes (see 5. Strategies and Scenarios). On the other hand, supply chain risks leading to stochastic irregularities in wood harvest and transport are implemented through triangular distributions. The Transport and Terminal Modules include triangular distributions for process durations in minutes (Table 3) and truckload capacities (MIN = 20, MODE = 22, MAX = 30) in solid cubic meters. Based on expert interviews, the parameters for the triangular distribution of the unloading duration for trucks at the industry were increased for the storm scenario to take into account the considerable increased queuing times after storm events.

(Table 3: Simulation processes and their parameters for triangular distributions)

The input parameters for truck transport costs from forest landings to terminal including loading and unloading costs are provided for every district in Table 4. Moreover, Table 4 shows average transport costs of 15 supplied industries, where the individual transport costs range from 7.13 to 21.75 € per solid cubic meter. Multimodal transport costs from terminal to 17 forest based industry plants range from 6.21 to 14.67 with an average of 8.9 € per solid cubic meter.

(Table 4: Average truck transport costs (€ per solid cubic meter*)*

A great effort was invested in the verification and validation process of the simulation model to provide a sound basis for decision-making and establish credibility. To ensure, that the right model is being built and hot topics are addressed, a comprehensive problem formulation phase, case study, literature review and method selection was performed. For the verification of the model, professional and scientific experts were involved on a regular basis in the development of the simulation model. Therefore, methods such as structural, step-by-step walkthroughs, detailed animation during execution, a written assumption document and periodic discussions on core assumptions and visualization of critical processes in business process diagrams were used. Moreover, modular design, component testing, code review by more than one person, trace-driven debugging, output checks and model runs under simplified assumptions (for which true characteristics can be computed) were applied. In addition, frequent reruns of experiments, inclusion of warming up periods and usage of the same seeds for random generators as well as statistical analysis of input and output data, distribution fitting and extreme scenarios (e.g., use of very high/low parameters) were done. To validate the model, considerable effort was invested in expert involvement and appraisals. This proved to be the most promising approach to validate the simulation model because most of the available real life case study data did not match the necessary quality requirements and no equivalent literature data was available. In cooperation with experienced industry representatives, input- (e.g., close to reality parameter settings, restrictions, decision variables, case study settings) and output checks (e.g., realistic KPIs, transportation plans, volumes) were performed and the model and its results were further confirmed.

5. Strategies and Scenarios

The described simulation model offers a wide range of applications. Therefore, as a first step, three highly relevant practical scenario settings (Figure 9) representing different weather impacts on production and transport as well as a focus on multimodal versus unimodal transport strategies were defined in discussions at respective workshops with the Austrian industry partners. Therefore, a clear focus was set to observe system capacities (i.e., transported volume) and bottlenecks under similar system configurations (e.g., same production amounts) in every scenario. The first scenario setting, BAU, represents an average yearly production volume based on historical data. The production usually starts low at the beginning of the year and increases steadily to peak around the third quarter. One frequent occurring weather event is a high level of snow coverage in the first quarter of the year. The resulting impact due to difficulties in accessing harvesting areas are investigated in the SNOW scenario, which reduces the production of the BAU scenario in the first quarter by 75%. Nevertheless, the most influencing weather event is a windstorm as it immediately triggers high production. Therefore, the STORM scenario increases the production of the BAU scenario in the third quarter of the year by 300%.

(Figure 9: Weekly harvesting volumes according to the defined scenarios: snow in first quarter, storm in third quarter, business as usual)

Furthermore, three strategy options were compared on the basis of the same expert heuristic to generate the transport plan (decision variables: number of wagons and trucks) as well as same decision variables for transport priority (largest stock first) and maximal number of train pickups a day (1) to reflect a realistic setting for the case study region. The decision variable transport mode split was used to create three different transportation strategies. Strategy BOTH indicates combined multimodal and unimodal transport (50% multimodal and 50% unimodal transport), strategy MULTI, only multimodal transport and strategy UNI, only unimodal transport.

Firstly, for the expert based heuristic, the number of trucks per week was defined by dividing transport volume per week by 1.5 (the average truck drives per day) by 22 (the average truck payload per trip) and by 5 (the working days per week). Secondly, the number of wagons per day was calculated by dividing the number of trucks per week by two as two truckloads equal one wagon load. Lastly, to meet capacity restrictions of the supply chain, the initial solutions were adjusted to keep the maximum number of trucks per week equal to or less than 20 and the maximum number of wagons per day equal to or less than 9.

6. KPIs and Simulation Runs

To evaluate strategy performance under the different scenario settings, the results of these nine simulation outcomes (i.e., 3 different strategy options under 3 different scenarios) were compared according to the KPIs: transported volume (solid cubic meters), average delivery quota (%), stockyard volume (truckloads), average queuing time at terminal (minutes), average lead time (days), amount of fully loaded wagons, amount of half-loaded wagons, amount of empty wagons, CO_2 equivalents (t), fulfillment level (%), truck utilization (%) and transport costs per transported m^3 (€/m^3).

Therefore, transported volume defines the amount of wood that was transported from the forest to industry with both unimodal and multimodal transport. Average delivery quota combines the weekly delivery quotas, which were calculated by dividing the actual delivered transport amount of the actual week by the scheduled transport amount. If there was no production in a district in one week, the delivery quota was set to 1 (= 100%). Stockyard volume is a sum of the amount of truckloads at the stockyards of the four districts and at the train terminal. Average queuing time is the average of all waiting times of trucks at the train terminal. A waiting time arises if the terminal is fully utilized so that no other truck can enter the terminal or if another truck in the front needs longer processing time and blocks a truck in the back. Average lead time defines the average transport time from forest to industry for both unimodal and multimodal transport. The amount of fully loaded wagons reflects the number of train wagons that were successfully loaded before the scheduled train pick up, whereas half-loaded wagons and empty wagons are not picked up and, therefore produce additional standing costs, which were not represented in the model. CO_2 equivalents are the sum of emitted CO_2 equivalents calculated based on average distances from forest to terminal or industry customers, average speeds for truck transport considering road type and emissions KPIs (i.e., truck 148,8 g/Tkm and train 5,8 g/Tkm) for freight transport (Environment-Agency-Austria 2018). The applied truck emission values are at the upper end of range because in the mountainous case study region, the truck carriers use heavy trucks with cranes and four-wheel drive. Railcargo Austria uses electrified trains from renewable energy sources and, therefore the emissions are on the lower end of the range. The fulfillment level combines the fulfillment level of the four districts that were calculated by dividing the number of unfinished truck transport jobs by the number of scheduled transport jobs per week and subtracting the result from one. To calculate truck utilization, truck waiting time at the truck garage is counted by multiplying the number of unengaged trucks with waiting time. KPI truck utilization is calculated as one minus the quotient of total waiting time and working time. Finally, transport costs per transported cubic meter were calculated by dividing the overall transport costs by the transported amount of wood.

Interviews with managers of the AFF were conducted to rank the KPIs according to their importance. The transported volume was defined as the most critical KPI because harvested and not picked up wood is the major risk factor boosting bark beetle infestation and wood quality loss. Also the delivery quota was set as an important KPI because the key customers of the AFF are pulp- and paper industries, who crucially depend on a constant wood supply and, therefore impose penalties for unreliable deliveries. Furthermore, the managers complained about missing information on truck queuing times at wood terminals, which result in surcharges on truck carriers, who are subject to long waiting times at terminals, especially after windstorms.

In addition to these three critical KPIs, managers were also interested in stockyard volumes as well as lead times in order to get a clearer picture about potential wood quality loss, which is particularly relevant to their sawmill customers. Strained relations to the Railcargo Austria, forced the managers to complete the list of second level KPIs with half-loaded and empty wagons. Resilience was emphasized as a major focus for this study by managers and scientists and therefore, advantageous strategies have to outperform others in all three critical KPIs in all three scenario settings. These KPIs are highly relevant not only for the observed case study region, but also for Austria and Central Europe. Other KPIs such as fully loaded wagons and CO_2 emission were tracked to measure sustainability as well as efficiency with the KPIs fulfillment level, truck utilization and transport costs per transported cubic meter.

Every simulation run covered a simulation period of one year, with minutes as resolution time to match manager's requirements as well as common scientific practice (Kogler and Rauch 2018). Therefore, on every working day, wood-, truck- and train agents pass through the respective processes of the supply chain (Table 1), sometimes also for multiple times (e.g., truck picks up multiple truckloads at landings to load multiple wagons), resulting in complex interdependencies due to stochastic effects.

In a restricted Monte Carlo simulation, each of the nine scenario (BAU, SNOW, STORM) and strategy (BOTH, UNI, MULTI) combinations was executed 10 times to fulfill the defined stopping criterion. Lorscheid et al. (2012) recommended the coefficient of variation to determine the number of needed repetitions for a simulation scenario. Here, if the standard deviations for the critical KPIs transported volume, delivery quota and queuing time as target values are within an acceptable threshold of 5%, which is the number of repetitions that is estimated to sufficiently verify the robustness of results. Furthermore, this statistical threshold ensures simulation results that provide a sound basis for interpretations and conclusions.

7. Results

The results of 90 simulation runs, each covering a one year simulation period (with minutes as resolution time) are presented in Table 5, providing average values for each scenario and strategy combination. Production volume (i.e., wood demand of the forest based industry) in the BAU scenario was 43,491 solid cubic meters. It is 7.3 % lower for the SNOW and 101% higher for the STORM scenario.

(Table 5: Results according to the most important key performance indicators (KPIs))

The strategy BOTH results in a high transported volume and delivery quota, but low queuing time, stockyard, lead time, number of half-loaded wagons and empty wagons. This holds true for all three scenario settings and only in the SNOW scenario MULTI reaches the same value for the delivery quota and UNI provides a slightly lower lead time. In all other cases, the strategy BOTH outperforms MULTI and UNI with respect to the three crucial and four second level KPIs and, therefore, proved to be resilient. MULTI performs with a high fulfillment level and number of full loaded wagons, but the lowest CO_2 equivalents resulting in good sustainability measures. In the BAU (SNOW) scenario, the CO_2 emissions of the MULTI strategy were 19.5% (18.6%) lower as in BOTH and 24% (25%) lower as in UNI. Also, in the STORM scenario, emissions are 15.4% lower compared with BOTH and 12.2% lower compared to UNI. Due to a higher transport volume of MULTI in the STORM scenario, the overall CO_2 emissions are higher compared to those in the BAU and SNOW scenario. Disadvantages of MULTI are high costs and long queuing times. The lead time of MULTI is around two times as high as the lead time of BOTH and only smaller than UNI in the STORM scenario. Truck utilization is highest and transport costs per transported cubic meter are lowest in all scenarios for UNI, indicating a high transport efficiency. In contrast, major disadvantages exist reducing resilience (e.g. stockyard, lead time in storm scenario) and sustainability (i.e., CO_2 equivalents). Additional KPIs (e.g., stored wood, truck utilization, number of wagons, lead and queuing time, and fulfillment level) were investigated and provided a valuable decision support especially for iterative adjustments of parameters and decision variables. Moreover, many KPIs are split into results for the four forest districts to allow detailed comparisons of, for example, multimodal (e.g., number of loaded and delivered wagons as well as loaded and delivered trains) or unimodal KPIs (e.g., number of loaded trucks, number of not delivered transport tasks and delivered transport tasks).

8. Conclusion and further research

The case study showed that wood supply chains are constantly changing as disturbances and supply chain risks are not the exception, but part of normal, yearly operations. In this context, resilience signifies the amount of stresses that a system can absorb without becoming radically transformed and unstable. In research, if one finds different levels of resilience, diversity is often mentioned. As an example, a forest with a diversity of plants is more resistant and more adaptable to negative environmental influences. As a result, a forest still remains a forest after a fire if the ecosystem is resilient, otherwise it would turn into a meadow. Similarities for supply chains can be found according to the combination of diverse transport modes enhancing the resilience of a system. The combination of multimodal as well as unimodal transport strategies - each with its own advantages and disadvantages - provides the potential for a greener and more resilient wood supply.

The discrete event simulation model proves the advantage of such a combination of unimodal and multimodal transport. The related strategy BOTH outperforms others in all observed scenario settings and especially shows its strengths for resilience under challenging conditions like windstorms. It stands out in terms of critical (i.e, transported volume, delivery quota, queuing time) and second level KPIs (i.e., stockyard, lead time, half loaded wagons, empty wagons). Compared to strategy UNI, strategy BOTH reduces CO_2 emissions through train transport in different scenario settings but is more costly. Moreover, it avoids bottlenecks and ill-timed plans and fits perfectly in the observed case. Therefore, it indicates that in similar supply chain designs, including a train terminal can also perform well in other regions.

The additional transport capacities of trains as well as stockyards at the terminals are crucial to transport and manage high amounts of wood. Experienced truck drivers, who are able to navigate without GPS support on steep mountain roads are often the bottleneck in Austria. Therefore, they should be assigned for short transport distances to terminals, where the wood is transshipped to trains and not for long distances to industry. This strategy significantly reduces the risk for bark beetle infestation and helps to maintain wood quality. In a real life situation after windstorms, truck carriers often re-negotiate the former agreed transport price to compensate (sometimes dramatically) increasing queuing times for unloading at the industry. This additional costs can be reduced in multimodal supply chains because well managed terminals (e.g., time slots for delivery, appropriate system configuration regarding number of trucks and wagons) result in shorter queuing times (less than one hour in all scenario settings, based on simulation runs) than industry plants (up to three hours, based on expert estimations). Additional costs for queuing times were not implemented in the model. They would especially affect the strategy UNI in the STORM scenario and increase its low transport costs. The number of half-loaded and empty wagons is higher for MULTI compared to BOTH, especially in the STORM scenario, which indicates an ill-timed transport plan. But the relatively high number of half-loaded and empty wagons in both strategies could not be observed in reality and, therefore indicate that truck drivers in Austria might exceed their legal working hours limit per day or maximum legal payload, which are both strictly restricted in the simulation model.

In addition to the presented analyses, the simulation model was used to improve normal business conditions by finding best fits, test new strategies to adapt to changed conditions, figure out impacts of decisions before real, costly system changes are made and manage risks by preparing contingency plans. In particular, the intuitive usability of the simulation model through the animation view as well as the management cockpit was well-received by industry representatives, scientists and students at workshops.

Extensions and improvements such as new scenario settings and refined strategies as well as layout and capacity adaption and additional statistics provide many opportunities for future research. Scenario settings can include new production patterns as well as various impacts of natural disturbances or seasonal irregularities. In addition, other supply chain risks such as wood quality degradation, delivery stops, wagon availability and machine breakdowns should be observed. New strategies can include better fitting transport plans, which should be developed by detailed bottleneck analyses. According to its bad performance indicated by the KPIs, the expert-based heuristic to generate the transport plan for all scenario settings was not suitable for the MULTI scenario. In order to find better transport plans, a (meta) heuristic approach would be useful in future studies to generate transport plans that outperform the actual transport plans (rule of thumb refined by iterative expert involvement) that were applied in this study. Moreover, stock policy, number of train pickups, varying truck driver shift starting times and time slots for trucks at the terminal can improve the supply chain. A promising approach for a terminal capacity improvement would be a second truck lane at the terminal to allow arriving trucks to pass already unloading trucks in order to avoid queuing. Statistics regarding the distribution of the waiting times during one day could give additional information to find better strategies. Furthermore, closer modeling and detailed analyses of queuing- and lead time data are highly promising to influence the wood supply chain as they were not reported thus far. Finally, future research should concentrate on wood value and develop models enabling log value-tracking and interactive testing of harvesting and transport responses to challenging climate scenarios.

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9. Reference

Asikainen, A. 2001. Simulation of logging and barge transport of wood from forests on islands. International Journal of Forest Engineering **12**(2): 43-50. doi: https://doi.org/10.1080/14942119.2001.10702445.
Atashbar, N.Z., Labadie, N., and Prins, C. 2016. Modeling and optimization of biomass supply chains: a review and a critical look. IFAC-PapersOnLine **49**(12): 604-615. doi: http://dx.doi.org/10.1016/j.ifacol.2016.07.742.
D'Amours, S., Ronnqvist, M., and Weintraub, A. 2008. Using operational research for supply chain planning in the forest products industry. Infor **46**(4): 265-281. doi: http://dx.doi.org/10.3138/infor.46.4.265.
Environment-Agency-Austria. 2018. Comparison of transport emissions. Available from http://www.umweltbundesamt.at/fileadmin/site/umweltthemen/verkehr/1_verkehrsmittel/EKZ_Pkm_Tkm_Verkehrsmittel.pdf [accessed 23.11.2018].
Etlinger, K., Rauch, P., and Gronalt, M. 2014. Improving rail road terminal operations in the forest wood supply chain - a simulation based approach. *In* 16th International Conference on Harbor, Maritime and Multimodal Logistics Modelling and Simulation, HMS 2014. *Edited by* Y. Merkuryev and A.G. Bruzzone and F. Longo and M.A. Piera and D. Del Rio Vilas. Dime University of Genoa. pp. 199-206.
FHP. 2017. Overview of the Austrian forest-, wood-, and paper industry. Available from https://www.forstholzpapier.at/images/Downloads/FHP_english_2017.pdf [accessed 10.10.2018].
Gronalt, M., and Rauch, P. 2018. Analyzing railroad terminal performance in the timber industry supply chain – a simulation study. International Journal of Forest Engineering **29**(3): 162-170. doi: https://doi.org/10.1080/14942119.2018.1488913.
GIS-Steiermark. 2017. Digital atlas of the Austrian regional government in Styria [online]. Available from https://gis.stmk.gv.at/atlas/(S(mivxwbwxegg3nkbudgqp5ksr))/init.aspx?cms=da&karte=emptymap&layout=gisstmk&styles=gisstmk&template=gisstmk&gdiservices=hintergr,gel,dopags_tc,opbmgrau,opbm,uctc,opoverlay&sichtbar=_ortsplanGrau&gdiservices=kat,orient_adr.
Karttunen, K., Lättilä, L., Korpinen, O.-J., and Ranta, T. 2013. Cost-efficiency of intermodal container supply chain for forest chips. Silva Fenn **47**(4): 1-24. doi: https://doi.org/10.14214/sf.1047.
Karttunen, K., Vaatainen, K., Asikainen, A., and Ranta, T. 2012. The operational efficiency of waterway transport of forest chips on Finland's lake Saimaa. Silva Fenn **46**(3): 395-413. doi: http://dx.doi.org/10.14214/sf.49.
Kogler, C., and Rauch, P. 2018. Discrete event simulation of multimodal and unimodal transportation in the wood supply chain: a literature review. Silva Fenn **52**(4): 29. doi: https://doi.org/10.14214/sf.9984.
Lautala, P.T., Hilliard, M.R., Webb, E., Busch, I., Hess, J.R., Roni, M.S., Hilbert, J., Handler, R.M., Bittencourt, R., Valente, A., and Laitinen, T. 2015. Opportunities and challenges in the design and analysis of biomass supply chains. Environmental Management **56**(6): 1397-1415. doi: http://dx.doi.org/10.1007/s00267-015-0565-2.
Lorscheid, I., Heine, B.-O., and Meyer, M. 2012. Opening the 'black box' of simulations: increased transparency and effective communication through the systematic design of experiments. Computational and Mathematical Organization Theory **18**(1): 22-62. doi: http://10.1007/s10588-011-9097-3.
Mobini, M., Meyer, J.C., Trippe, F., Sowlati, T., Frohling, M., and Schultmann, F. 2014. Assessing the integration of torrefaction into wood pellet production. Journal of Cleaner Production **78**: 216-225. doi: http://dx.doi.org/10.1016/j.jclepro.2014.04.071.
Mobini, M., Sowlati, T., and Sokhansanj, S. 2013. A simulation model for the design and analysis of wood pellet supply chains. Applied Energy **111**: 1239-1249. doi: http://dx.doi.org/10.1016/j.apenergy.2013.06.026.
Opacic, L., and Sowlati, T. 2017. Applications of discrete-event simulation in the forest products sector: a review. Forest Products Journal **67**(3-4): 219-229. doi: http://dx.doi.org/10.13073/fpj-d-16-00015.
Rahman, A., Yella, S., and Dougherty, M. 2014. Simulation model using meta heuristic algorithms for achieving optimal arrangement of storage bins in a sawmill yard. Journal of Intelligent Learning Systems and Applications **6**(2): 125-139. doi: http://dx.doi.org/10.4236/jilsa.2014.62010.
Saranen, J., and Hilmola, O.-P. 2007. Evaluating the competitiveness of railways in timber transports with discrete-event simulation. World Review of Intermodal Transportation Research **1**(4): 445-458. doi: http://dx.doi.org/10.1504/writr.2007.017097.
Seay, J.R., and Badurdeen, F.F. 2014. Current trends and directions in achieving sustainability in the biofuel and bioenergy supply chain. Curr Opin Chem Eng **6**: 55-60. doi: http://dx.doi.org/10.1016/j.coche.2014.09.006.

Shahi, S., and Pulkki, R. 2013. Supply chain network optimization of the Canadian forest products industry: a critical review. American Journal of Industrial and Business Management 03(07): 631-643. doi: http://dx.doi.org/10.4236/ajibm.2013.37073.
Shahi, S., and Pulkki, R. 2015. A simulation-based optimization approach to integrated inventory management of a sawlog supply chain with demand uncertainty. Canadian Journal of Forest Research **45**(10): 1313-1326. doi: http://10.1139/cjfr-2014-0373.
Wolfsmayr, U.J., Merenda, R., Rauch, P., Longo, F., and Gronalt, M. 2016. Evaluating primary forest fuel rail terminals with discrete event simulation: a case study from Austria. Ann for Res 59(1): 145-164. doi: http://dx.doi.org/10.15287/afr.2015.428.
Wolfsmayr, U.J., and Rauch, P. 2014. The primary forest fuel supply chain: a literature review. Biomass Bioenerg 60: 203-221. doi: http://dx.doi.org/10.1016/j.biombioe.2013.10.025.

Table 1: Main inputs, processes and outputs of the simulation model

	INPUTS	PROCESSES	OUTPUTS
FOREST	production volume per day weekly production plan forwarding capacity forwarding time forest stockyard capacity landing stockyard capacity truckload size	generate wood queue wood batch wood forward truckload queue truckload	distribution of production amount stockyard at forest landing provided wood for transport per district
TRUCK	number of trucks transport cost to terminal transport cost to industry drive time to landing loading time transport time to terminal transport time to industry transport priority transport mode type (unimodal, multimodal, both)	generate trucks enter trucks delete trucks queue at truck garage queue at terminal pickup truckloads transport to industry transport to terminal drive to terminal drive to landing drive to garage	loaded trucks not delivered transport tasks delivered transport tasks fulfillment level truck utilization delivery quota
TERMINAL	remove belts time load wagon time secure wagon load time clean loading platform time complete delivery ticket time unload at terminal stockyard time unload at industry time capacity terminal stockyard	drive to loading siding remove belts pickup truckload from stockyard unload at wagon unload at stockyard secure wagon load clean loading platform complete delivery ticket queue at loading siding drive to garage drive to landing	stockyard terminal queuing time distribution of queuing times number of trucks at the terminal
TRAIN	number of train pickups transport cost to industry transport time to industry number of wagons	generate trains pickup wagons transport to industry delete trains	loaded wagons delivered wagons full loaded wagons half-loaded wagons empty wagons loaded trains delivered trains
INDUSTRY	unload at industry stockyard time	unlodad wagons at industry unload truckloads at industry delete wood	received wood CO_2 emissions transport costs lead times

Table 2: Decision Variables

DECISION VARIABLE	VALUES	EXPLAINATION
wagon	between 0 and 9	Number of ordered wagons, which will be delivered when the next train picks up loaded wagons at the terminal
truck	1 to 20	Number of trucks, which will be provided during operating hours
train pick up	1 or 2	Maximal number of train arrivals during a day to pick up full loaded wagons, drop off empty wagons and sort wagons according to their loading status at the terminal
transport mode split	%	Proportion of wood that is transported multimodal or unimodal
transport priority	largest stock or oldest wood	Trucks pick up wood first at the landing with the largest stockyard or the oldest wood

Table 3: Simulation processes and their parameters for triangular distributions (duration in minutes)

PROCESSES	MIN	MODE	MAX
drive to landing	10	46	83
load truck	30	35	40
truck transport to terminal	15	45	105
truck transport to industry	60	105	150
train transport to industry	1440	3258	10080
remove belts	7	10	12
load wagon	35	45	45
secure wagon load	5	8	10
clean loading platform	3	5	10
complete delivery ticket	10	13	15
unload at terminal stockyard	35	45	55
unload at industry (BAU and SNOW / STORM)	35 / 80	60 / 160	180 / 200

Table 4: Average truck transport costs (€ per solid cubic meter)

TRUCK TRANSPORT	DISTRICT 1	DISTRICT 2	DISTRICT 3	DISTRICT 4
to terminal	8.2	9.1	9.8	9.8
to industry	14.22	12.75	17.72	13.15

Table 5: Results according to the most important key performance indicators (KPIs)

SCENARIO	BAU			SNOW			STORM		
STRATEGY / KPI	**BOTH**	**MULTI**	**UNI**	**BOTH**	**MULTI**	**UNI**	**BOTH**	**MULTI**	**UNI**
transported (m^3)	41,581	37,563	39,771	38,360	35,082	37,628	86,651	80,258	75,469
delivery quota (%)	112	111	104	108	108	107	132	125	120
queuing time (minutes)	13.21	24.38	-	13.76	24.93	-	20.26	41.83	-
stockyard (truckloads)	66	225	158	67	195	111	0	183	487
lead time (days)	10.37	23.09	14.57	10.12	21.74	9.14	16.98	30.33	37.3
half-loaded wagons	85	92	-	81	90	-	140	310	-
empty wagons	77	119	-	77	106	-	107	338	-
full loaded wagons	437	819	-	398	751	-	913	1534	-
CO_2–eq (in million tonnes)	719	579	762	665	541	721	1,500	1,270	1,447
fulfillment level (%)	96	98	81	98	99	96	90	97	67
truck utilization (%)	80	80	97	79	79	97	79	78	99
transport costs per transported m^3	16.01	17.91	14.11	15.99	17.94	14.10	16.02	17.57	14.06

Figure 1: Process map of wood supply chain of the AFF

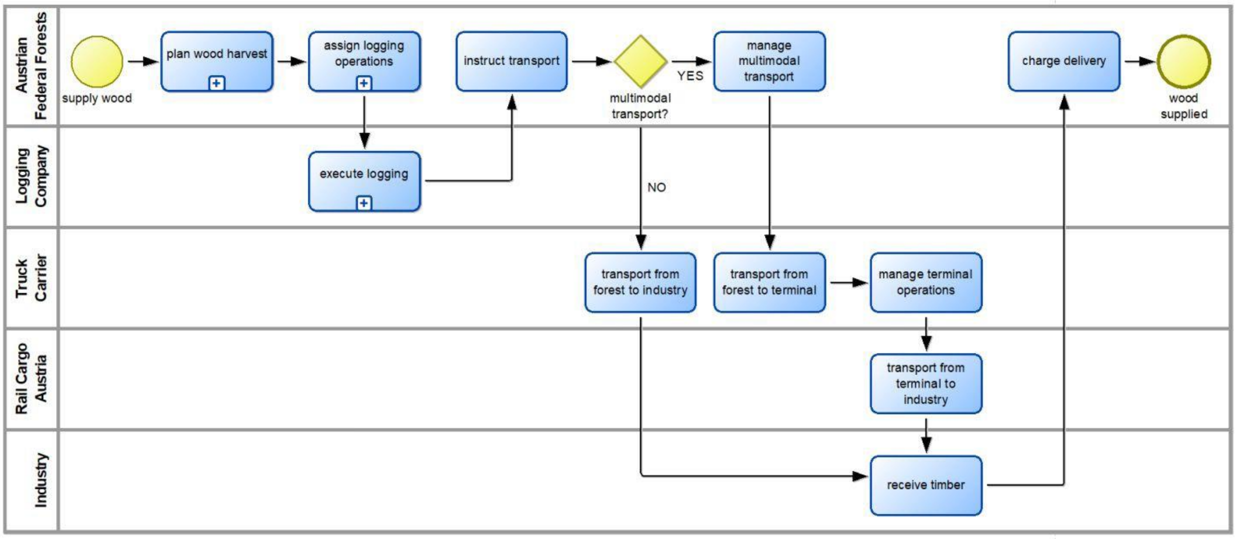


Figure 2: Aerial photograph of the terminal in Großreifling (modified from original photograph © GIS-Steiermark 2017, licensed under CC BY 3.0 AT)

Figure 3: Wood Supply Chain with multimodal and unimodal transport

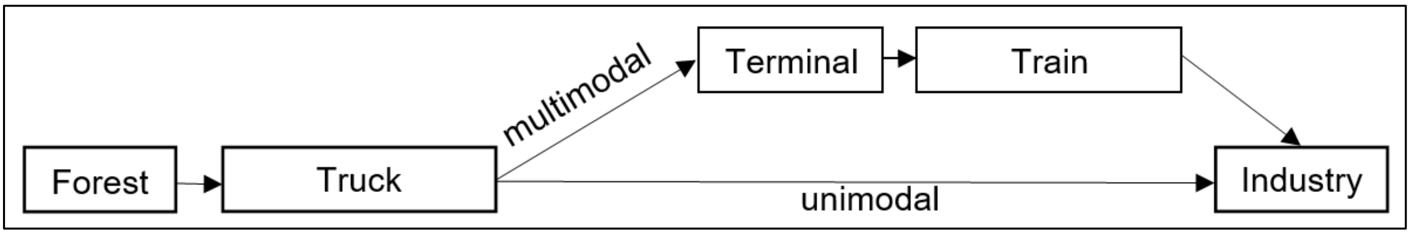


Figure 4: Wood flow

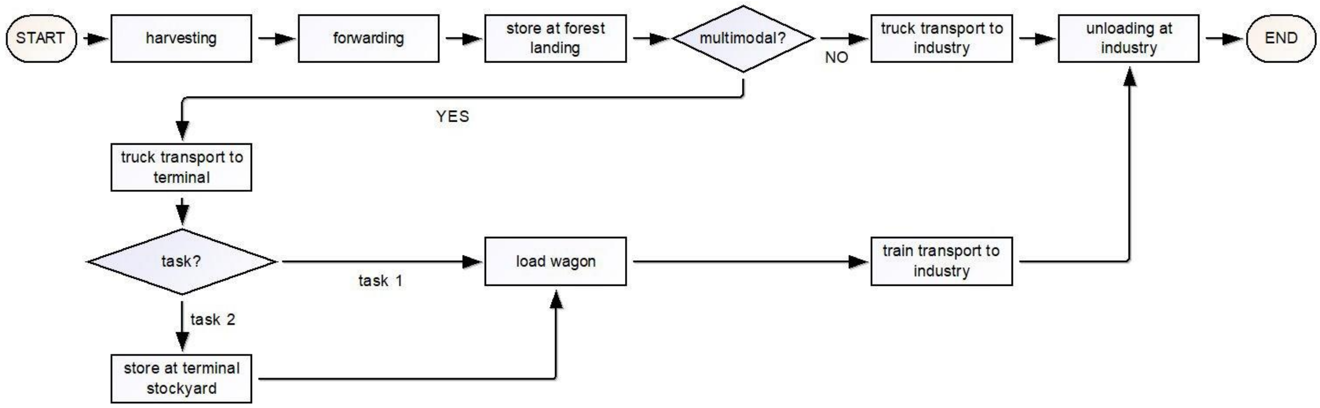


Figure 5: Truck flow

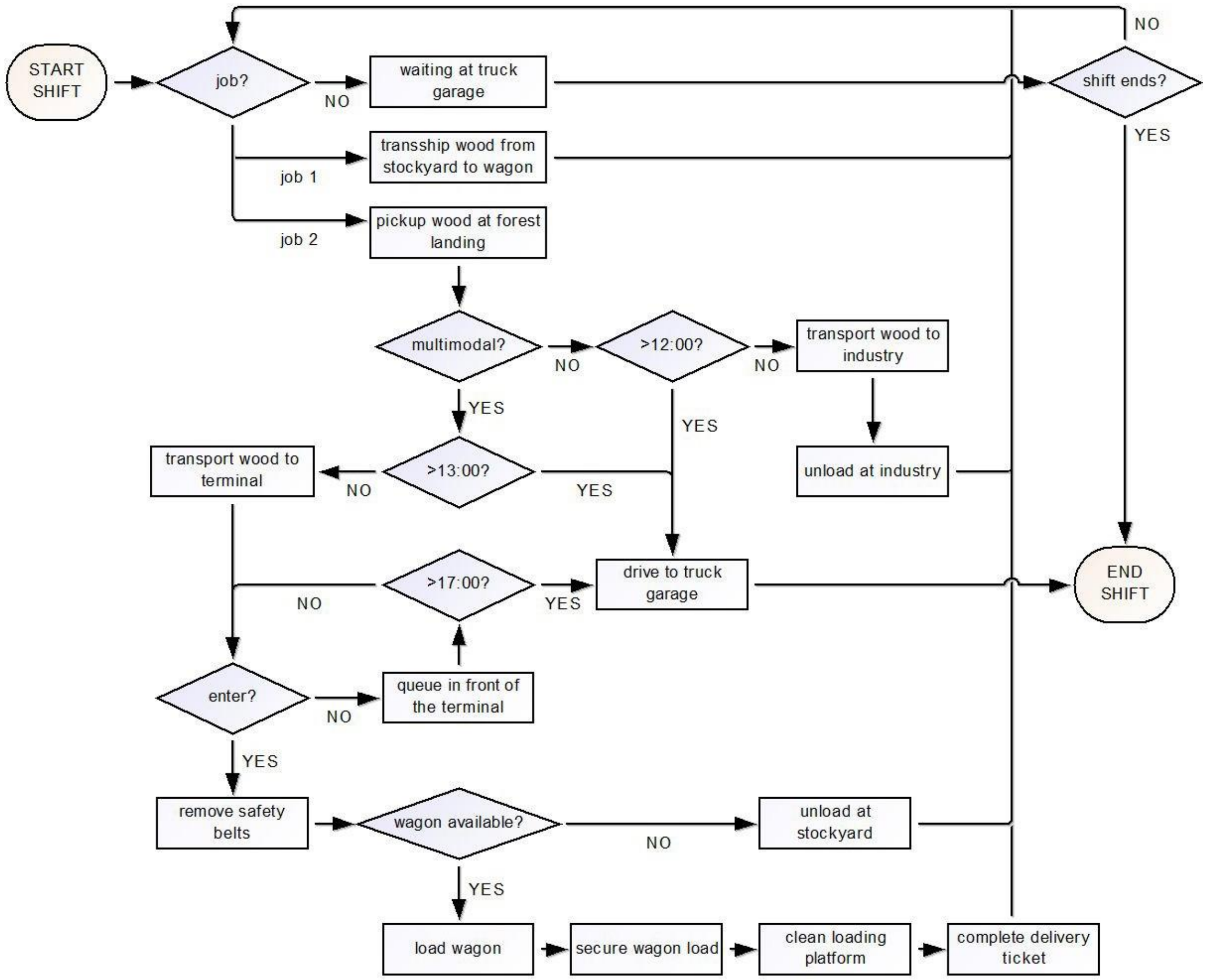


Figure 6: Animation view with truck garage, forests, landings, industry, terminal, trees (1 m3 wood), truckloads (20–30 m3 wood), trainloads, trucks and trains (modified from original photograph © GIS-Steiermark 2017, licensed under CC BY 3.0 AT)

Figure 7: Statistic view (management cockpit)

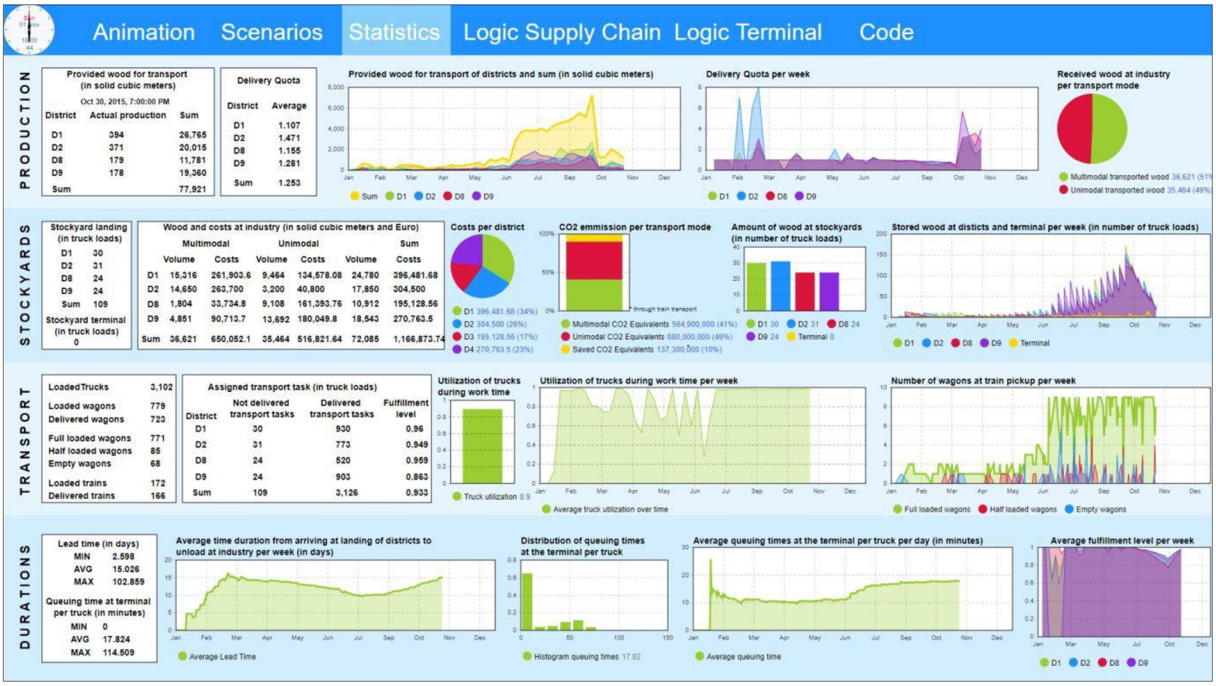


Figure 8: Parameterization view

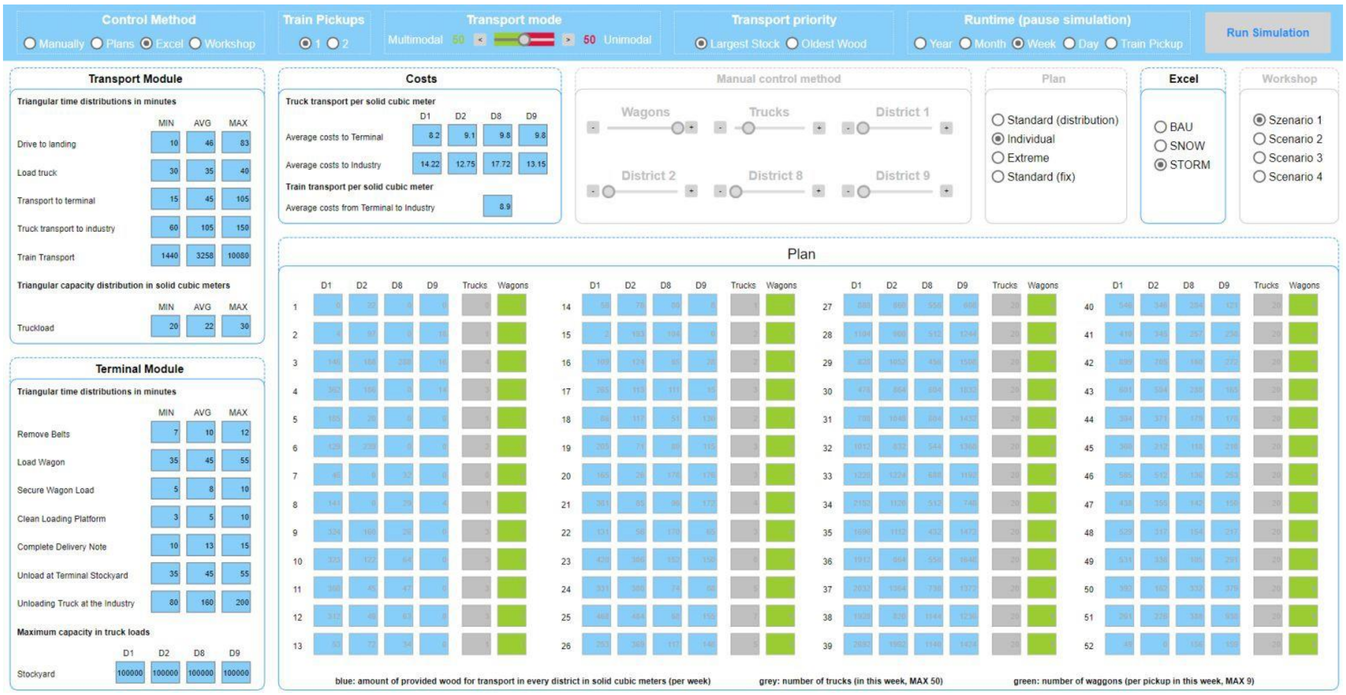
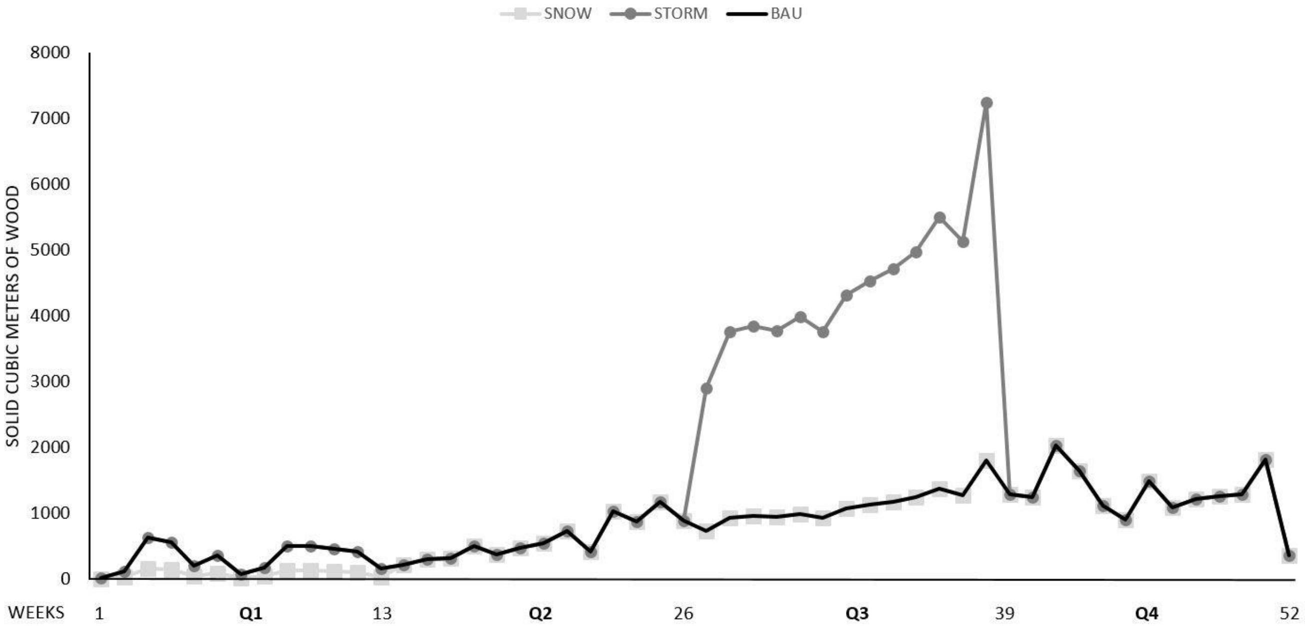
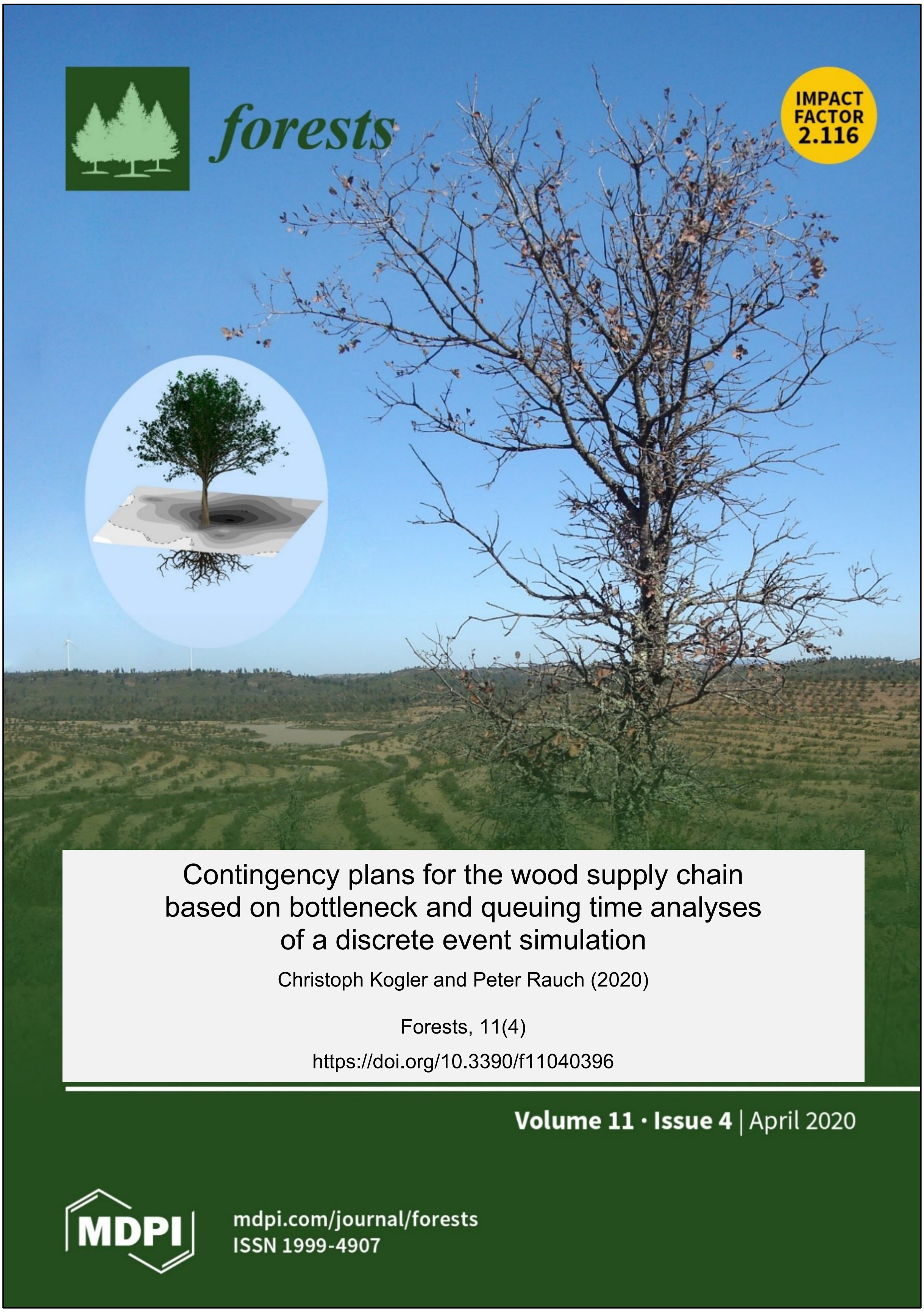


Figure 9: Weekly harvesting volumes according to the defined scenarios: snow in first quarter, storm in third quarter, business as usual



3.3 Contingency Plans for the Wood Supply Chain based on Bottleneck and Queuing Time Analyses of a Discrete Event Simulation



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Article

Contingency Plans for the Wood Supply Chain Based on Bottleneck and Queuing Time Analyses of a Discrete Event Simulation

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Abstract: Wood supply chain performance suffers from risks intensified by more frequent and extreme natural calamities such as windstorms, bark beetle infestations, and ice-break treetops. In order to limit further damage and wood value loss after natural calamities, high volumes of salvage wood have to be rapidly transported out of the forest. In these cases, robust decision support and coordinated management strategies based on advanced contingency planning are needed. Consequently, this study introduces a contingency planning toolbox consisting of a discrete event simulation model setup for analyses on an operational level, strategies to cope with challenging business cases, as well as transport templates to analyze outcomes of decisions before real, costly, and long-lasting changes are made. The toolbox enables wood supply managers to develop contingency plans to prepare for increasing risk events and more frequent natural disturbances due to climate change. Crucial key performance indicators including truck to wagon ratios, truck and wagon utilization, worktime coordination, truck queuing times, terminal transhipment volume, and required stockyard are presented for varying delivery time, transport tonnage, and train pick-up scenarios. The strategy BEST FIT was proven to provide robust solutions which saves truck and train resources, as well as keeps transhipment volume on a high level and stockyard and queuing time on a low level. Permission granted for increased truck transport tonnages was evaluated as a potential means to reduce truck trips, if working times and train pick-ups are coordinated. Furthermore, the practical applicability for contingency planning is demonstrated by highly relevant business cases such as limited wagon or truck availability, defined delivery quota, terminal selection, queuing time reduction, or scheduled stock accumulation. Further research should focus on the modeling and management of log quality deterioration and the resulting wood value loss caused by challenging transport and storage conditions.

Keywords: contingency planning; discrete-event simulation model; forest-based industry; logistics; multimodal transport; natural calamities; risk; supply chain management

1. Introduction

Wood is the only sustainable natural resource available in Austria [1]. Consequently, the forest-based industry is a crucial economic sector profiting from Austria's abundant forests, well-developed infrastructure, highly skilled workers, and a rich research environment, which enables export rates of 87% in the paper industry [2] and 70% in the wood industry [3]. For every additional 100 m^3 of wood harvested, a new green job is added to the 300,000 existing ones (i.e., 1/10 of Austria's working population: 175,700 forestry, 40,000 joineries, 27,900 wood industry, 23,000 timber trade, 11,400 timber construction, 8100 paper industry, 6000 forest management) [4]. To ensure economic success and sustainability and to secure the existing jobs, the industry is dependent on a stable wood supply. The current challenges of the Austrian wood supply chain include decreasing numbers of both crane-truck drivers and train terminals, rapid market price fluctuations, as well as long lead and queuing times. These challenges are reinforced by supply chain risks that may be technical (e.g., machine and truck breakdowns), managerial (e.g., delivery stops at mills and reliability of rail wagon delivery), or inclement weather (e.g., high snow cover, heavy rain, and low temperature).

Climate change increases the frequency and impact of extreme natural calamities which results in high volumes of salvage wood (more than 50% of the harvested wood in Austria in 2018 [5]) and an intensification of risk in the wood supply chain. The Austrian government in its Forest Strategy 2020+, recognized the risks to productivity and the economic deployment of Austria's forests and set the strategic goal of building and developing resilient risk management instruments and contingency plans [1]. Natural calamities such as windstorms, bark beetle infestations, and ice break treetops produce high volumes of salvage wood, which have to be quickly transported out of the forest to limit further damage or wood value loss. Train terminals have proven to be effective in securing a stable wood supply to the industry as they provide the high transport capacity of railroads and connected storage areas. In Austria there are 153 active train terminals (i.e., 60 wood industry terminals, 65 wood shipping terminals, seven private terminals, 12 temporary terminals, nine terminals with special status), and a considerable number of inactive but recoverable terminals, where wood can be transhipped from truck to train [6]. The management of such a multimodal wood supply chain is more challenging than that of a unimodal supply by utilizing trucks only. However, it reduces the effects of climate changes (e.g., CO_2 emissions), supply chain risks (e.g., buffer capacity to supply industry when harvesting is not possible), and supply chain challenges (e.g., reducing the bottleneck of crane truck capacity by limiting their operation to unavoidable short distance wood transport by trucks to terminals).

To provide decision support for the management of a multimodal supply chain, many companies in the forest-based industry have been trying to digitalize. Concepts such as Industry 4.0 and the internet of things (IoT) have inspired companies to collect large amounts of data, but in most cases they are not analyzed, shared, or used for the decision making process required to mitigate risks. For this reason, industry representatives are considering the development of digital twins of their supply chains. The term digital twin is used as an umbrella term and can be further divided in a wide range of maturity levels. Based on an earlier framework [7] steps for a virtual factory were defined [8], which are also generally appropriate for virtual supply chain models. They define a digital model as a virtual representation that reaches a connected model state (also designated as digital twin), if it is supplied with real-time data. Others define a digital twin as a "virtual representation of a real-world system and its status", distinguishing it from simple simulation models by "the ability to determine the state of a specific object", which is "achieved by combining current data from the subject with its simulation model" [9]. Based on these definitions, Austria's forest-based industry is a long way from creating a real digital twin or virtual supply chain. However, the first step in this direction can be made by creating digital models, which reduce uncertainty at a reasonable cost. This leads companies away from educated guesses and gut decision making based on rule-of-thumb estimates to decision making based on data already collected but not properly analyzed.

In the literature, digital models for multimodal wood supply chains including terminals have been delivered in the form of discrete event simulation (DES) models. DES fits perfectly for modeling the wood supply chain in a dynamic (i.e., variables change over time), discrete (i.e., system changes occur at specific events), and stochastic (i.e., random observations) way [10]. The wood supply chain covers growing, harvesting, extraction, transporting, storing, (pre-)processing, (re)using, and recycling of wood. Wood supply chain management deals with relevant decisions to plan, design, operate, control, and monitor material-, service-, financing-, and information flows within and between various actors [10]. Appropriately, the wood supply chain can be represented by standard DES elements such as entities or resources (e.g., wood, trucks, trains), delays (e.g., processes, tasks, service times), queues (e.g., waiting lines to enter terminal or industry stockyards), or system capacities (e.g., transport or stockyard capacity). Furthermore, DES is appropriate for advanced contingency planning because complex interdependencies can be modeled and visually illustrated in animations to demonstrate model internals to stakeholders. DES models for wood transport were reviewed and the suitability of multimodal DES models for building efficient, resilient, green and socially sustainable wood supply chains was confirmed [10]. Existing multimodal DES models including train terminals [11–15] cover timber, forest chip, or biomass transport at an operational level. They use different supply chain network configurations for regional case studies in Austria or Finland. Other multimodal DES models also consider vessel terminals [16–19]. These multimodal DES studies are important contributions to obtain a better understanding of the complex interdependencies of multimodal wood supply chains, yet none have focused on risk mitigation and generalizable contingency planning.

Especially after extreme natural calamities, when decisions have to be made quickly, there are neither coordinated plans nor elaborated management strategies available. As a result, supply chain performance suffers and will suffer even more due to risks intensified by more frequent and extreme natural calamities driven by climate change. Consequently, a research gap exists to derive concrete contingency plans for wood transport. To help close the current research gap, this study delivers elaborated contingency planning for train terminals based on DES. In particular, this study sets up a DES model to deliver crucial key performance indicators (KPIs) and develops transportation templates for different delivery time, tonnage, and train pick-up scenarios as a basis for contingency planning. Furthermore, contingency planning is illustrated by practical and highly relevant business cases. Consequently, it answers the research questions "Which parameters are critical for multimodal contingency planning?", "How many trucks and wagons are needed for short-, medium-, and long delivery times, respectively, with one or two train pick-ups to perform best", and "How many truck trips can be avoided, if the maximal transport tonnage increases and how would this effect the terminal performance"?

2. Method and Model

Simulation models facilitate understanding of complex systems and their behavior in a variety of scenarios. They provide superior benefits for managerial contingency planning in nonstationary systems under uncertainty in contrast to mental, conceptual, physical, or mathematical models. In simulation modeling, methods such as DES, agent based simulation (ABS), and system dynamics (SD) are general frameworks for mapping a real-world system [20]. DES focuses on manmade systems, where large and complex operations can be broken into a sequence of straightforward tasks or processes, which are often illustrated in flowcharts [21]. Moreover, different model configurations and what-if analyses show the effects of decisions before real, costly, dangerous, inefficient, or long-lasting changes are made and therefore provide valuable decision support for today's challenges.

The applied DES model is an extension of Kogler and Rauch [15] including a new generic model structure enabling generalizable results for various train terminals. The model was sufficiently validated including expert involvement, appraisals, real life case study data, input (e.g., restrictions, decision variables, case study settings), and output checks (e.g., transportation plans, volumes). Moreover, the identification of critical parameters resulted in the design of new scenario settings taking into consideration different delivery times, transport tonnages, and number of train pick-ups. Additionally, refined parameterizations, as well as an enhanced system logic now enable advanced contingency planning. The parameterizations of Kogler and Rauch [15] included only one broad triangular distribution for delivery times, which, for this study, was split into narrow triangular distributions for short, medium, and long delivery times to provide more appropriate configurations for different train terminals with various delivery times. This approach was also used for the parameterization of low, moderate, and heavy transport tonnages to evaluate permissions granted for higher truck transport tonnages. The implementation of a second train pick-up per day expanded the system logic, but required coordinating truck working times with train pick-ups to ensure a solution quality of both a truck utilization rate over 95% and no empty wagons at the time of train pick-up. Comprehensive sensitivity analyses for the decision variables (i.e., number of trucks and number of wagons) provide advanced multimodal transport plans which outperform the simple expert-based heuristic of Kogler and Rauch [15]. Furthermore, this study defines and calculates new KPIs, which are especially relevant for contingency planning.

The model maps the flow of wood entities through the supply chain by facilitating processes for wood harvest, storing at forest landings, truck transport to terminal, storing at terminal stockyard, transhipment to wagon, and train transport to industry (Figure 1).

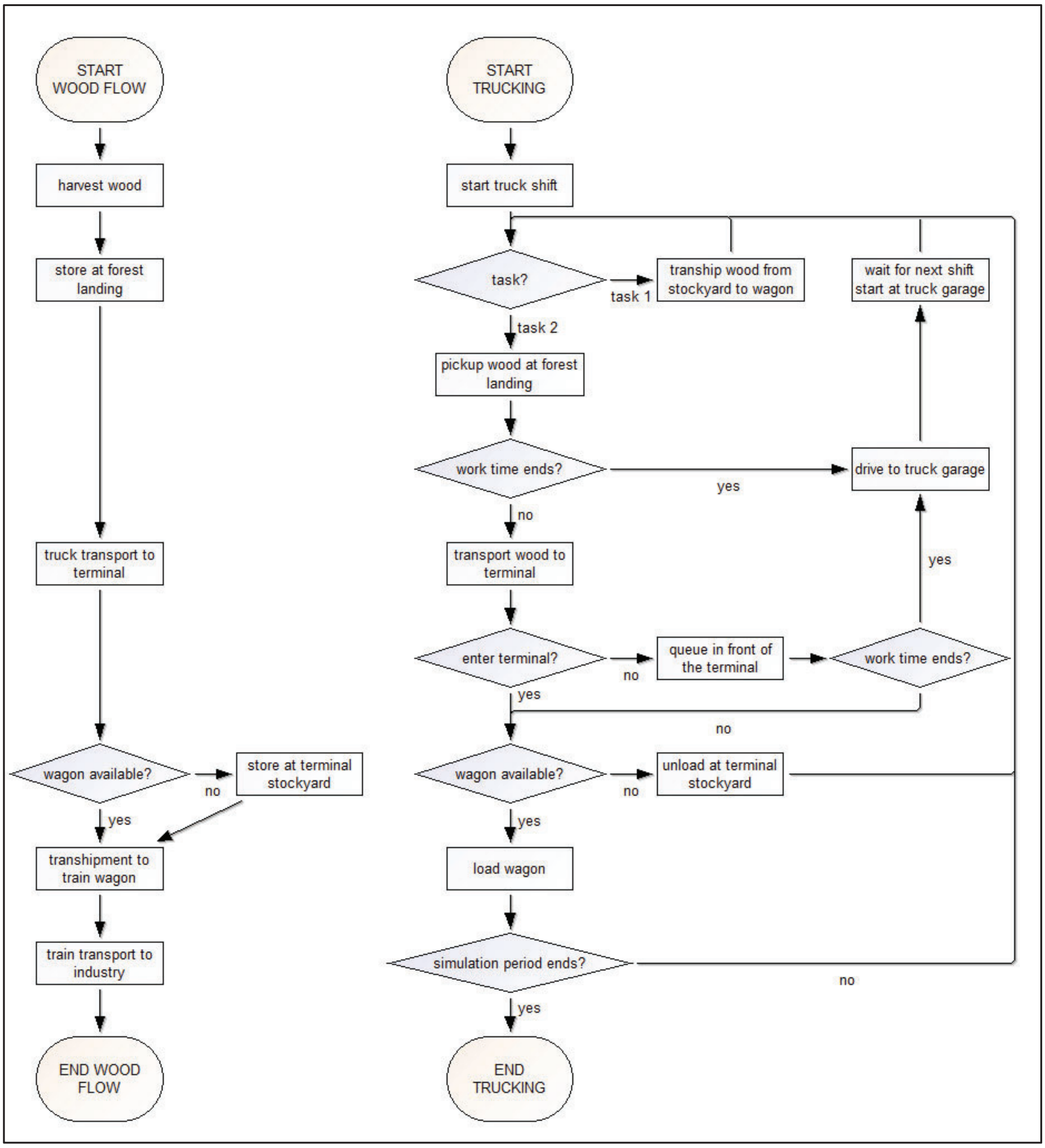

Figure 1. Flowcharts of the wood and transporting flows of the simulation model.

Trains and trucks move the wood during their working hours through the supply chain. Trucks fulfill the tasks of picking up wood at the forest landing and transporting it either directly to wagons or via terminal stockyards. The processes at the terminal are modeled in detail and close to reality, which enables the tracking of truck queuing times. Thus, the following activities are covered: Queuing in front of the terminal, removing safety belts, loading wagon, securing wagon load, unloading at stockyard, cleaning truck platform, and completing delivery documentation. Consequently, a complex logic controls the transhipment process from trucks to stockyard or wagons, as well as the potential truck queuing at the terminal. Trains pick up fully loaded wagons, transport them to industry, leave empty wagons for loading, and sort wagons according to their loading status at the terminal. For a detailed description of the DES model refer to Kogler and Rauch [15].

Sensitivity analyses of preliminary simulation runs indicated that results are sensitive to changes in delivery time from forest to terminal, number of train pick-ups at the terminal, and the transport tonnages. Consequently, these parameters were critical for multimodal contingency planning. Based on input data analysis (e.g., process times) of Austrian case studies and consultation with experts (i.e., foresters as well as wood, transport, and logistic managers), realistic parameter settings were specified, which lead to the formulation of scenarios to cover small-scale train terminals with similar layouts: One loading siding, no overtaking at the roughly elliptical inbound truck driving route, loading track length of maximum seven wagons, and two truckloads filling one wagon (Figure 2). This represents the majority of Austria's train terminals for wood transhipment.

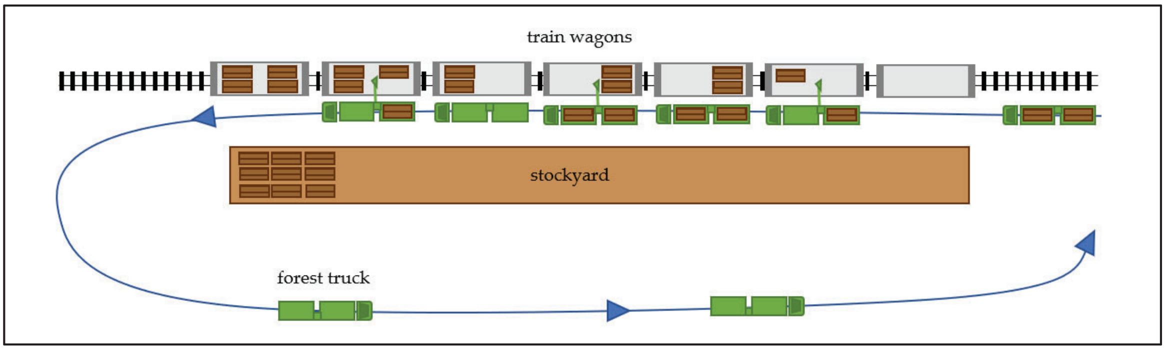

Figure 2. General layout of small scale train terminals displaying loading track, stockyard, and truck driving route.

Thus, simulating 18 scenario combinations (Table 1) covers a broad range of potential logistic cases and facilitates the generation of generalizable results as a basis for the development of robust transport strategies for contingency planning.

Table 1. 18 scenario settings for simulation.

One Train Pick-Up (P1)				Two Train Pick-Ups (P2)			
	Delivery Time (D)				Delivery Time (D)		
Tonnage (T)	P1D1T1	P1D2T1	P1D3T1	Tonnage (T)	P2D1T1	P2D2T1	P2D3T1
	P1D1T2	P1D2T2	P1D3T2		P2D1T2	P2D2T2	P2D3T2
	P1D1T3	P1D2T3	P1D3T3		P2D1T3	P2D2T3	P2D3T3

P = train wagons pick-ups: P1 = one a day, P2 = two a day. T = tonnage of forest trucks equipped with crane: T1 = low (MIN = 23 t/MODE = 24 t/MAX = 25 t), T2 = moderate (26/27/28), T3 = high (29/30/31). D = delivery time to train terminal: D1 = short (MIN = 5 min/MODE = 10 min/MAX = 15 min), D2 = medium (35/40/45), D3 = long (65/70/75).

The truck delivery time covers categories representing regions with short-, medium-, and long delivery times between forest landings and terminal. Triangular distributions were used to take into account different street and traffic conditions and possible process delays (Table 2).

Table 2. One way truck delivery time.

Delivery Time	Drive Time (min)			Number of Trips Per Truck Per Day
	MIN	MODE	MAX	
short	5	10	15	3–4
medium	35	40	45	2–3
long	65	70	75	1–2

Scenarios for low, moderate, and high truck loads were designed to consider actual weight limits (e.g., 44 t in Austria) for forest trucks equipped with a crane, as well as exemption clauses granted by the authorities after massive windthrows with bark beetle burdens or potential future liberalization. For heavier tonnages one additional minute of loading/unloading time per additional ton was assumed. A truck driver cannot exactly estimate the weight of the loaded wood due to natural variations in bulk density and moisture content, as well as a lack of crane scales in the majority of Austrian forest trucks. Consequently, the variation was implemented applying triangular distribution of tonnages and dependent process times (Table 3). General truck tasks at the terminal such as removing belts (i.e., MIN = 7 min/MODE = 10 min/MAX = 12 min), securing wagon loads (i.e., 5/8/10), cleaning loading platform (i.e., 3/5/10), as well as completion of delivery documentation (i.e., 10/13/15) are the same in all scenarios [15].

Table 3. Truck tonnages and dependent process times.

Transport Tonnages	Tonnage (t)			Load Truck Time (min)			Unload Time at Stockyard/Wagon (min)		
	MIN	MODE	MAX	MIN	MODE	MAX	MIN	MODE	MAX
low	23	24	25	30	35	40	35	45	55
moderate	26	27	28	33	38	43	38	48	58
high	29	30	31	36	41	46	41	51	61

Once or twice a day, a locomotive picks up full loaded wagons and provides the number of ordered empty wagons. Train pick-up times are fixed by the train carrier at 9 am and 3 pm (i.e., for two pick-ups). The start of truck shifts was coordinated with delivery times and train pick-ups resulting in a high ratio of fully loaded wagons at the time of a train pick-up. This ensures high truck utilization, as well as high terminal handling volume. Trucks start their shift at 7 am (adjusted to 5 am for medium and long delivery time scenarios with two train pick-ups) giving them enough time to fill the wagons before the first pick-up at 9 am. This approach of working time and train pick-up coordination was validated for its practical usability by terminal managers of the Austrian Federal Forests (i.e., largest forest owner in Austria) and Rail Cargo Austria (i.e., main cargo operator on Austrian railways), who confirmed similar strategies, if high terminal handling volume was needed after natural calamities. In accordance with European law, truck shifts were set to 8 h a day for five days a week.

Extensive test runs were performed to understand the interdependencies of the system and to select and track the most important KPIs for contingency planning. The resolution time was set as minutes and the simulation period as one week in order to both match manager's requirements and follow common scientific practice [10]. To ensure the predefined solution quality necessary for practical usability, all results that satisfy a truck utilization of over 95%, allow no empty wagons at the time of train pick-up and allow fewer than 20 half loaded wagons per week for one train pick-up (i.e., respectively 40 half loaded wagons for two train pick-ups). The simulations were replicated 52 times for every scenario to cover a full year of observation time. This resulted in 936 single simulation runs consisting of 52 weeks for a total of 18 scenarios.

2.1. KPIs and Transport Strategies

Four KPIs were identified as necessary to provide decision support for contingency planning. The KPI "terminal transhipment volume" defines the maximal amount of wood in solid cubic meters, which can be transhipped at the terminal from truck to wagon per week for a given truck and train wagon configuration. The KPI "required terminal stockyard" shows the amount of wood in solid cubic meters which is stored to guarantee a high truck and wagon utilization, as well as smooth wood flow from forest to the industry. The KPI "average queuing time" reports on the average truck waiting time in minutes at the terminal, which consists of the waiting times to enter the terminal, remove the safety belts, load the wagon or unload at the stockyard, and clean the loading platform. The KPI "maximal queuing time" reveals the longest waiting time in minutes for trucks to pass through the processes at the terminal.

Contingency planning requires the consideration of those KPIs, as well as reflection on the different, often competing objectives. In order to provide decision support for different planning objectives, various sets of KPI rankings were developed with stakeholder participation and analyzed for low tonnages and short, medium, and long delivery times. After extreme natural calamities the contingency planners are challenged to transport the wood out of the forest as fast as possible to avoid wood value loss. Consequently, the first strategy MAX VOLUME solely focuses on the maximal terminal transhipment volume. In cases where beneficial solutions had the same maximal terminal transhipment volume, the solution with the lowest number of wagons and trucks (i.e., decision variables) was selected to save resources. In some cases, contingency planners have to deal with terminals which do not provide space for a stockyard. Thus, the second strategy NO STOCKYARD was developed, which selects a solution where no stockyard is needed (i.e., if there are no solutions with no stockyard availability, the one with the lowest stockyard was chosen). From those solutions with the lowest stockyard, the one with the highest transhipment volume was chosen. The resulting solutions performed well according to their main KPIs, but also showed limitations regarding others. Thus, the MAX VOLUME strategy requires high transport resources. This also holds true in some cases for the NO STOCKYARD strategy, which provided comparatively low transhipment volume. Consequently, a third strategy BEST FIT was developed. In order to save both truck and train resources and to simultaneously keep transhipment volume on a high level, solutions with an up to 10% lower maximal transhipment volume were considered. Among all feasible solutions the one with the lowest number of wagons and trucks was selected, and if these were equal the solution with the lowest required stockyard was chosen.

2.2. Business Cases for Evaluating Managerial Impact

In order to evaluate the practicability of simulation results provided as tables as a basis for operational transport planning, three different business cases are formulated: (1) Restricted wagon availability, (2) restricted truck availability, and (3) defined delivery quotas. The first business case discusses the handling of restricted wagon availability. The terminal size limits the number of wagons for simultaneous transhipment and rail carriers define the maximal number of train pick-ups a day. However, after natural calamities or capacity planning errors (e.g., misjudgment of demand), as well as during harvesting periods of other train shipped goods such as beets, the number of available wagons can further decrease and fluctuate on a weekly basis. The transport templates should be used to find the appropriate number of trucks for a given number of train pick-ups, wagons, delivery time, and transport tonnage to guarantee an efficient (i.e., high volume and utilization, low resources and queuing times) wood transport.

The second business case provides a guideline for planning under restricted truck availability. In mountainous regions which have steep and widely ramified forest roads and lack GPS reception, planning should focus on a high utilization of the limited number of local forest truck drivers (= bottleneck), which are able to navigate through the forest road network. Here, the transport templates can be used to find an efficient number of wagons for a given number of train pick-ups, trucks, delivery time, and transport tonnage.

The third business case covers the common issue of defined delivery quotas. Wood based industry factories such as sawmills or pulp and paper mills, depend on a stable wood supply to guarantee smooth-running production. Furthermore, harvesting teams are dependent on constantly available transport to maintain enough space for harvested wood and its extraction (e.g., especially for cable logging to narrow mountain roads). Consequently, fixed delivery quotas are arranged to enable a smooth flow of wood. The transport templates permit the selection of an appropriate terminal, as well as transport configurations and provide KPIs in order to compare the effects of potential exemption clauses for higher transport tonnages after natural calamities.

3. Results

The managerial practice for operational wood transport planning follows a rolling weekly planning horizon. Thus, all results were aggregated to a weekly level and rounded to the nearest ten to provide a clear overview for short-term contingency planning. This approach allows contingency planners to react dynamically to changing conditions and restrictions after natural calamities or other disturbances. The numbers of available trucks and wagons are the main decision variables for contingency planners and thus, define the structure of the resulting templates (Appendices A and B; Tables 4–11; Figures 3 and 4).

Table 4. Best performing simulation results for strategy MAX VOLUME (maximal terminal transhipment volume) for one train pick-up.

Wagons	Number of Trucks			Terminal Transhipment Volume (m^3)			Required Terminal Stockyard (m^3)			Average Queuing Time (min)			Maximal Queuing Time (min)		
	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3
1	3	5	4	240	250	240	950	1070	320	20	10	70	120	120	120
2	3	2	4	490	470	470	710	0	130	10	0	60	110	70	110
3	3	5	6	730	710	730	360	530	170	10	10	60	70	70	120
4	9	4	9	980	940	980	2610	0	290	20	0	70	130	70	140
5	4	8	12	1220	1220	1180	0	770	430	20	10	80	90	80	150
6	12	12	12	1470	1470	1410	3000	1500	180	30	20	70	140	110	140
7	7	8	13	1710	1650	1640	830	160	0	10	10	70	80	80	140

Table 5. Best performing simulation results for strategy NO STOCKYARD (no or low required terminal stockyard) for one train pick-up.

Wagons	Number of Trucks			Terminal Transhipment Volume (m^3)			Required Terminal Stockyard (m^3)			Average Queuing Time (min)			Maximal Queuing Time (min)		
	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3
1	1	1	2	230	230	230	120	0	80	10	0	50	60	70	110
2	2	2	3	450	470	440	240	0	0	10	0	40	80	70	110
3	2	3	5	710	680	660	0	0	0	10	0	50	70	70	110
4	3	4	7	940	940	930	0	0	0	10	0	60	80	70	120
5	4	5	9	1220	1170	1170	0	0	0	20	10	60	90	100	130
6	4	6	11	1350	1350	1400	0	0	0	20	20	70	120	90	150
7	5	7	13	1630	1640	1640	0	0	0	20	30	70	130	110	140

Table 6. Best performing simulation results for strategy BEST FIT (at least 90% terminal transhipment volume) for one train pick-up.

Wagons	Number of Trucks			Terminal Transhipment Volume (m^3)			Required Terminal Stockyard (m^3)			Average Queuing Time (min)			Maximal Queuing Time (min)		
	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3
1	1	1	2	230	230	230	120	0	80	10	0	50	60	70	110
2	2	2	3	450	470	440	240	0	0	10	0	40	80	70	110
3	2	3	5	710	680	660	0	0	0	10	0	50	70	70	110
4	3	4	7	940	940	930	0	0	0	10	0	60	80	70	120
5	4	5	8	1220	1170	1100	0	0	0	20	10	50	90	100	120
6	4	6	10	1350	1350	1320	0	0	0	20	20	60	120	90	140
7	5	7	11	1630	1640	1490	0	0	0	20	30	60	130	110	140

Table 7. Strategy comparison for one train pick-up (in %).

Delivery Time	MAX VOLUME	NO STOCKYARD			BEST FIT		
		Short	Medium	Long	Short	Medium	Long
Number of trucks	100	−49	−36	−17	−49	−36	−23
Transhipment volume	100	−5	−3	−3	−5	−3	−7
Required stockyard	100	−96	−100	−95	−96	−100	−95
Average queuing times	100	−17	0	−17	−17	0	−23
Maximal queuing times	100	−15	−3	−5	−15	−3	−8

Table 8. Best performing simulation results for strategy MAX VOLUME (maximal terminal transhipment volume) for two train pick-ups.

Wagons	Number of Trucks			Terminal Transhipment Volume (m^3)			Required Terminal Stockyard (m^3)			Average Queuing Time (min)			Maximal Queuing Time (min)		
	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3
1	2	2	4	490	470	470	360	0	160	20	10	30	70	120	120
2	4	4	6	940	980	940	710	0	10	20	20	30	120	110	80
3	10	6	9	1420	1410	1470	2500	0	10	30	20	30	130	110	90
4	11	8	12	1880	1880	1880	2410	0	0	30	20	30	120	120	160
5	11	10	15	2390	2350	2360	1750	0	0	40	20	40	140	120	170
6	13	12	18	2830	2820	2820	1910	0	0	30	20	50	150	130	180
7	12	15	21	3300	3430	3300	1100	130	0	30	30	60	130	190	250

Table 9. Best performing simulation results for strategy NO STOCKYARD (no or low required terminal stockyard) for two train pick-ups.

Wagons	Number of Trucks			Terminal Transhipment Volume (m^3)			Required Terminal Stockyard (m^3)			Average Queuing Time (min)			Maximal Queuing Time (min)		
	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3
1	1	2	2	240	470	360	120	0	0	0	10	20	50	120	70
2	3	4	5	930	980	820	190	0	0	20	20	20	100	110	80
3	2	6	8	830	1410	1300	0	0	0	10	20	30	80	110	90
4	3	8	12	1170	1880	1880	0	0	0	20	20	30	110	120	160
5	5	10	15	1710	2350	2360	0	0	0	10	20	40	90	120	170
6	7	12	18	2460	2820	2820	0	0	0	20	20	50	110	130	180
7	8	14	21	2820	3300	3300	0	0	0	20	20	60	100	120	250

Table 10. Best simulation results for strategy BEST FIT (at least 90% terminal transhipment volume) for two train pick-ups.

Wagons	Number of Trucks			Terminal Transhipment Volume (m^3)			Required Terminal Stockyard (m^3)			Average Queuing Time (min)			Maximal Queuing Time (min)		
	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3
1	2	2	3	490	470	460	360	0	20	20	10	20	70	120	80
2	3	4	6	930	980	940	190	0	10	20	20	30	100	110	80
3	4	6	9	1310	1410	1470	100	0	10	10	20	30	100	110	90
4	6	8	11	1770	1880	1760	430	0	0	20	20	30	110	120	160
5	8	9	14	2180	2120	2240	690	0	0	20	20	40	110	130	170
6	9	11	16	2650	2590	2590	500	0	0	20	20	40	120	120	180
7	10	14	18	2990	3300	3060	380	0	0	20	20	50	120	120	190

Table 11. Strategy comparison for two train pick-ups (in %).

Delivery Time	MAX VOLUME	NO STOCKYARD			BEST FIT		
		Short	Medium	Long	Short	Medium	Long
Number of trucks	100	−54	−2	−5	−33	−5	−9
Transhipment volume	100	−23	−1	−3	−7	−4	−5
Required stockyard	100	−97	−100	−100	−75	−100	−78
Average queuing times	100	−50	−7	−7	−35	−7	−11
Maximal queuing times	100	−26	−8	−5	−15	−8	−10

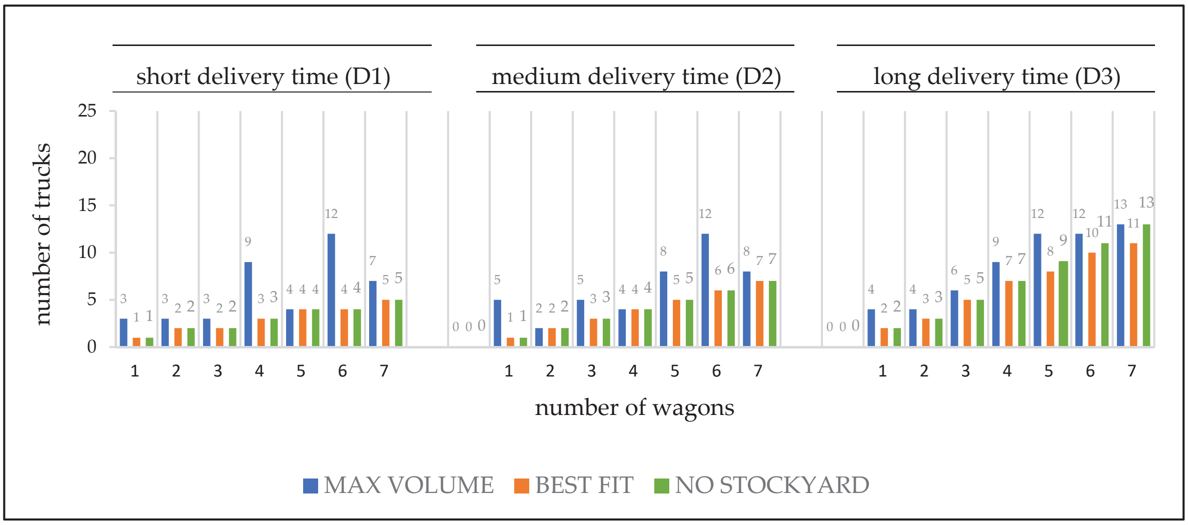

Figure 3. Best performing truck to wagon ratios for one train pick-up and low tonnages regarding three strategies.

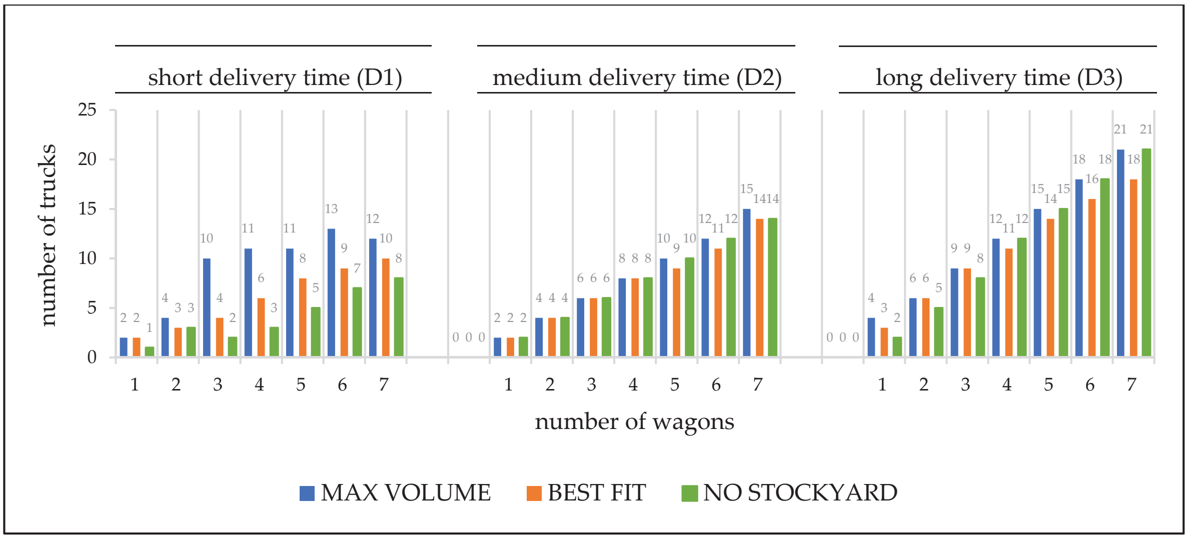

Figure 4. Best performing truck to truck ratios for two train pick-ups and low tonnages regarding three strategies.

For the one train pick-up scenario the BEST FIT strategy provided the lowest number of trucks per wagon, closely followed by the NO STOCKYARD strategy, which performed worse for long delivery times whenever it goes beyond four wagons (Figure 3). Moreover, the BEST FIT strategy reduced the number of trucks compared to the MAX VOLUME strategy and transhipped similar amounts of wood (Table 7). Additionally, both the BEST FIT strategy and the NO STOCKYARD strategy reduced the required stockyard compared to the MAX VOLUME strategy. The BEST FIT strategy also outperformed MAX VOLUME, as well as the NO STOCKYARD strategy with regard to queuing times.

Two train pick-ups show a more diverse picture, because the lowest number of trucks per wagon switches between the BEST FIT strategy with 12 times lowest value and the NO STOCKYARD strategy with 15 times lowest value (Figure 4). If the MAX VOLUME strategy is used as a benchmark, on the one hand, the number of trucks is lower for the BEST FIT strategy and the NO STOCKYARD strategy (Table 11). On the other hand, the transhipment volume is slightly lower for the BEST FIT strategy, but drops sharply for short delivery times for the NO STOCKYARD strategy. Regarding the required terminal stockyard the NO STOCKYARD strategy outperforms BEST FIT strategy. For queuing times, the BEST FIT strategy outperforms for long delivery time, and the NO STOCKYARD strategy for short ones.

A framework for beneficial wagon to truck ratios is provided in Figure 3 for one train pick-up and Figure 4 for two train pick-ups. High quality solutions can be compared and selected according to the main contingency planning objective and strategy. Thereby, the framework is complemented by the transport configuration tables (Tables 4–6 and 8–10), as well as transport templates (Appendices A and B) where KPIs can be compared in detail. For instance, it can be observed that the MAX VOLUME strategy builds up higher stockyards and thus, also more trucks and wagons are needed. Simultaneously those figures and tables are also useful, if contingency planners have other customizable decision variables such as delivery time or to deal with transport capacity limitation such as fewer truck or wagon availability. For example, Figure 4 shows, that if there are only 10 trucks available to supply a terminal with seven wagons and two train pick-ups, only supplying forests with short delivery time to the terminal would enable full utilization of the terminal capacity. Moreover, decision support can be provided regarding terminal selection, if different terminals are available.

In business cases where higher transport tonnages are possible due to legislative changes or exemption clauses invoked by the authorities, the relevant KPIs can be looked up in the complete transport templates (Appendices A and B). Furthermore, the Appendix shows the potential for truck trip reduction. On average, the number of truck trips can be reduced by 6% for one train pick-up (short delivery time 9%/medium 8%/long 2%) and 10% for two train pick-ups (8%/11%/9%), when tonnages change from low to moderate. If tonnages change from low to high, the number of truck trips can be reduced by 10% for one train pick-up (14%/14%/7%) and 17% for two train pick-ups (14%/19%/16%). The distribution of the number of reduced truck trips per week is shown for one train pick-up in Figure 5 and two train pick-ups in Figure 6. In addition to tonnages and delivery times, the number of trucks in the system (i.e., higher for two train pick-ups), the number of wagons (i.e., from one up to seven), the average queuing times for one train pick-up (minutes: 20/12/74) and two train pick-ups (25/14/35) influence the number of reduced truck trips per week.

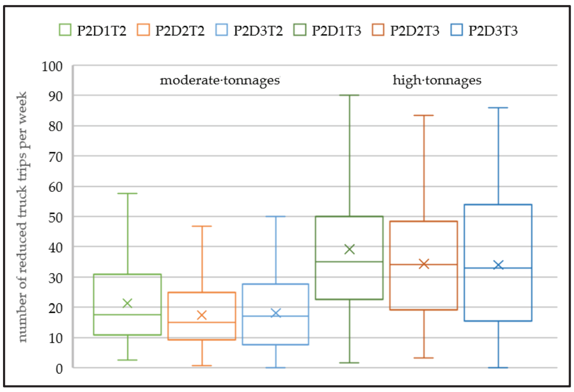

Figure 5. Reduced truck trips for one train pick-up. P = train wagons pick-ups: P1 = one a day, P2 = two a day. T = tonnage of forest trucks equipped with crane: T1 = low, T2 = moderate, T3 = high. D = delivery time to train terminal: D1 = short, D2 = medium, D3 = long.

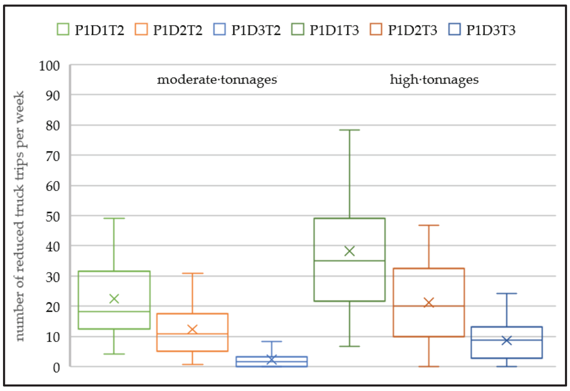

Figure 6. Reduced truck trips for two train pick-ups. P = train wagons pick-ups: P1 = one a day, P2 = two a day. T = tonnage of forest trucks equipped with crane: T1 = low, T2 = moderate, T3 = high. D = delivery time to train terminal: D1 = short, D2 = medium, D3 = long.

3.1. Contingency Planning Under Restricted Wagon Availability

The practical applicability of the simulation model for short-term transport and especially contingency planning is demonstrated by selected realistic business cases. For the first business case, contingency planning under restricted wagon availability, the transport templates can be used to find the appropriate number of trucks for a given number of train pick-ups (e.g., two), wagons (e.g., five), delivery time (e.g., medium), and transport tonnage (e.g., low). If there is no stockyard available, the corresponding transport template (Appendix Table A5) shows for 10 trucks a maximal weekly transhipment volume of 2350 m^3 and an average queuing time of 20 min, as well as a maximal queuing time of 120 min. If there are only five trucks available, a switch to only one train pick-up a day (Appendix Table A2) with a maximal transhipment volume of 1170 m^3 is the better option. For terminals with stockyards a controlled inventory accumulation at the train terminal (e.g., to prevent bark beetle infestation in the forest) can be achieved with one additional (11 trucks 250 m^3) or two additional (12 trucks 490 m^3) trucks per week. If truck carriers would not accept an average queuing time of 20 min (i.e., truck carrier paid per transhipped m^3 tries to use negotiation power due to limited transport options after natural calamities), the number of trucks could be reduced from 10 to 8 to lower the average queuing time to 10 min (resulting in a transhipment volume of 1890 m^3).

3.2. Contingency Planning Under Restricted Truck Availability

The second business case considers contingency planning under restricted truck availability, where transport templates can be used to find an efficient number of wagons for a given number of train pick-ups (e.g., two), trucks (e.g., five), delivery time (e.g., short), and transport tonnage (e.g., low). Without a stockyard available, five wagons can provide a transhipment volume of 1710 m^3, an average of 10 min, and maximal queuing time of 90 min (Appendix Table A4). If more wagons (e.g., seven) are available, one train pick-up (Appendix Table A1) may be an alternative (providing 1630 m^3, 20 min average, and 130 min maximal queuing time). In order to guarantee supply security from terminal to industry (e.g., restrictions in forest road usability due to snow, rain, or maintenance) buffer inventory at terminals with stockyards can be a strategic advantage. To build up inventory at a terminal supplied by five trucks, the number of wagons can be reduced to one, allowing a weekly stockyard accumulation of 1670 m^3 (Appendix Table A1) for one train pick-up and 1430 m^3 (Appendix Table A4) for two train pick-ups, respectively. If the queuing time for five trucks and wagons at the terminal needs to be reduced (e.g., because of negotiations or complaints), one train pick-up would lower the average queuing time to 10 min and the maximal queuing time to 80 min (transhipment volume 1130 m^3, required stockyard 600 m^3).

3.3. Contingency Planning Under Defined Delivery Quotas

The common issue of defined delivery quotas is showcased by the third business case. If a transport quota of 3300 m^3 per week is designated, it can be achieved by a terminal with two train pick-ups per working day providing seven wagons each. For short delivery time 12 trucks (Appendix Table A4), for medium14 trucks (Appendix Table A5), and for long 21 trucks are needed (Appendix Table A6). If it is possible to increase the transport tonnage from low to moderate, the quota could be fulfilled with 11 trucks for short, 13 trucks for medium, and 19 trucks for long distances. In case of an increase from low to high, for short delivery time 8 trucks, for medium 12 trucks, and for long 17 trucks would be sufficient. In order to classify the truck savings through multimodal transport, one scenario setting for a similar unimodal supply chain was calculated (i.e., drive time forest MIN = 35 min/MODE = 40 min/MAX = 45 min, drive time industry 145/150/155, unloading and queuing time industry 85/90/95; resulting in one trip per truck per day to achieve an equivalent truck utilization for comparable results). To achieve a unimodal transport quota of 3300 m^3 per week for low, moderate, and high tonnages the number of required trucks would be 28, 25, and 22 trucks, respectively.

4. Discussion

Comprehensive transport templates structured by main decision variables were proven to provide contingency planners with decision support for various conditions and objectives. Recommended transport configurations can be further refined by negotiations, legal adjustments, or process optimization that were not evaluated in the simulation model. Refinements by negotions may include modifying industry delivery quota to enable a higher utilization, providing additional transport capacity to fulfill required delivery quota, switching supply to an alternative forest region or adding additional train pick-ups. Legal adjustment could include the targeted use of over-time working to fill all wagons or exemption clauses regarding both worktime or tonnages to prevent bark beetle infestations. Further process optimization could be achieved by shorter process times, business process reengineering, learning curve or staggered shifts.

The results were obtained for rail terminal configurations that are typical for Austria's mountainous regions. Due to limited space there is usually only a single, short loading track for transhipping wood to few wagons. Therefore, developed measures and strategies cannot be generalized for conditions where rail terminal have more than one loading track and provide space for a whole block train as is common in other countries. Another important restriction is the one-way truck driving route within the rail terminal, which provides no possibility for passing, since this causes trucks to queue up. In order to support a detailed planning for similar rail terminal configurations, main input parameters of the simulation model such as legal payload for trucks and wagons need to be adapted. If these restrictions apply, the general findings can be transferred to provide support for basic contingency planning in other regions of the world.

For the purpose of discussing the findings in a broader scientific context, it is vital to mention that there are also DES studies, which concentrate on specific parts of the wood supply chain such as harvesting [22] and log yard logistics at industry sites [23,24]. These studies consider in greater detail modules for harvesting and industry site management. However, the simulation model of this study concentrates on the logistics of the wood supply chain and thus connects the initial harvesting and final industry consumption of those studies [22–24]. Furthermore, impacts of climate change and risks were simulated on a higher abstraction level with other methods for upstream processes such as primal tree planting, forest stand growths, and forest management, but the studies did not focus on supply chain management and wood logistic [25–28]. Others simulated wood supply chains and pointed out the resulting outcomes of risks such as raw material availability and quality [19], quality loss during storage [29], and oversupply [13,14], but did not focus on concrete contingency strategies and plans to give operative decision support to manage those risks. In the past, many studies observed biomass supply chains and concentrated on logistics for in-wood operations [30,31] and there are also contributions for moisture content reduction during in-wood storage for wood biomass feedstock [32], but they did not focus on discrete event simulation nor on multimodal timber transport.

In order to enable short-term contingency planning for multimodal wood supply chains, the terminal and queuing processes need to be modeled in detail. In a recent review [33], the simulation model of Kogler and Rauch 2019 [15] was described as "perhaps the most detailed railroad terminal study to date for the wood supply chain" (i.e., presumable Acuna et al. [33] accidentally interchanged the references of [10] and [15] in their paper). For this study, that model was further developed to cover identified sensible factors, as well as various scenario designs, KPIs, and strategies to provide robust results for a variety of small scale train terminals with different delivery times, train pick-ups, and tonnages. This was supported by comprehensive business process mapping and reengineering, which was also heavily used for other detailed DES studies in the wood supply chain [34,35].

The results indicate in line with Korpinen et al. [36] that higher truck transport tonnages provide potential to reduce truck trips and thus, transport costs and emissions. However, for political discourse further factors such as potential shifts from rail to road, traffic intensity, social compatibility, technical reliability, and unified competition regulations in the European Union have to be taken into consideration. In accordance with Eliasson et al. [37] emphasis was put on observing the impacts of transport distance, number of trucks in the system, and stockyards. Contrary to Eliasson et al. [37] staggered truck shifts were not implemented in this study, rather, truck shifts were coordinated with train schedules to guarantee high utilization. A potential for improvement could be the modeling of wood value loss during long lead times and the implementation of different delivery strategies [29]. Next to advantages such as buffer capacity and saved emission, terminals also show disadvantages such as higher costs, which were accordingly discussed for the wood assortment chips [38]. Managerial options such as staggered shifts, or targeted use of over-time working were not considered in this study but provide promising opportunities for further research. Another future approach is to focus on the modeling and management of log quality deterioration and the resulting wood value loss, caused by challenging transport (e.g., long lead times), as well as storage (e.g., weather, temperature) conditions.

5. Conclusions

The management of wood supply chains is a complex task facing many challenges such as decreasing forest truck transport capacity, lack of digitalization, and increasing risks of natural calamities due to climate change. The transhipment of wood from trucks to trains at terminals offers important strategy options and operational advantages including additional transport capacity, shorter truck queuing times at industrial sites, and reduced CO_2 emissions. Moreover, fewer bottlenecks caused by the limited availability of forest trucks equipped with cranes occur, since trucks are deployed on indispensible short-distance wood transport from forest landings to terminals rather than long trips to industry.

Simulation provides powerful methods to cover dynamic and interdependent changes and analyze bottlenecks and queuing times to support advanced short-term contingency planning. Consequently, this study introduced a toolbox consisting of a discrete event simulation model set up for analyses on an operational level, strategies to cope with challenging business cases, as well as transport templates and tables including critical parameters, decision variables, and KPIs to facilitate contingency planning.

Identified critical factors such as the number of wagons and trucks in the system, terminal transhipment volume, required terminal stockyard, average and maximal queuing times at the terminal, truck and train utilization, as well as worktime coordination provide useful decision support for a variety of objectives. The multiobjective transport planning strategy BEST FIT provides robust solutions which save truck and train resources, as well as keep the transhipment volume on a high and the stockyard and queuing time on a low level.

Furthermore, different planning conditions such as the number of train pick-ups, the delivery time from forest to industry (i.e., resulting in different number of truck trips per day), as well as the truck transport tonnage (i.e., varies between regions or due to exemption clauses) influence contingency plans. Thus, the transport templates presented provide a sound overview of beneficial (i.e., high truck and wagon utilization) solutions to compare alternatives and support developing customized plans. The results supported contingency planning in common business cases such as restricted wagon or truck availability, defined delivery quota, terminal selection, inventory accumulation, and queuing time reduction.

The simulation model provided a variety of supply chain configurations outcomes of decisions before real, costly, and wide-ranging changes have to be made. Consequently, simulation results provided a well performing configuration which can be fine-tuned in real life business and contingency cases. For example, the permission granted for higher truck transport tonnages (e.g., after natural calamities) was evaluated as a potential means to reduce truck trips.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Terminal transport template for one train pick-up, short delivery time, and all tonnages (P1D1 T1/2/3).

Wagons	Trucks	Terminal Transhipment Volume [1]			Required TERMINAL Stockyard [1]			Average Queuing Time [2]			Maximal Queuing Time [2]			Half loaded Train Wagons [3]			Reduced Truck Trips [3]	
		T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T2	T3
1	1	230	270	290	120	130	140	10	0	0	60	0	60	0	0	0	4	7
1	2	230	260	290	590	660	660	10	10	20	110	120	120	0	0	0	8	11
1	3	240	260	280	950	1060	1110	20	20	20	120	130	130	0	0	0	11	17
1	4	240	260	280	1310	1470	1560	20	20	30	130	140	130	0	0	0	15	24
1	5	240	260	290	1670	1870	2010	30	30	30	140	140	140	0	0	0	18	33
2	2	450	530	590	240	270	250	10	0	0	80	60	60	0	0	0	9	13
2	3	490	530	570	710	760	750	10	10	10	110	120	110	0	0	0	8	10
2	4	470	530	590	1190	1310	1290	10	10	20	110	120	130	0	0	0	15	18
2	5	470	530	590	1550	1710	1740	20	20	20	120	130	130	0	0	0	18	26
3	2	710	790	880	0	0	0	10	10	20	70	70	70	0	0	0	7	14
3	3	730	790	880	360	400	360	10	0	0	70	60	60	0	0	0	8	13
3	4	700	770	880	830	850	890	10	10	10	110	120	70	0	0	0	8	20
3	5	700	760	880	1300	1390	1380	10	10	20	110	120	120	0	0	0	13	22
3	6	730	790	880	1780	1940	1900	10	20	20	110	120	130	0	0	0	18	23
3	7	710	790	910	2140	2340	2360	20	20	20	120	130	130	0	0	0	23	35
3	8	700	790	880	2480	2740	2760	20	20	30	130	140	140	0	0	0	29	38
3	9	710	820	880	2780	3070	3210	30	30	30	130	140	130	0	0	0	33	50
3	10	700	820	880	3210	3500	3620	20	30	30	130	140	140	0	0	0	34	49
4	3	940	1060	1170	0	0	0	10	20	20	80	110	90	0	0	0	10	19
4	4	940	1060	1170	480	530	440	10	0	10	80	60	90	0	0	0	14	16
4	5	940	1020	1180	940	940	1000	10	10	10	110	110	70	0	0	0	7	25
4	6	940	1020	1180	1410	1430	1490	10	10	10	120	120	100	0	0	0	8	27
4	7	940	1060	1180	1900	2000	2000	10	20	20	120	120	120	0	0	0	18	28
4	8	940	1060	1170	2300	2480	2490	20	20	20	130	130	130	0	0	0	25	35
4	9	980	1060	1130	2610	2830	2920	20	20	20	130	140	130	0	0	0	25	38
4	10	940	1020	1180	2870	3160	3270	30	30	30	150	140	140	0	0	0	31	53
4	11	940	1090	1170	3350	3630	3730	20	20	30	130	150	150	0	0	0	36	51

Table A1. *Cont.*

Wagons	Trucks	Terminal Transhipment Volume [1]			Required TERMINAL Stockyard [1]			Average Queuing Time [2]			Maximal Queuing Time [2]			Half loaded Train Wagons [3]			Reduced Truck Trips [3]	
		T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T2	T3
5	4	1220	1320	1470	0	0	0	20	20	20	90	90	110	0	0	0	8	21
5	5	1130	1330	1470	600	660	540	10	0	10	80	60	70	0	0	0	22	23
5	6	1170	1370	1470	1060	1070	1090	10	10	10	120	70	70	0	0	0	18	28
5	7	1170	1320	1470	1540	1510	1630	10	10	10	110	110	80	0	0	0	10	33
5	8	1180	1320	1420	1880	2020	2070	20	20	20	120	120	120	0	0	0	23	36
5	9	1170	1320	1470	2320	2480	2550	20	20	20	120	130	130	0	0	0	26	44
5	10	1170	1320	1470	2670	2920	2960	30	30	30	130	140	140	0	0	0	33	49
5	11	1170	1320	1510	2920	3210	3300	30	30	30	140	130	150	0	0	0	37	60
5	12	1120	1320	1420	3340	3680	3850	30	30	30	130	150	140	0	0	0	45	68
6	4	1350	1620	1740	0	0	0	20	20	20	120	140	120	0	0	0	23	33
6	5	1410	1580	1700	20	0	0	20	20	30	160	130	130	0	0	0	13	23
6	6	1410	1580	1770	720	770	620	10	0	10	70	60	70	0	0	0	18	22
6	7	1410	1580	1830	1170	1200	1190	10	10	10	120	70	70	0	0	0	17	37
6	8	1410	1580	1760	1560	1590	1690	20	10	10	130	100	110	0	0	0	17	40
6	9	1410	1580	1820	1940	1990	2090	20	20	20	140	140	90	0	0	0	18	47
6	10	1350	1590	1690	2310	2450	2450	30	20	30	130	140	140	0	0	0	32	40
6	11	1410	1580	1760	2650	2890	2820	30	30	30	140	150	140	0	0	0	34	43
6	12	1470	1590	1750	3000	3300	3320	30	30	40	140	140	150	0	0	0	35	50
6	13	1410	1520	1700	3340	3730	3990	30	30	30	140	130	140	0	0	0	42	78
6	14	1350	1580	1760	3580	3890	4320	40	30	30	190	140	140	0	0	0	45	96
7	5	1630	1850	2120	0	0	0	20	20	30	130	160	150	0	0	0	18	41
7	6	1640	1850	2050	50	0	0	20	40	30	120	140	130	0	0	0	13	30
7	7	1710	1850	1990	830	890	680	10	0	10	80	60	110	0	0	0	17	11
7	8	1640	1910	2060	1230	1300	1270	10	10	10	130	100	110	0	0	0	28	38
7	9	1640	1910	2050	1680	1640	1740	20	10	10	130	120	130	0	0	0	19	39
7	10	1570	1850	2050	2060	2050	2200	20	20	20	140	130	130	0	0	0	23	52
7	11	1570	1850	2060	2430	2470	2560	20	20	20	150	140	140	0	0	0	27	52
7	12	1640	1850	2060	2760	2910	2900	30	30	30	140	140	140	0	0	0	30	47
7	13	1650	1850	1990	3080	3340	3400	30	30	30	140	140	150	0	0	0	38	55
7	14	1640	1850	2060	3400	3750	4160	30	30	20	150	140	130	0	0	0	47	98
7	15	1640	1850	2130	3510	3890	4320	40	40	30	200	140	140	0	0	0	49	108
7	16	1650	1850	2050	3640	4020	4460	50	50	40	210	150	140	0	0	0	48	102

[1] Average per week in solid cubic meters (rounded to the nearest ten). [2] In minutes (rounded to the nearest ten). [3] Average quantity per week.

Table A2. Terminal transport template for one train pick-up, medium delivery time, and all tonnages (P1D2 T1/2/3).

Wagons	Trucks	Terminal Transhipment Volume [1]			Required Terminal Stockyard [1]			Average Queuing Time [2]			Maximal Queuing Time [2]			Half Loaded Train Wagons [3]			Reduced Truck Trips [3]	
		T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T2	T3
1	1	230	260	290	0	0	0	0	0	0	70	70	70	0	0	0	3	5
1	2	240	260	290	280	270	300	10	10	10	70	70	70	0	0	0	1	6
1	3	240	260	300	540	540	600	10	10	10	80	130	80	0	0	0	2	10
1	4	230	260	290	800	820	890	10	10	10	80	150	130	0	0	0	4	13
1	5	250	260	280	1070	1100	1190	10	10	10	120	80	130	0	0	0	3	13
2	1	240	260	300	0	0	0	0	0	0	70	0	70	0	0	0	2	5
2	2	470	530	570	0	0	0	0	0	0	70	70	70	0	0	0	5	8
2	3	470	530	590	270	270	240	10	10	10	70	70	70	0	0	0	5	8
2	4	470	530	590	530	540	600	10	10	10	70	70	70	0	0	0	6	16
2	5	450	530	590	770	810	890	10	10	10	70	80	80	0	0	0	10	22
3	1	250	260	300	0	0	0	0	0	0	70	70	70	0	0	0	1	4
3	2	480	530	590	0	0	0	10	10	10	70	70	70	0	0	0	4	9
3	3	680	790	880	0	0	0	0	0	0	70	70	80	0	0	0	9	17
3	4	710	790	910	240	230	140	10	0	0	70	70	70	0	0	0	6	8
3	5	710	790	880	530	530	550	10	10	10	70	70	80	0	0	0	7	16
3	6	700	790	880	770	810	890	10	10	10	80	80	80	0	0	0	11	25

Table A2. *Cont.*

Wagons	Trucks	Terminal Transhipment Volume [1]			Required Terminal Stockyard [1]			Average Queuing Time [2]			Maximal Queuing Time [2]			Half Loaded Train Wagons [3]			Reduced Truck Trips [3]	
		T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T2	T3
3	7	710	790	880	1020	1080	1190	10	10	10	80	80	90	0	0	0	12	28
3	8	700	790	880	1270	1350	1490	10	10	10	80	150	150	0	0	0	14	33
3	9	700	790	880	1540	1630	1790	10	10	10	90	80	90	0	0	0	15	36
3	10	680	820	880	1830	1900	2090	10	20	20	90	140	150	0	0	0	18	38
4	2	500	530	590	0	0	0	0	0	0	70	70	70	10	10	10	3	8
4	3	750	760	910	0	0	0	10	10	10	80	80	80	0	0	0	1	13
4	4	940	1060	1210	0	0	0	0	0	0	70	70	80	0	0	0	10	23
4	5	940	1020	1180	220	210	20	10	0	0	80	70	70	0	0	0	6	3
4	6	940	1060	1170	510	510	440	10	0	10	70	80	80	0	0	0	10	13
4	7	940	1060	1170	780	800	850	10	10	10	80	90	80	0	0	0	12	25
4	8	940	1060	1170	1020	1070	1180	10	10	10	80	80	150	0	0	0	14	33
4	9	940	1060	1170	1280	1350	1470	10	10	10	140	150	150	0	0	0	16	35
4	10	940	1060	1140	1520	1630	1770	10	20	10	110	90	160	0	0	0	19	38
4	11	940	1060	1170	1770	1890	2070	20	20	20	140	140	160	0	0	0	20	44
5	3	740	800	880	0	0	0	10	0	0	80	70	70	10	10	10	5	12
5	4	950	1060	1170	0	0	0	10	10	10	80	80	80	0	0	0	9	18
5	5	1170	1270	1470	0	0	0	10	10	10	100	80	90	0	0	0	8	25
5	6	1180	1320	1470	190	130	0	0	0	0	70	80	100	0	0	0	7	8
5	7	1170	1270	1470	500	490	310	10	0	10	70	80	80	0	0	0	8	9
5	8	1220	1270	1460	770	780	730	10	10	10	80	100	90	0	0	0	5	17
5	9	1170	1320	1470	1020	1070	1090	10	10	10	80	140	90	0	0	0	17	31
5	10	1120	1320	1480	1270	1340	1410	10	10	10	100	100	100	0	0	0	23	42
5	11	1180	1320	1420	1510	1620	1660	20	20	20	110	140	100	0	0	0	21	33
5	12	1170	1320	1520	1760	1890	1970	20	20	20	100	140	160	0	0	0	23	47
6	4	950	1060	1170	0	0	0	10	0	0	80	80	80	10	10	10	9	18
6	5	1180	1330	1420	0	0	0	20	20	20	90	90	90	0	0	0	13	20
6	6	1350	1650	1760	0	0	0	20	20	20	90	90	90	0	0	0	25	34
6	7	1410	1640	1770	160	60	0	0	0	10	70	80	100	0	0	0	11	17
6	8	1410	1530	1760	500	430	150	10	10	10	100	90	90	0	0	0	4	0
6	9	1410	1580	1820	770	760	530	10	10	10	80	100	90	0	0	0	13	14
6	10	1350	1590	1750	1020	1050	900	10	10	10	120	100	100	0	0	0	23	23
6	11	1350	1580	1770	1250	1320	1250	20	10	20	110	110	110	0	0	0	25	35
6	12	1470	1520	1760	1500	1600	1540	20	20	20	110	170	180	0	0	0	13	28
6	13	1410	1590	1760	1750	1870	1810	20	20	20	160	160	180	0	0	0	25	34
6	14	1410	1590	1760	1980	2130	2080	30	20	30	160	170	170	0	0	0	28	38
7	5	1190	1320	1470	0	0	0	10	10	10	90	80	80	10	10	10	11	23
7	6	1420	1580	1760	0	0	0	20	20	10	90	90	90	0	0	0	13	28
7	7	1640	1850	2060	0	0	0	30	30	30	110	110	90	0	0	0	18	35
7	8	1650	1850	2040	160	20	0	10	10	10	80	120	100	0	0	0	5	19
7	9	1640	1850	2050	480	380	20	10	10	10	100	100	100	0	0	0	9	0
7	10	1640	1910	1980	770	710	430	10	10	10	100	100	150	0	0	0	18	0
7	11	1650	1850	2060	1020	1010	760	10	10	10	110	100	170	0	0	0	16	13
7	12	1570	1850	2120	1260	1300	1100	20	10	20	110	120	100	0	0	0	27	33
7	13	1640	1780	2060	1490	1570	1430	20	20	20	170	170	170	0	0	0	18	30
7	14	1570	1850	1980	1740	1830	1690	20	20	30	160	170	190	0	0	0	31	30
7	15	1640	1850	2050	1970	2080	1960	30	30	30	170	180	180	0	0	0	27	33
7	16	1640	1850	2120	2200	2350	2220	30	30	40	180	170	190	0	0	0	30	42

[1] Average per week in solid cubic meters (rounded to the nearest ten). [2] In minutes (rounded to the nearest ten). [3] Average quantity per week.

Table A3. Terminal transport template for one train pick-up, long delivery time, and all tonnages (P1D3 T1/2/3).

Wagons	Trucks	Terminal Transhipment Volume [1]			Required Terminal Stockyard [1]			Average Queuing Time [2]			Maximal Queuing Time [2]			Half Loaded Train Wagons [3]			Reduced Truck Trips [3]	
		T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T2	T3
1	2	230	260	300	80	30	10	50	60	70	110	110	110	0	0	0	0	0
1	3	230	260	290	190	160	150	70	80	80	120	130	130	0	0	0	0	2
1	4	240	260	290	320	310	300	70	80	90	120	130	130	0	0	0	1	3
1	5	230	260	290	440	430	450	80	90	90	120	130	130	0	0	0	2	6
2	3	440	430	450	0	0	0	40	50	60	110	110	110	0	0	0	0	1
2	4	470	530	590	130	50	0	60	70	70	110	120	120	0	0	0	0	0
2	5	470	530	590	260	170	160	60	80	80	120	130	130	0	0	0	0	2
3	5	660	700	740	0	0	0	50	60	70	110	120	120	0	0	0	3	7
3	6	730	790	880	170	50	10	60	70	70	120	120	120	0	0	0	0	0
3	7	700	760	880	290	180	150	70	80	80	130	130	130	0	0	0	0	3
3	8	700	790	850	400	310	300	70	80	90	130	130	140	0	0	0	0	4
3	9	730	790	880	510	440	450	80	90	90	130	140	140	0	0	0	0	8
3	10	710	790	880	630	580	600	80	90	90	140	140	150	0	0	0	3	12
4	5	730	740	740	0	0	0	40	50	60	110	110	110	0	10	10	1	1
4	6	850	860	890	0	0	0	50	60	60	110	120	120	0	0	0	1	3
4	7	930	960	1040	0	0	0	60	70	70	120	130	130	0	0	0	3	9
4	8	940	1060	1170	180	60	10	60	70	80	120	130	130	0	0	0	0	5
4	9	980	1060	1170	290	190	150	70	80	80	140	150	150	0	0	0	0	4
4	10	980	1020	1210	420	320	300	70	80	90	140	150	150	0	0	0	0	9
4	11	940	1060	1130	540	440	450	80	90	90	150	150	150	0	0	0	2	8
5	6	910	830	910	0	0	0	40	50	50	110	110	110	10	10	10	0	0
5	7	980	1000	990	0	0	0	50	60	60	120	120	120	0	10	10	2	1
5	8	1100	1140	1180	0	0	0	50	70	70	120	130	130	0	0	0	3	7
5	9	1170	1230	1320	0	0	0	60	70	80	130	140	140	0	0	0	5	13
5	10	1170	1270	1470	180	40	10	70	80	80	140	140	140	0	0	0	0	11
5	11	1170	1370	1470	330	180	150	70	80	90	140	150	150	0	0	0	4	10
5	12	1180	1310	1470	430	320	300	80	90	90	150	150	160	0	0	0	2	13
6	9	1210	1230	1320	0	0	0	60	70	70	140	140	140	0	10	10	2	9
6	10	1320	1360	1470	0	0	0	60	70	80	140	140	150	0	0	0	3	13
6	11	1400	1490	1620	0	0	0	70	80	80	150	140	140	0	0	0	8	18
6	12	1410	1580	1760	180	40	0	70	80	90	140	140	140	0	0	0	3	14
6	13	1410	1580	1760	330	170	150	80	90	90	150	150	150	0	0	0	1	14
6	14	1410	1640	1770	420	320	300	80	90	100	190	200	200	0	0	0	11	20
7	10	1340	1370	1470	0	0	0	60	70	70	140	140	140	10	10	10	3	11
7	11	1490	1450	1620	0	0	0	60	70	80	140	140	150	0	10	10	0	11
7	12	1560	1620	1760	0	0	0	70	80	80	140	140	140	0	0	0	5	17
7	13	1640	1760	1910	0	0	0	70	80	80	140	150	150	0	0	0	10	23
7	14	1640	1850	2050	220	50	10	80	80	90	150	150	150	0	0	0	3	17
7	15	1640	1850	1990	300	180	150	80	90	100	210	210	220	0	0	0	8	17
7	16	1640	1850	2060	430	320	300	90	100	100	220	220	230	0	0	0	8	24

[1] Average per week in solid cubic meters (rounded to the nearest ten). [2] In minutes (rounded to the nearest ten). [3] Average quantity per week.

Appendix B

Table A4. Terminal transport template for two train pick-ups, short delivery time, and all tonnages (P2D1 T1/2/3).

Wagons	Trucks	Terminal Transhipment Volume [1]			Required Terminal Stockyard [1]			Average Queuing Time [2]			Maximal Queuing Time [2]			Half Loaded Train Wagons [3]			Reduced Truck Trips [3]	
		T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T2	T3
1	1	240	270	380	120	120	0	0	0	10	50	60	70	0	0	0	3	2
1	2	490	530	590	360	390	370	20	10	20	70	120	120	0	0	0	6	9
1	3	470	530	590	710	800	810	30	30	30	120	140	130	0	0	0	13	18
1	4	450	530	590	1070	1200	1260	40	40	40	130	130	140	0	0	0	18	28
1	5	450	530	590	1430	1600	1710	50	40	40	130	140	130	0	0	0	21	35

Table A4. *Cont.*

Wagons	Trucks	Terminal Transhipment Volume [1]			Required Terminal Stockyard [1]			Average Queuing Time [2]			Maximal Queuing Time [2]			Half Loaded Train Wagons [3]			Reduced Truck Trips [3]	
		T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T2	T3
2	2	460	820	910	230	0	0	10	10	10	60	70	70	0	0	0	11	18
2	3	930	880	960	190	320	310	20	20	20	100	100	100	0	0	0	7	13
2	4	940	1060	1170	710	780	700	20	10	20	120	120	120	0	0	0	16	18
2	5	900	1060	1170	1070	1170	1140	30	20	30	120	130	130	0	0	0	22	28
3	2	830	860	890	0	0	0	10	20	30	80	120	120	0	0	0	3	5
3	3	810	1090	1310	230	20	0	10	10	10	70	70	70	0	10	10	6	23
3	4	1310	1260	1470	100	260	150	10	20	20	100	100	100	0	10	10	9	18
3	5	1330	1240	1470	610	790	660	20	20	20	110	120	120	0	10	10	8	16
3	6	1360	1530	1750	1070	1140	1000	20	10	30	120	120	130	0	0	0	20	27
3	7	1410	1580	1700	1430	1520	1470	20	20	30	120	130	130	0	0	0	22	28
3	8	1410	1590	1820	1770	1920	1880	30	30	30	130	130	130	0	0	0	28	43
3	9	1410	1530	1760	2070	2280	2320	30	30	40	130	130	140	0	0	0	28	50
3	10	1420	1590	1770	2500	2700	2720	30	30	40	130	140	130	0	0	0	31	48
4	3	1170	1230	1350	0	0	0	20	20	20	110	80	110	10	10	10	5	15
4	4	1030	1470	1760	420	20	0	10	10	10	70	70	80	0	10	10	3	26
4	5	1600	1620	1860	110	230	120	10	10	10	100	100	100	10	10	10	12	23
4	6	1770	1650	1820	430	760	650	20	20	20	110	110	110	0	10	10	18	23
4	7	1830	1690	1940	930	1110	1050	20	20	20	110	120	120	0	10	10	3	19
4	8	1810	2070	2310	1390	1450	1320	20	20	30	130	120	130	0	0	0	27	36
4	9	1830	2070	2340	1660	1790	1730	30	30	30	130	140	140	0	0	0	31	48
4	10	1820	2080	2430	1930	2100	2110	40	30	30	150	150	140	0	0	0	36	66
4	11	1880	2120	2350	2410	2570	2550	30	30	30	120	150	140	0	0	0	33	51
5	4	1530	1680	1790	0	0	0	10	20	20	80	80	100	10	10	10	13	22
5	5	1710	1930	2270	0	0	0	10	10	20	90	70	90	10	10	10	18	47
5	6	1970	2100	2260	30	20	10	10	20	10	100	100	100	10	10	10	10	23
5	7	2130	2080	2320	320	540	510	20	20	20	110	120	110	0	10	10	14	32
5	8	2180	2160	2400	690	870	870	20	20	20	110	120	120	0	10	10	13	33
5	9	2270	2520	2690	1160	1120	1130	30	20	30	120	120	120	0	0	0	18	33
5	10	2260	2560	2910	1540	1640	1470	30	30	30	130	130	150	0	0	0	33	48
5	11	2390	2700	2940	1750	1910	1810	40	30	40	140	140	150	0	0	0	39	51
5	12	2360	2640	2940	2160	2340	2370	30	30	30	130	140	130	0	0	0	38	66
6	4	1620	1750	1770	0	0	0	20	20	30	100	130	110	10	10	10	11	13
6	5	1850	2060	2220	0	0	0	20	20	20	130	170	130	10	10	10	18	31
6	6	2090	2400	2640	0	0	0	10	10	20	80	70	100	10	10	10	26	46
6	7	2460	2550	2920	0	0	0	20	20	20	110	100	150	10	10	10	8	38
6	8	2530	2620	2800	170	270	240	20	20	20	120	120	130	10	10	10	16	28
6	9	2650	2870	3090	500	450	540	20	20	20	120	130	130	0	10	10	14	40
6	10	2740	2980	3510	870	770	730	30	30	30	130	130	130	0	0	0	12	53
6	11	2640	3080	3440	1270	1240	1070	30	30	40	130	130	130	0	0	0	34	50
6	12	2780	3160	3400	1590	1720	1540	40	30	30	130	130	140	0	0	0	43	48
6	13	2830	3180	3540	1910	2110	2210	30	30	30	150	130	130	0	0	0	46	84
6	14	2820	3300	3530	2010	2150	2380	50	40	40	190	140	140	0	0	0	52	90
7	5	1980	2090	2220	0	0	0	20	20	30	120	120	130	10	10	10	9	20
7	6	1960	2220	2580	0	0	0	20	20	30	180	180	160	20	20	10	22	52
7	7	2420	2810	3060	0	0	0	10	10	20	70	160	160	10	10	10	33	53
7	8	2820	3120	3250	0	0	0	20	20	20	100	100	140	10	10	10	25	36
7	9	2820	3140	3510	130	80	10	20	20	20	110	110	130	10	10	10	23	48
7	10	2990	3160	3690	380	340	260	20	20	20	120	130	110	10	10	10	11	48
7	11	3130	3400	3840	690	650	600	30	30	30	120	120	130	0	10	0	19	52
7	12	3300	3510	3780	1100	1030	990	30	30	30	130	130	130	0	0	0	12	31
7	13	3200	3740	4010	1450	1460	1390	30	30	40	150	140	140	0	0	0	46	63
7	14	3300	3700	4250	1710	1880	2080	40	30	30	150	140	130	0	0	0	48	110
7	15	3300	3700	4110	1690	1880	2080	60	50	40	190	150	160	0	0	0	49	100
7	16	3280	3840	4110	1750	1880	2090	70	60	60	210	160	160	0	0	0	58	98

[1] Average per week in solid cubic meters (rounded to the nearest ten). [2] In minutes (rounded to the nearest ten). [3] Average quantity per week.

Table A5. Terminal transport template for two train pick-ups, medium delivery time, and all tonnages (P2D2 T1/2/3).

Wagons	Trucks	Terminal Transhipment Volume [1]			Required Terminal Stockyard [1]			Average Queuing Time [2]			Maximal Queuing Time [2]			Half Loaded Train Wagons [3]			Reduced Truck Trips [3]	
		T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T2	T3
1	1	250	260	290	0	0	0	0	0	0	10	10	0	0	0	0	1	3
1	2	470	530	590	0	0	0	10	10	20	120	110	110	0	0	0	5	10
1	3	470	530	570	240	270	300	20	20	20	130	110	120	0	0	0	8	13
1	4	470	530	590	480	540	590	20	30	30	120	120	110	0	0	0	10	19
1	5	470	530	590	720	800	890	30	30	30	120	120	110	0	0	0	12	24
2	1	250	280	290	0	0	0	0	0	0	10	0	0	0	0	0	3	3
2	2	490	530	570	0	0	0	0	0	0	20	20	20	0	0	0	3	7
2	3	710	760	880	0	0	0	10	10	10	110	110	110	0	0	0	4	14
2	4	980	1060	1210	0	0	0	20	20	20	110	110	110	0	0	0	7	19
2	5	940	1060	1170	240	270	300	20	20	20	80	120	130	0	0	0	13	24
3	1	240	270	290	0	0	0	0	0	0	10	10	0	0	0	0	3	4
3	2	470	550	590	0	0	0	0	0	0	20	20	20	0	0	0	7	10
3	3	710	790	880	0	0	0	0	0	0	20	20	20	0	0	0	7	14
3	4	940	1060	1140	0	0	0	10	10	10	110	110	100	10	10	10	10	17
3	5	1180	1320	1470	0	0	0	10	10	10	110	110	110	0	0	0	12	24
3	6	1410	1590	1760	0	0	0	20	20	20	110	110	110	0	0	0	15	29
3	7	1410	1530	1770	250	270	300	20	20	20	120	120	120	0	0	0	12	34
3	8	1410	1590	1760	480	540	600	20	20	20	120	120	110	0	0	0	20	39
3	9	1410	1590	1770	720	800	890	20	30	30	120	130	130	0	0	0	22	44
3	10	1350	1590	1820	960	1070	1190	30	30	30	120	130	120	0	0	0	29	58
4	2	470	530	590	0	0	0	0	0	0	20	20	10	0	0	0	5	10
4	3	680	800	890	0	0	0	0	0	0	20	20	20	10	0	0	10	18
4	4	900	1060	1180	0	0	0	0	0	0	20	20	20	0	0	0	13	23
4	5	1170	1330	1470	0	0	0	10	10	10	110	110	110	10	10	10	13	25
4	6	1420	1590	1830	0	0	0	10	10	10	120	110	110	10	10	10	14	34
4	7	1640	1860	2060	0	0	0	20	20	20	110	120	100	0	0	0	18	35
4	8	1880	2120	2350	0	0	0	20	20	20	120	120	110	0	0	0	20	39
4	9	1800	2110	2270	240	270	300	20	20	20	130	130	130	0	0	0	28	44
4	10	1880	2190	2270	480	540	600	20	20	30	130	130	140	0	0	0	31	43
4	11	1880	2110	2280	720	800	890	30	30	30	130	130	130	0	0	0	26	48
5	3	740	790	910	0	0	0	0	0	0	20	20	20	10	0	0	4	14
5	4	950	1020	1180	0	0	0	0	0	0	20	20	20	10	0	0	6	19
5	5	1170	1370	1470	0	0	0	0	0	0	20	20	20	0	0	0	17	25
5	6	1420	1590	1710	0	0	0	10	10	10	110	110	100	20	20	20	14	24
5	7	1650	1860	2060	0	0	0	10	10	10	120	110	110	10	10	10	18	34
5	8	1890	2120	2350	0	0	0	10	20	20	120	120	120	10	10	10	19	38
5	9	2120	2380	2560	0	0	0	20	20	20	130	120	120	0	0	0	22	37
5	10	2350	2650	2850	0	0	0	20	20	20	120	120	120	0	0	0	25	42
5	11	2350	2650	2940	250	270	300	20	20	20	130	130	130	0	0	0	27	53
5	12	2350	2550	2940	490	540	600	20	30	30	130	130	130	0	0	0	21	58
6	4	950	1060	1180	0	0	0	0	0	0	20	20	20	10	0	0	9	19
6	5	1230	1320	1470	0	0	0	0	0	0	20	20	20	20	0	0	8	20
6	6	1420	1590	1770	0	0	0	0	0	0	20	20	20	0	0	0	14	29
6	7	1650	1850	2070	0	0	0	10	10	10	110	100	100	20	20	20	17	35
6	8	1960	2120	2350	0	0	0	10	10	10	110	120	110	20	20	20	13	33
6	9	2040	2390	2650	0	0	0	10	10	20	120	120	110	10	10	10	29	51
6	10	2360	2650	2940	0	0	0	20	20	20	130	120	120	10	10	10	24	48
6	11	2590	3020	3220	0	0	0	20	20	20	120	120	120	0	0	0	36	53
6	12	2820	3180	3650	0	0	0	20	20	20	130	120	130	0	0	0	30	69
6	13	2820	3300	3520	250	270	300	20	20	30	140	130	120	0	0	0	42	63
6	14	2820	3170	3520	370	400	450	30	30	30	190	190	190	0	0	0	32	65
7	5	1190	1320	1470	0	0	0	0	0	0	40	20	20	10	0	0	11	23
7	6	1480	1590	1770	0	0	0	0	0	0	20	20	20	20	0	0	9	24
7	7	1650	1930	2060	0	0	0	0	0	0	20	20	20	0	0	0	23	34
7	8	1890	2120	2350	0	0	0	10	10	10	100	100	100	30	30	30	19	38
7	9	2110	2380	2560	0	0	0	10	10	10	110	100	110	20	20	20	23	38
7	10	2260	2650	2940	0	0	0	10	10	20	110	110	100	20	20	20	33	57
7	11	2600	2910	3240	0	0	0	20	20	20	110	110	100	10	10	10	26	53

Table A5. *Cont.*

Wagons	Trucks	Terminal Transhipment Volume [1]			Required Terminal Stockyard [1]			Average Queuing Time [2]			Maximal Queuing Time [2]			Half Loaded Train Wagons [3]			Reduced Truck Trips [3]	
		T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T2	T3
7	12	2820	3170	3530	0	0	0	20	20	20	110	110	110	10	10	10	29	59
7	13	3060	3310	3830	0	0	0	20	20	20	120	110	110	0	0	0	21	64
7	14	3300	3840	4130	0	0	0	20	20	20	120	110	110	0	0	0	45	69
7	15	3430	3560	4110	130	140	150	30	30	30	190	190	190	0	0	0	12	58
7	16	3150	3700	4110	260	270	300	40	40	40	200	200	210	0	0	0	47	83

[1] Average per week in solid cubic meters (rounded to the nearest ten). [2] In minutes (rounded to the nearest ten). [3] Average quantity per week.

Table A6. Terminal transport template for two train pick-ups, long delivery time, and all tonnages (P2D3 T1/2/3).

Wagons	Trucks	Terminal Transhipment Volume [1]			Required Terminal Stockyard [1]			Average Queuing Time [2]			Maximal Queuing Time [2]			Half Loaded Train Wagons [3]			Reduced Truck Trips [3]	
		T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T2	T3
1	1	230	230	230	0	0	0	0	0	10	60	60	60	0	0	0	0	0
1	2	360	370	410	0	0	0	20	20	20	70	70	70	0	0	0	1	4
1	3	460	480	530	20	50	50	20	20	20	80	90	90	0	0	0	4	8
1	4	470	510	540	160	170	240	30	30	30	120	110	120	0	0	0	4	13
1	5	470	490	550	280	350	380	30	30	40	120	120	130	0	0	0	8	15
2	1	230	220	230	0	0	0	0	0	10	60	60	60	0	0	0	0	0
2	2	470	430	450	0	0	0	0	10	10	60	60	60	0	0	0	0	0
2	3	580	640	630	0	0	0	10	20	10	70	70	70	0	0	0	5	4
2	4	710	780	820	0	0	0	20	20	20	80	80	80	0	0	0	6	9
2	5	820	920	1000	0	0	0	20	20	30	80	80	90	0	0	0	8	15
2	6	940	1030	1160	10	30	20	30	30	30	80	80	90	0	0	0	9	19
2	7	930	990	1160	140	170	170	30	30	30	80	110	110	0	0	0	8	22
3	6	1010	1210	1210	0	0	0	20	20	20	80	80	110	10	10	10	17	17
3	7	1180	1350	1390	0	0	0	20	30	20	80	90	80	0	0	10	14	18
3	8	1300	1450	1590	0	0	0	30	30	30	90	120	110	0	0	0	13	24
3	9	1470	1580	1760	10	10	0	30	30	30	90	90	90	0	0	0	9	23
3	10	1410	1560	1760	130	170	150	30	30	30	110	120	120	0	0	0	16	31
4	9	1510	1620	1810	0	0	0	30	30	30	160	160	100	10	10	10	9	25
4	10	1650	1830	2000	0	0	0	30	30	30	160	160	110	0	10	10	15	29
4	11	1760	1980	2180	0	0	0	30	30	30	160	160	100	0	0	0	18	35
4	12	1880	2190	2430	0	0	0	30	30	30	160	160	160	0	0	0	26	46
4	13	1880	2040	2360	120	140	150	40	40	40	170	160	160	0	0	0	15	43
5	12	2000	2230	2390	0	0	0	30	30	30	180	170	120	10	10	10	19	33
5	13	2030	2370	2590	0	0	0	40	30	30	170	170	160	0	10	10	28	47
5	14	2240	2520	2690	0	0	0	40	30	30	170	160	170	0	0	0	23	38
5	15	2360	2650	2940	0	0	0	40	40	40	170	170	160	0	0	0	24	48
5	16	2360	2550	2930	120	140	150	50	40	40	180	180	170	0	0	0	18	50
6	15	2480	2760	2880	0	0	0	40	30	30	240	170	160	10	10	10	23	33
6	16	2590	2810	3270	0	0	0	40	30	30	180	180	180	0	10	10	18	57
6	17	2710	3050	3360	0	0	0	50	40	30	260	180	170	0	0	0	28	54
6	18	2820	3050	3510	0	0	0	50	40	40	180	180	180	0	0	0	19	58
6	19	2700	3290	3410	120	130	90	60	50	50	230	180	230	0	0	0	50	57
7	18	3060	3290	3570	0	0	0	50	40	40	190	190	180	10	10	10	19	43
7	19	3050	3420	3740	0	0	0	50	40	40	250	190	190	0	10	10	31	58
7	20	3170	3580	3930	0	0	0	50	40	40	190	190	190	0	0	0	34	63
7	21	3300	3830	4040	0	0	0	60	50	50	250	180	220	0	0	0	44	62
7	22	3290	3690	4050	120	100	0	60	60	60	270	250	220	0	0	0	32	53
7	23	3300	3690	4050	240	260	150	70	70	60	260	220	220	0	0	0	34	55
7	24	3290	3700	4080	360	410	370	70	70	70	250	260	240	0	0	0	38	67
7	25	3290	3690	4200	480	540	600	80	80	70	250	250	220	0	0	0	38	86

[1] Average per week in solid cubic meters (rounded to the nearest ten). [2] In minutes (rounded to the nearest ten). [3] Average quantity per week.

References

1. Federal Ministry for Sustainability and Tourism, Republic of Austria. Austrian Forest Strategy 2020+. BMNT 2018. Available online: https://www.bmlrt.gv.at/forst/oesterreich-wald/waldstrategie-2020/waldstrategie_paper.html (accessed on 27 March 2020).
2. Austrian Paper Industry Association. Annual Report 2018/19. Austropapier 2019. Available online: https://www.austropapier.at/fileadmin/austropapier.at/dateiliste/Dokumente/Downloads/Jahresberichte/19.04.10__Gesamter_Bericht__9MB_.pdf (accessed on 27 March 2020).
3. Austrian Wood Industry Association. Annual Report 2018/19. Fachverband der Holzindustrie 2019. Available online: https://www.wko.at/branchen/industrie/holzindustrie/branchenbericht-2018-2019.pdf (accessed on 27 March 2020).
4. Cooperation Association Forest Wood Paper. Performance Report Value Chain Wood. FHP 2019. Available online: https://www.forstholzpapier.at/images/Leistungsbericht_kompakt_2019_Ansicht_FINAL.pdf (accessed on 27 March 2020).
5. Federal Ministry for Sustainability and Tourism, Republic of Austria. Green Report. BMNT 2019. Available online: https://gruenerbericht.at/cm4/jdownload/send/2-gr-bericht-terreich/2007-gb2019 (accessed on 27 March 2020).
6. Rail Cargo Austria. *Wood Terminals in Austria*; Rail Cargo Austria: Vienna, Austria, 2019.
7. Bjarnehed, H.; Dotevall, J. Increased business value with digital twins. In Proceedings of the The Energiforsk Annual Nuclear Conference, Stockholm, Sweden, 24 January 2018; pp. 1–16.
8. Dalstam, A.; Engberg, M.; Nafors, D.; Johansson, B.; Sundblom, A. A stepwise implementation of the virtual factory in manufacturing industry. In *Proceedings of the 2018 Winter Simulation Conference, Gothenburg, Sweden, 9–12 December 2018*; Rabe, M., Juan, A.A., Mustafee, N., Skoogh, A., Jain, S., Johansson, B., Eds.; Institute of Electrical and Electronics Engineers, Inc.: Piscataway, NJ, USA; pp. 3229–3240.
9. The Anylogic Company. White Paper: An introduction to Digital Twin Development. Anylogic 2018. Available online: https://www.anylogic.com/resources/white-papers/an-introduction-to-digital-twin-development/ (accessed on 27 March 2020).
10. Kogler, C.; Rauch, P. Discrete event simulation of multimodal and unimodal transportation in the wood supply chain: A literature review. *Silva Fenn.* **2018**, *52*, 1–29. [CrossRef]
11. Saranen, J.; Hilmola, O.-P. Evaluating the competitiveness of railways in timber transports with discrete-event simulation. *World Rev. Intermod. Transp. Res.* **2007**, *1*, 445–458. [CrossRef]
12. Karttunen, K.; Lättilä, L.; Korpinen, O.-J.; Ranta, T. Cost-efficiency of intermodal container supply chain for forest chips. *Silva Fenn.* **2013**, *47*, 1–24. [CrossRef]
13. Wolfsmayr, U.J.; Merenda, R.; Rauch, P.; Longo, F.; Gronalt, M. Evaluating primary forest fuel rail terminals with discrete event simulation: A case study from Austria. *Ann. For. Res.* **2016**, *59*, 145–164. [CrossRef]
14. Gronalt, M.; Rauch, P. Analyzing railroad terminal performance in the timber industry supply chain—A simulation study. *Int. J. For. Eng.* **2018**, *29*, 162–170. [CrossRef]
15. Kogler, C.; Rauch, P. A discrete event simulation model to test multimodal strategies for a greener and more resilient wood supply. *Can. J. For. Res.* **2019**, *49*, 1298–1310. [CrossRef]
16. Asikainen, A. Simulation of logging and barge transport of wood from forests on islands. *Int. J. For. Eng.* **2001**, *12*, 43–50. [CrossRef]
17. Karttunen, K.; Väätäinen, K.; Asikainen, A.; Ranta, T. The operational efficiency of waterway transport of forest chips on Finland's Lake Saimaa. *Silva Fenn.* **2012**, *46*, 395–413. [CrossRef]
18. Mobini, M.; Sowlati, T.; Sokhansanj, S. A simulation model for the design and analysis of wood pellet supply chains. *Appl. Energy* **2013**, *111*, 1239–1249. [CrossRef]
19. Mobini, M.; Meyer, J.-C.; Trippe, F.; Sowlati, T.; Fröhling, M.; Schultmann, F. Assessing the integration of torrefaction into wood pellet production. *J. Clean. Prod.* **2014**, *78*, 216–225. [CrossRef]
20. Borshchev, A. *The Big Book of Simulation Modeling: Multimethod Modeling with AnyLogic*; Anylogic: Chicago, IL, USA, 2014; p. 612. ISBN 0989573176.
21. Mahdavi, A. The Art of Process-Centric Modeling with AnyLogic. Available online: https://www.anylogic.com/resources/books/the-art-of-process-centric-modeling-with-anylogic/ (accessed on 27 March 2020).
22. She, J.; Chung, W.; Kim, D. Discrete-event simulation of ground-based timber harvesting operations. *Forests* **2018**, *9*, 683. [CrossRef]

23. Kons, K.; La Hera, P.; Bergström, D. Modelling dynamics of a log-yard through discrete-event mathematics. *Forests* **2020**, *11*, 155. [CrossRef]
24. Beaudoin, D.; LeBel, L.; Soussi, M.A. Discrete event simulation to improve log yard operations. *INFOR Inf. Syst. Oper. Res.* **2012**, *50*, 175–185. [CrossRef]
25. Anyomi, K.A.; Mitchell, S.J.; Perera, A.H.; Ruel, J.-C. Windthrow dynamics in boreal Ontario: A simulation of the vulnerability of several stand types across a range of wind speeds. *Forests* **2017**, *8*, 233. [CrossRef]
26. Jandl, R.; Ledermann, T.; Kindermann, G.; Freudenschuss, A.; Gschwantner, T.; Weiss, P. Strategies for climate-smart forest management in Austria. *Forests* **2018**, *8*, 233. [CrossRef]
27. Cristal, I.; Ameztegui, A.; González-Olabarria, J.R.; Garcia-Gonzalo, J. A decision support tool for assessing the impact of climate change on multiple ecosystem services. *Forests* **2019**, *10*, 440. [CrossRef]
28. Iverson, L.R.; Prasad, A.M.; Peters, M.P.; Matthews, S.N. Facilitating adaptive forest management under climate change: A spatially specific synthesis of 125 species for habitat changes and assisted migration over the eastern United States. *Forests* **2019**, *10*, 989. [CrossRef]
29. Eriksson, A.; Eliasson, L.; Sikanen, L.; Hansson, P.-A.; Jirjis, R. Evaluation of delivery strategies for forest fuels applying a model for weather-driven analysis of forest fuel systems (WAFFS). *Appl. Energy* **2017**, *188*, 420–430. [CrossRef]
30. Paulson, J.S.; Kizha, A.R.; Han, H.-S. Integrating biomass conversion technologies with recovery operations in-woods: Modelling supply chain. *Logistics* **2019**, *3*, 16. [CrossRef]
31. Montgomery, T.D.; Han, H.-S.; Kizha, A.R. Modeling work plan logistics for centralized biomass recovery operations in mountainous terrain. *Biomass Bioenergy* **2016**, *85*, 262–270. [CrossRef]
32. Kizha, A.R.; Han, H.-S.; Paulson, J.; Koirala, A. Strategies for reducing moisture content in forest residues at the harvest site. *Appl. Eng. Agric.* **2018**, *34*, 25–33. [CrossRef]
33. Acuna, M.; Sessions, J.; Zamora, R.; Boston, K.; Brown, M.; Ghaffariyan, M.R. Methods to manage and optimize forest biomass supply chains: A review. *Curr. For. Rep.* **2019**, *5*, 124–141. [CrossRef]
34. Windisch, J.; Röser, D.; Mola-Yudego, B.; Sikanen, L.; Asikainen, A. Business process mapping and discrete-event simulation of two forest biomass supply chains. *Biomass Bioenergy* **2013**, *56*, 370–381. [CrossRef]
35. Windisch, J.; Röser, D.; Sikanen, L.; Routa, J. Reengineering business processes to improve an integrated industrial roundwood and energywood procurement chain. *Int. J. For. Eng.* **2013**, *24*, 233–248. [CrossRef]
36. Korpinen, O.J.; Aalto, M.; Venäläinen, P.; Ranta, T. Impacts of a high-capacity truck transportation system on the economy and traffic intensity of pulpwood supply in southeast Finland. *Croat. J. For. Eng.* **2019**, *40*, 89–105.
37. Eliasson, L.; Eriksson, A.; Mohtashami, S. Analysis of factors affecting productivity and costs for a high-performance chip supply system. *Appl. Energy* **2017**, *185*, 497–505. [CrossRef]
38. Fernandez-Lacruz, R.; Eriksson, A.; Bergström, D. Simulation-based cost analysis of industrial supply of chips from logging residues and small-diameter trees. *Forests* **2020**, *11*, 1. [CrossRef]