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

Christoph Kogler and Peter Rauch

Christoph Kogler
University of Natural Resources and Life Sciences, Vienna
Institute of Production and Logistics
Feistmantelstrasse 4, A-1180 Vienna, Austria
Guttenberghaus 02/13
christoph.kogler@boku.ac.at
T: 004314765473421
F: 004314765473409

Peter Rauch
University of Natural Resources and Life Sciences, Vienna
Institute of Production and Logistics
Feistmantelstrasse 4, A-1180 Vienna, Austria
Guttenberghaus 02/09
peter.rauch@boku.ac.at
T: 004314765473414
F: 004314765473409
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 CO₂ 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.
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.

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 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 on 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%.

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\textsubscript{2} equivalents (t), fulfillment level (%), truck utilization (%) and transport costs per transported m\textsuperscript{3} (€/m\textsuperscript{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\textsubscript{2} equivalents are the sum of emitted CO\textsubscript{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\textsubscript{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.

Acknowledgements

The authors gratefully acknowledge that this research was funded within the MultiStrat project by the Austrian Federal Ministry for Transport, Innovation, and Technology (bmvit) through the framework of the ERA-NET Transport Flagship Call 2015 for Sustainable Logistics and Supply Chains.
9. Reference


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

<table>
<thead>
<tr>
<th>INPUTS</th>
<th>PROCESSES</th>
<th>OUTPUTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>production volume per day</td>
<td>generate wood</td>
<td>distribution of production amount</td>
</tr>
<tr>
<td>weekly production plan</td>
<td>queue wood</td>
<td>stockyard at forest landing</td>
</tr>
<tr>
<td>forwarding capacity</td>
<td>batch wood</td>
<td>provided wood for transport</td>
</tr>
<tr>
<td>forwarding time</td>
<td>forward wood</td>
<td>per district</td>
</tr>
<tr>
<td>forest stockyard capacity</td>
<td>truckload</td>
<td></td>
</tr>
<tr>
<td>truckload size</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| TRUCK | |
|-------| |
| number of trucks | generate wood | loaded trucks |
| transport cost to terminal | queue wood | not delivered transport tasks |
| drive time to landing | batch wood | delivered transport tasks |
| loading time | forward truckload | fulfillment level |
| transport time to terminal | queue truckload | truck utilization |
| transport time to industry | | |
| transport priority | | delivery quota |
| transport mode type (unimodal, multimodal, both) | | |

| TERMINAL | |
|----------| |
| remove belts time | generate trucks | stockyard terminal |
| load wagon time | enter trucks | queuing time |
| secure wagon load time | delete trucks | distribution of queuing times |
| clean loading platform time | queue at truck garage | number of trucks at the terminal |
| complete delivery ticket time | pickup truckloads | |
| unload at terminal stockyard time | transport to industry | |
| unload at industry time | transport to terminal | |
| capacity terminal stockyard | drive to terminal | |
| | drive to landing | |
| | drive to garage | |

| TRAIN | |
|-------| |
| number of train pickups | generate trains | loaded wagons |
| transport cost to industry | pickup wagons | delivered wagons |
| transport time to industry | transport to industry | full loaded wagons |
| number of wagons | delete trains | half-loaded wagons |

| INDUSTRY | |
|----------| |
| unload at industry stockyard time | unloadad wagons at industry | received wood |
| | transport costs | CO₂ emissions |
| | lead times | |
### Table 2: Decision Variables

<table>
<thead>
<tr>
<th>DECISION VARIABLE</th>
<th>VALUES</th>
<th>EXPLANATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>wagon</td>
<td>between 0 and 9</td>
<td>Number of ordered wagons, which will be delivered when the next train picks up loaded wagons at the terminal</td>
</tr>
<tr>
<td>truck</td>
<td>1 to 20</td>
<td>Number of trucks, which will be provided during operating hours</td>
</tr>
<tr>
<td>train pick up</td>
<td>1 or 2</td>
<td>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</td>
</tr>
<tr>
<td>transport mode split</td>
<td>%</td>
<td>Proportion of wood that is transported multimodal or unimodal</td>
</tr>
<tr>
<td>transport priority</td>
<td>largest stock or oldest wood</td>
<td>Trucks pick up wood first at the landing with the largest stockyard or the oldest wood</td>
</tr>
</tbody>
</table>
Table 3: Simulation processes and their parameters for triangular distributions (duration in minutes)

<table>
<thead>
<tr>
<th>PROCESSES</th>
<th>MIN</th>
<th>MODE</th>
<th>MAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>drive to landing</td>
<td>10</td>
<td>46</td>
<td>83</td>
</tr>
<tr>
<td>load truck</td>
<td>30</td>
<td>35</td>
<td>40</td>
</tr>
<tr>
<td>truck transport to terminal</td>
<td>15</td>
<td>45</td>
<td>105</td>
</tr>
<tr>
<td>truck transport to industry</td>
<td>60</td>
<td>105</td>
<td>150</td>
</tr>
<tr>
<td>train transport to industry</td>
<td>1440</td>
<td>3258</td>
<td>10080</td>
</tr>
<tr>
<td>remove belts</td>
<td>7</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>load wagon</td>
<td>35</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>secure wagon load</td>
<td>5</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>clean loading platform</td>
<td>3</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>complete delivery ticket</td>
<td>10</td>
<td>13</td>
<td>15</td>
</tr>
<tr>
<td>unload at terminal stockyard</td>
<td>35</td>
<td>45</td>
<td>55</td>
</tr>
<tr>
<td>unload at industry (BAU and SNOW / STORM)</td>
<td>35 / 80</td>
<td>60 / 160</td>
<td>180 / 200</td>
</tr>
</tbody>
</table>
Table 4: Average truck transport costs (€ per solid cubic meter)

<table>
<thead>
<tr>
<th>TRUCK TRANSPORT</th>
<th>DISTRICT 1</th>
<th>DISTRICT 2</th>
<th>DISTRICT 3</th>
<th>DISTRICT 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>to terminal</td>
<td>8.2</td>
<td>9.1</td>
<td>9.8</td>
<td>9.8</td>
</tr>
<tr>
<td>to industry</td>
<td>14.22</td>
<td>12.75</td>
<td>17.72</td>
<td>13.15</td>
</tr>
</tbody>
</table>
Table 5: Results according to the most important key performance indicators (KPIs)

<table>
<thead>
<tr>
<th>SCENARIO</th>
<th>STRATEGY / KPI</th>
<th>BAU</th>
<th>SNOW</th>
<th>STORM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BOTH</td>
<td>MULTI</td>
<td>UNI</td>
<td>BOTH</td>
</tr>
<tr>
<td>transported (m³)</td>
<td>41,581</td>
<td>37,563</td>
<td>39,771</td>
<td>38,360</td>
</tr>
<tr>
<td>delivery quota (%)</td>
<td>112</td>
<td>111</td>
<td>104</td>
<td>108</td>
</tr>
<tr>
<td>queuing time (minutes)</td>
<td>13.21</td>
<td>24.38</td>
<td>-</td>
<td>13.76</td>
</tr>
<tr>
<td>stockyard (truckloads)</td>
<td>66</td>
<td>225</td>
<td>158</td>
<td>67</td>
</tr>
<tr>
<td>lead time (days)</td>
<td>10.37</td>
<td>23.09</td>
<td>14.57</td>
<td>10.12</td>
</tr>
<tr>
<td>half-loaded wagons</td>
<td>85</td>
<td>92</td>
<td>-</td>
<td>81</td>
</tr>
<tr>
<td>empty wagons</td>
<td>77</td>
<td>119</td>
<td>-</td>
<td>77</td>
</tr>
<tr>
<td>full loaded wagons</td>
<td>437</td>
<td>819</td>
<td>-</td>
<td>398</td>
</tr>
<tr>
<td>CO₂–eq (in million tonnes)</td>
<td>719</td>
<td>579</td>
<td>762</td>
<td>665</td>
</tr>
<tr>
<td>fulfillment level (%)</td>
<td>96</td>
<td>98</td>
<td>81</td>
<td>98</td>
</tr>
<tr>
<td>truck utilization (%)</td>
<td>80</td>
<td>80</td>
<td>97</td>
<td>79</td>
</tr>
<tr>
<td>transport costs per transported m³</td>
<td>16.01</td>
<td>17.91</td>
<td>14.11</td>
<td>15.99</td>
</tr>
</tbody>
</table>
Figure 1: Process map of wood supply chain of the AFF
Figure 2: Aerial photograph of the terminal in Großreifling
Figure 3: Wood Supply Chain with multimodal and unimodal transport
Figure 4: Wood flow

1. START
2. Harvesting
3. Forwarding
4. Store at forest landing
5. Multimodal?
   - YES
     1. Truck transport to industry
     2. Task 1
       - Task 2
       - Store at terminal stockyard
   - NO
     1. Truck transport to industry
     2. Unloading at industry
     3. END
Figure 5: Truck flow

START SHIFT

job?

waiting at truck garage

job 1

transport wood from stockyard to wagon

job 2

pickup wood at forest landing

multimodal?

>12:00?

NO

>13:00?

NO

>17:00?

YES

YES

YES

drive to truck garage

transport wood to industry

unload at industry

NO

queue in front of the terminal

enter?

remove safety belts

wagon available?

NO

unload at stockyard

YES

load wagon

secure wagon load

clean loading platform

complete delivery ticket

END SHIFT
Figure 6: Animation view with truck garage, forests, landings, industry, terminal, trees (1 m$^3$ wood), truckloads (20–30 m$^3$ wood), trainloads, trucks and trains
Figure 7: Statistic view (management cockpit)
Figure 8: Parameterization view

<table>
<thead>
<tr>
<th>Control Method</th>
<th>Train Pickups</th>
<th>Transport mode</th>
<th>Transport priority</th>
<th>Runtime (queue simulation)</th>
<th>Run Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual</td>
<td>Manual</td>
<td>Motorized</td>
<td>Largest Truck</td>
<td>Melt Box</td>
<td></td>
</tr>
<tr>
<td>Plan</td>
<td>Excel</td>
<td>Workshop</td>
<td>Workshop</td>
<td>Workshop</td>
<td></td>
</tr>
</tbody>
</table>

**Transport Module**
- Triangular time: 10 minutes
- Loading: 30 minutes
- Loading time: 15 minutes
- Loading time: 10 minutes
- Loading time: 7 minutes
- Loading time: 5 minutes
- Loading time: 3 minutes
- Loading time: 1 minute
- Loading time: 0 minutes

**Terminal Module**
- Triangular time: 10 minutes
- Loading: 30 minutes
- Loading time: 15 minutes
- Loading time: 10 minutes
- Loading time: 7 minutes
- Loading time: 5 minutes
- Loading time: 3 minutes
- Loading time: 1 minute
- Loading time: 0 minutes

**Plan**
- District 1: 10
- District 2: 15
- District 3: 20
- District 4: 25
- District 5: 30
- District 6: 35
- District 7: 40
- District 8: 45
- District 9: 50

**Costs**
- Truck transport per solid cubic meter
  - Average cost in kilometer
  - Average cost in kilometer
  - Average cost in kilometer
  - Average cost in kilometer

**Manual control method**
- Wagon
- Trucks
- District 1
- District 2
- District 3
- District 4
- District 5
- District 6
- District 7
- District 8
- District 9

**Excel**
- Scenario 1
- Scenario 2
- Scenario 3
- Scenario 4

**Workshop**
- Step A
- Step B
- Step C
- Step D

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