Research report No. 2.2.4
Helsinki 2015

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Development of simulation tools for terminal-based biomass feedstock logistics

Sustainable Bioenergy
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ISBN 978-952-5947-74-8

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Key words: biomass, combined heat and power generation, simulation modelling, transportation, bulk logistics, roundwood

Summary

The paper reports on the structures of two simulation modelling tools designed for logistical analyses of biomass-based raw material supply. The tools were designed in two industrial-sized case studies that were large-scale biomass supply systems of a multifuel concept power plant and a bioproduct mill. The following aspects were accounted for: spatial distribution of feedstocks using Geographical Information Systems (GIS), temporal modelling of supply and demand, transportation logistics (including road and railway transportation), terminal operations and roadside storages. The model used the latest research data on biomass availability, techno-economic harvest potentials, and logistical parameters as inputs. The main results were the applications themselves, but it was also found in both cases that temporal imbalance between supply and demand may be substantial. Terminals are key factors in preventing the situation of unfulfilled demand. Future development needs are to include new logistical solutions to the model, increase the significance of temporal parameters in decision-making rules, and make the application better available to the general public.

Helsinki, June 2015

Contents

1. Introduction

1.1 Background

A central topic in Task 2.2 for the first period of the BEST program (2013–2014) was a concept for a large-scale biofuel terminal that would presumably bring cost-efficiency to biomass supply chains due to radical improvements in operational efficiency and “returns to scale” impacts on biofuel logistics.

In the planning phase of the task it became clear that the entire supply chain system should be described and modelled as promptly as possible in order to assess the improvements in relation to conventional feedstock supply methods. It was also noted that variation of biomass supply and demand over time should be taken into account. In fact, the use of terminals is hardly reasonable in biomass supply logistics if the temporal aspect is totally excluded. Theoretically, a simple transport solution based on the shortest, fastest, or the most fuel-saving route without additional transshipments is the most profitable option if restrictions and limitations on such factors as biomass production, demand, storing and upgrading possibilities and workforce availability are omitted. However, restricting and time-dependent (or season-dependent) variables should be included in the studies, because they are significant factors in real-life operations too. Terminal-based supply chains have increased their proportion of all forest-fuel supply in Finland, comprising 27% in 2013 (Strandström 2014).

1.2 Purpose of the work

The work of Subtask 2.2.4 took place around two prospective industrial cases that were interesting either because of the scale of biomass volumes to be supplied, challenging environment in fuel processing, or novelty in possible transport or material handling solutions. Based on the new methods and concepts principally being developed in other subtasks of BEST, the purpose of this work was to build simulation modelling tools around these cases so that different scenarios (e.g. use of different machines, costs, or fuel volumes) could be tested in an environment that is free from economic risks. Accordingly, it was kept in mind that the basic structure of the tools should be built so that they could be used in different geographic environments, even though they were designed in the selected study cases.

The first case was based on the possible multi-fuel concept (MFC) power plant in Vuosaari, Helsinki, and its domestic biofuel supply (Helen 2015). In the second case the focus was on the feedstock supply of a planned bioproduct mill in Äänekoski (Metsä Group 2015), and the simulation environment was limited to roundwood supply. The decision on whether to build Vuosaari plant or not is expected to be made during 2015. Construction work in Äänekoski has already started (in April 2015).

1.3 Software

The following software was used in designing and running the simulation tool:

- ArcGIS Professional 10
  - ArcGIS Network Analyst extension
- AnyLogic Professional 7.0 and 7.1 (AnyLogic 2015a)
- Microsoft Excel 2013
- Microsoft Access 2013

2. Case I: Biofuel supply logistics of the MFC power plant

2.1 Case setup

The background for the case was in the planning project that has been described on Helen's web pages (Helen 2015). The study case was related to project alternative 1 (new multifuel power plant), and it focused on domestic biofuel supply of the planned power plant. It was assumed that the domestic biofuel demand would range from 0 to 4 TWh per year. The following fuel types suitable for combustion were included in the study:

- Undelimbed energy wood from young stands (EW)
- Harvest residues from regeneration fellings (HR)
- Stumps from regeneration fellings (ST)
- Delimbed energy wood from young stands (DLEW)
- Roundwood also suitable for wood-processing industries (RW)
- Residual straw from grain harvests (Agro)

It was also assumed that to fulfill domestic demand it is not necessarily the most profitable solution to acquire all biomass by trucks from the surrounding region of the plant. In addition, long-distance train transportation was considered as a possible option if the demand is high and competition is intense in Southern Finland. Therefore, two supply areas were included in the study: 1) Southern Finland, up to 225 km by road from the planned location of the plant; and 2) Kainuu, up to 150 km by road from the train loading terminal in Kontiomäki. The selection of the train loading point was based on existing terminal services at Kontiomäki (Iikkanen & Sirkiä 2011) and former studies about the balance of local energy wood supply and demand (Kainuun Etu Oy 2010, Anttila et al. 2013).

2.2 Model building

The tool was designed to run process modelling and simulation tasks, including entity-relationship-based structure. When applied in biomass supply logistics, the concept means that the entities are units representing biomass, such as units of energy or volume, and they are transported according to predefined rules. Accordingly, the rules and their output are dependent on parameters entered into the model by the user. The parameters are numerical (usually arithmetic or boolean) values that represent the real-life situations detailed as needed. A section from the simulation model structure is presented in Fig. 1. The section includes elements for actions taking place (i.e. nodes) and decisions being made during the supply chain. Each junction of two (or more) connector lines require a decision algorithm (e.g. if there is no biomass available, reserve fuel is used).

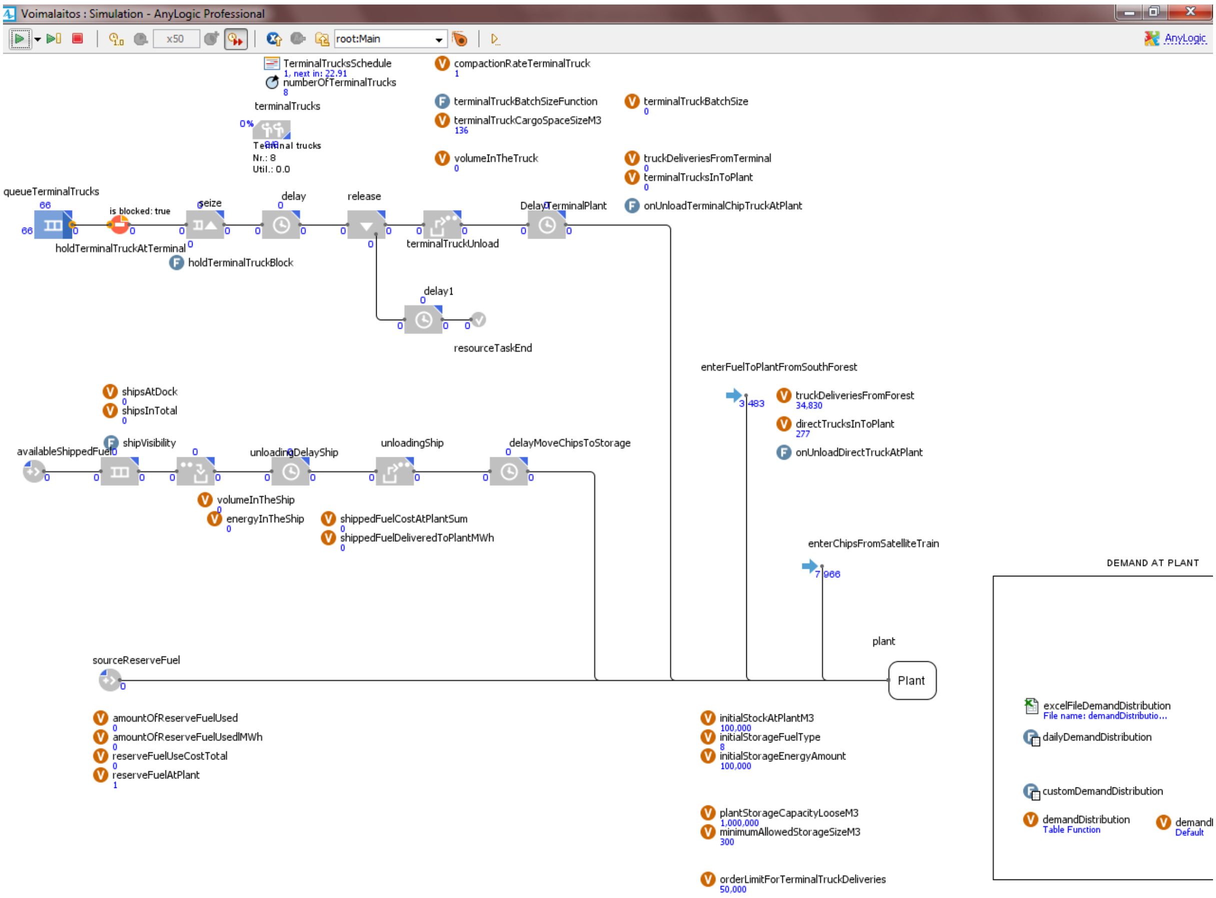

Figure 1. A section of the simulation model structure (events taking place before entering the plant yard) in Case I. Blue values represent entities being processed at different stages at a certain point of time.

Simulation system boundaries were defined so that the entities (energy units) are generated in “sources” (e.g. roadside storages of forest biomass or collecting points near fields) whose supply volumes vary according to predefined rules and terminated in a “sink” (power plant) whose demand also varies over time. This kind of system composition is typical for such an inbound logistics scheme.

Because biomass availability is largely dependent on geographical properties, the properties must be included in the model in one way or another. If there are only a few biomass origin points, they can all be presented as individual sources in the model. However, the fact is usually that the case contains hundreds or thousands of origin points. Therefore, the points should, for example, be combined into one source so that average supply volume distribution, transport costs, and times meeting the case are used for that source. In this case, there were sources for each feedstock type both in Southern Finland and Kainuu, and each source received its input values according to a rule collection which was based on real biomass availability and transport distance calculations in a Geographical Information System (GIS). The calculation method is described in the following subchapter.

The entity being processed in the simulation run was assumed to represent 10 m³ of loose (e.g. chipped) biomass regardless of the shape or type of the fuel fraction. In order to provide a sufficient amount of information from different phases of material flow, the entity was given properties describing its value or quality, such as solid volume, energy content, processing costs, or age (i.e. time after the entity was generated in the source). These properties were responsive to changes when entering or exiting different nodes in the system. A typical example is that the nodes generally accumulated the cost of the entity during the flow, while the energy content was changed only in certain parts of the system. The feed-in terminal located near the power plant is a fine example of a hub where both energy content and value in money are changed because of comminution activities, storing times, and all machine operations. This is also illustrated in the user interface of the simulation tool after starting a simulation run (Fig. 2).

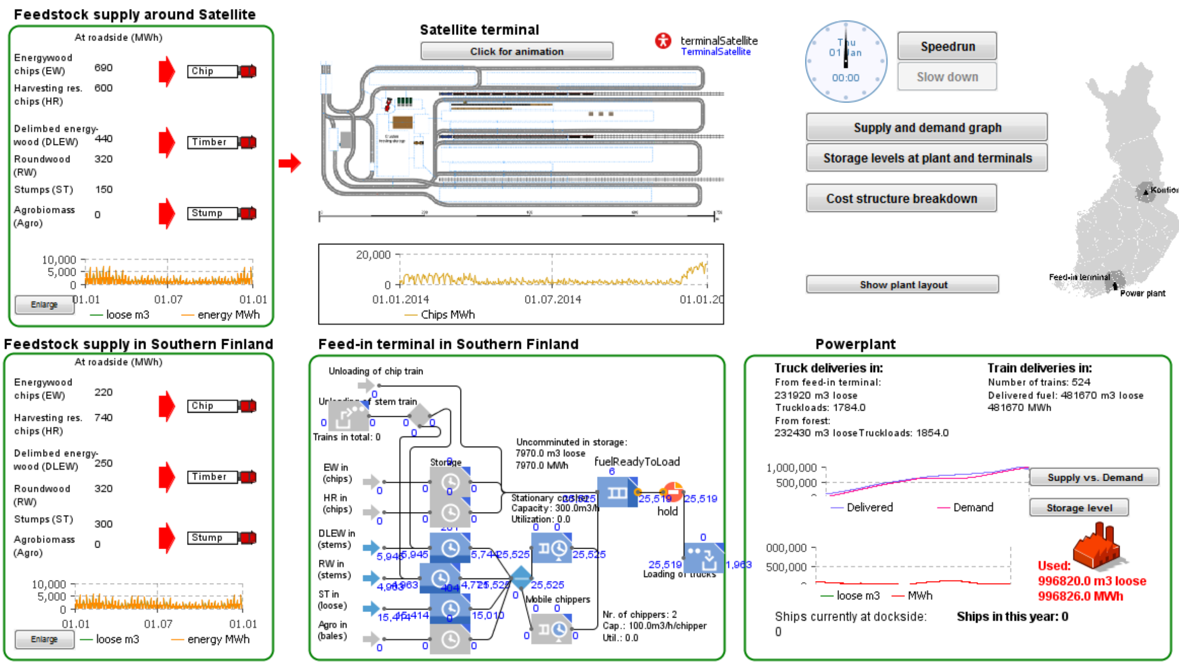

Figure 2. The simulation user interface after the start of a simulation run.

2.3 Feedstock availability analyses

2.3.1 Forest biomass

Forest biomass availability analysis was based on a method presented in the authors' earlier studies on forest-fuel supply costs and emissions deriving from supply logistics (Korpinen et al. 2013, Jäppinen et al. 2014). Source data was based on techno-economic harvest potentials of forest-fuel presented by Anttila et al. (2009), present use of forest-fuels in Finland (Torvelainen et al. 2014), and pulpwood cutting statistics (Metsäntutkimuslaitos

2014). It was assumed that the new power plant could access the remaining potential after the current use of forest fuels. As the pulpwood potential represents the current cutting level, the new power plant was expected to be capable of paying more than the current roadside prices whenever it needs pulpwood as its feedstock. This calculation method is presented on a general level in Fig. 3 and more detailed in presentations given at two Task 2.2 meetings (Jäppinen & Korpinen 2014).

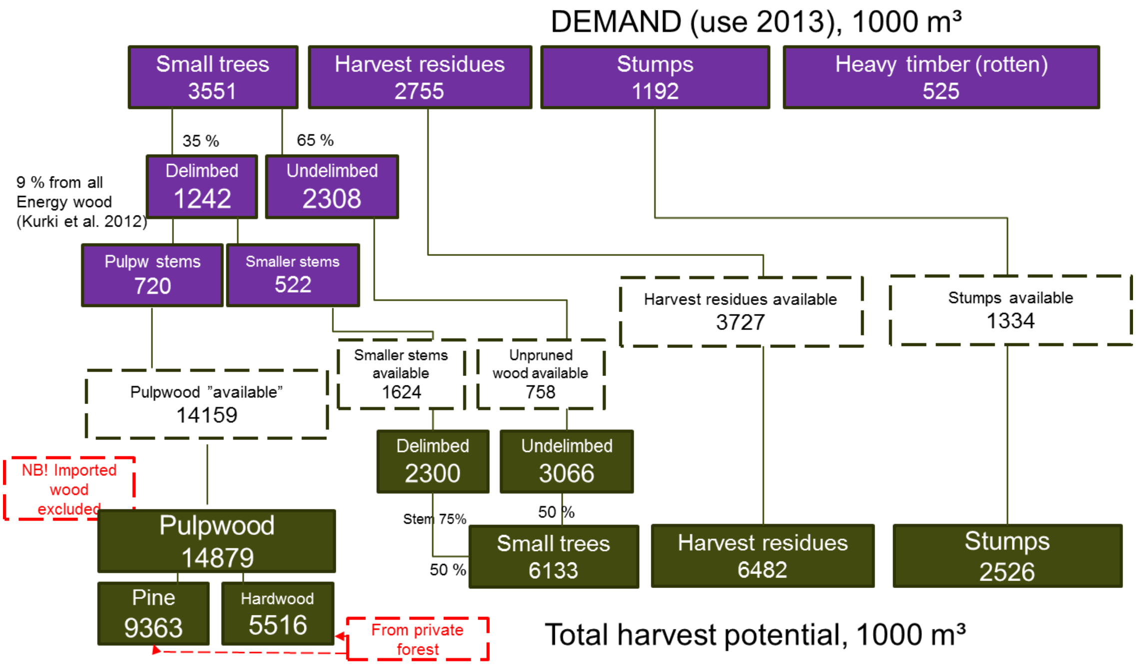

Figure 3. Flowchart representing the calculation of forest-fuel availability to the demand point of the case. Percentual figures without citation are based on the authors' own assumptions.

2.3.2 Straw

Straw was the only non-wood biomass type included in the model. Material for the feedstock availability analysis was acquired from the national field plot register, regional grain harvest, and animal production and reports about energy biomass potential from agriculture (Pahkala et al. 2009, Pahkala & Lötjönen 2012). The field plots and statistics were both provided by the Information Centre of the Ministry of Forestry and Agriculture. The techno-economic harvest potential was further limited by competing use for animal bedding. It was considered as the primary use ahead of energy straw due to the differences in paying capability. A more detailed description of the GIS-based calculation procedure will be published later on in 2015 (Korpinen et al. 2015).

2.4 Transport cost analysis

Truck transport costs between roadside storages and terminals or the power plant were based on costs' dependency on transport distances reported by Laitila et al. (2010) and Laitila and Väätäinen (2011). Average costs matching the annual demand for each fuel type from both supply areas were found through a GIS-based supply area analysis (Korpinen et al. 2013). The correct extent of the supply area was calculated for each fraction and, consequently, average transport distance in the area was matched with respective cost. An example of the results of the analysis is presented in Fig. 4. Competition for each fuel type in both regions was accounted for in the analysis.

Other transportation modes that were included in the model (i.e. transportation between terminals and power plant) were based on fixed transport routes, and thus costs for these actions were to be defined by the user. However, time usage for these actions was not variable. For feed-in transportation it was assumed that the truck deliveries take 30 minutes. For train transportation it was assumed that a train spends 24 hours for its rotation.

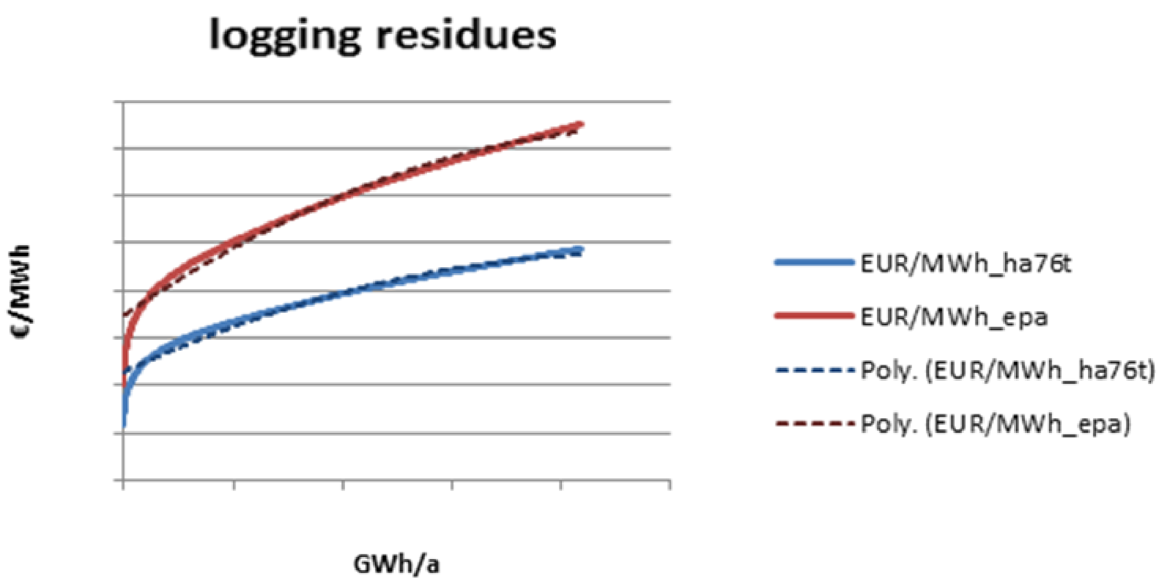

Figure 4. An example of case-specific costs for truck transportation as a function of annual demand. Blue is for chips and red for uncomminuted materials. A solid line represents results from the GIS analysis. The equations represented by dashed trendlines in the picture were entered into the simulation model.

2.5 User-defined parameters

Simulation parameters to be defined by the user are presented entirely in Appendix I, which consists of screenshots about the user interface of the model. In general, this group of parameters included following subjects:

- Annual volume of material flow
  - Biofuel demand
  - Proportion of supply (% of demand) by ship
  - Proportion of supply (% of demand) by train (from the satellite terminal in Kainuu)
  - Proportions of fuel types (% of demand per supply area)
- Fuel properties
  - Energy contents at roadside (MWh/m³)

  - Loose densities before and after comminution (m^3_{loose}/m^3)
- Fleet
  - Number of chip trucks, energy wood (or "stump trucks"), timber trucks, and terminal trucks and their cargo capacities
  - Number of trains for chip transportation, train cars, and containers per car and container volumes
  - Option for using roundwood trains
  - Capacities for stationary crushers and mobile chippers at feed-in and satellite terminal
  - Compaction rates of biomass in comminution operations
- Prioritization of biomass pickups from the roadside
- Supply-chain costs
  - Roadside costs of each fuel type
  - Comminution costs
  - Unloading costs at terminals
  - Additional costs for different fuel types and different transport chains
  - Costs of transportation by rail and loading of trains
  - Storage costs for each storage in the supply system
  - Costs of feed-in-truck transportation
- Distribution of demand and supply (of each fuel type) over time

2.6 Simulation output

Graphical presentations about the supply meeting the demand (Fig. 5), storage levels at roadside, terminals and plant, and the breakdown of used transport solutions (Fig. 6) were included in the model to indicate the performance of the supply system. In addition, average costs at the power plant gate were presented as numerical data for each fuel type and each transport solution.

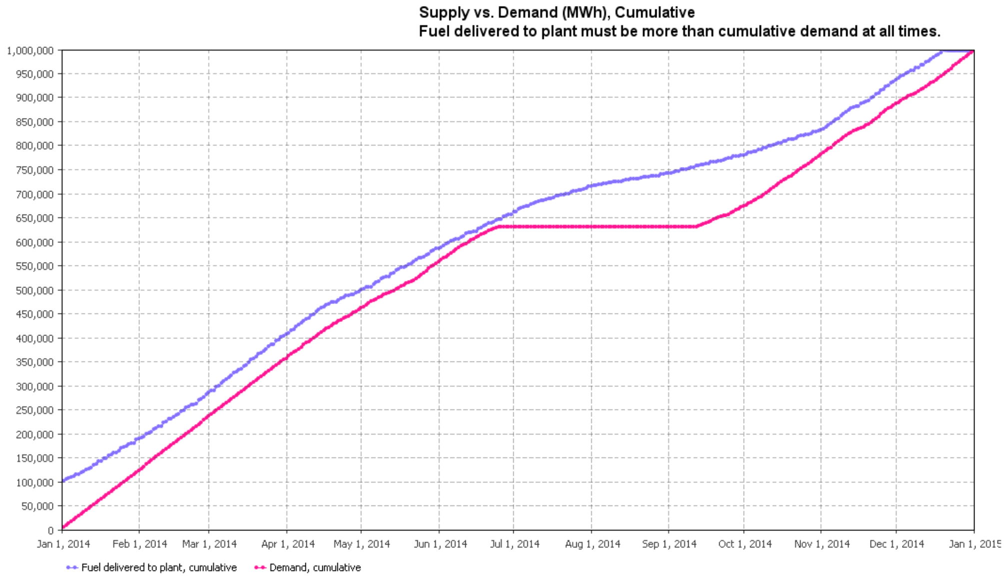

Figure 5. Supply and demand of a power plant according to a one-year simulation run.

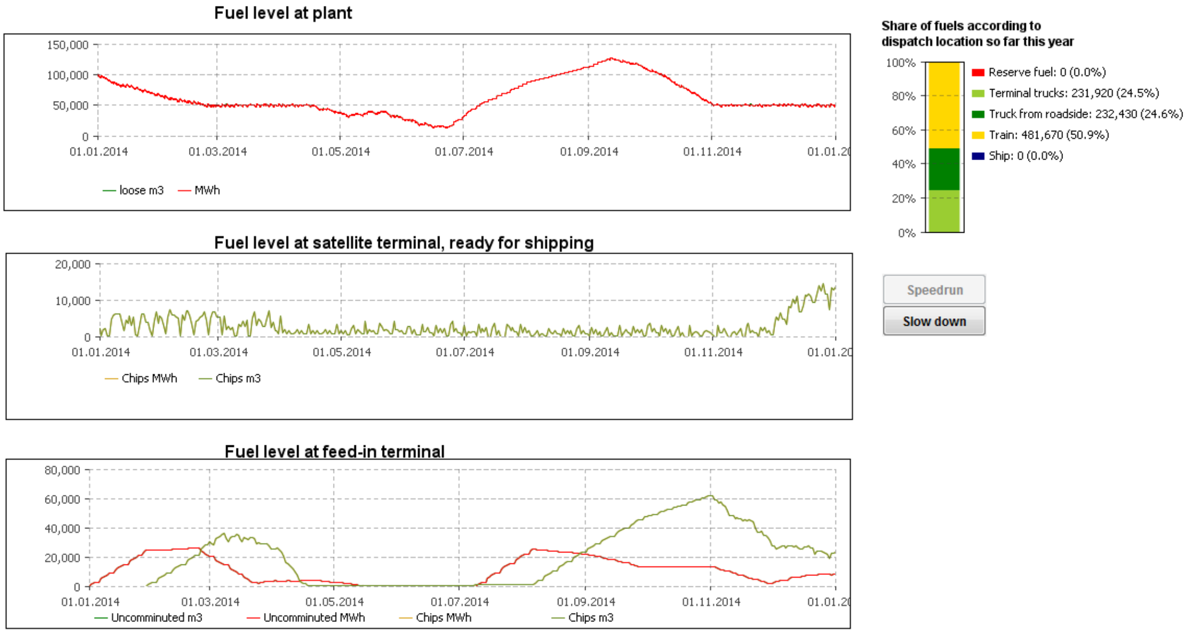

Figure 6. Fuel levels at the power plant and terminals according to a one-year simulation run.

As a special feature, an animation presenting the actions at the satellite terminal was added to the model (Fig. 7). This was done to demonstrate the possible bottlenecks of terminal operations, e.g. if handling capacity or transport capacity of trains is exceeded.

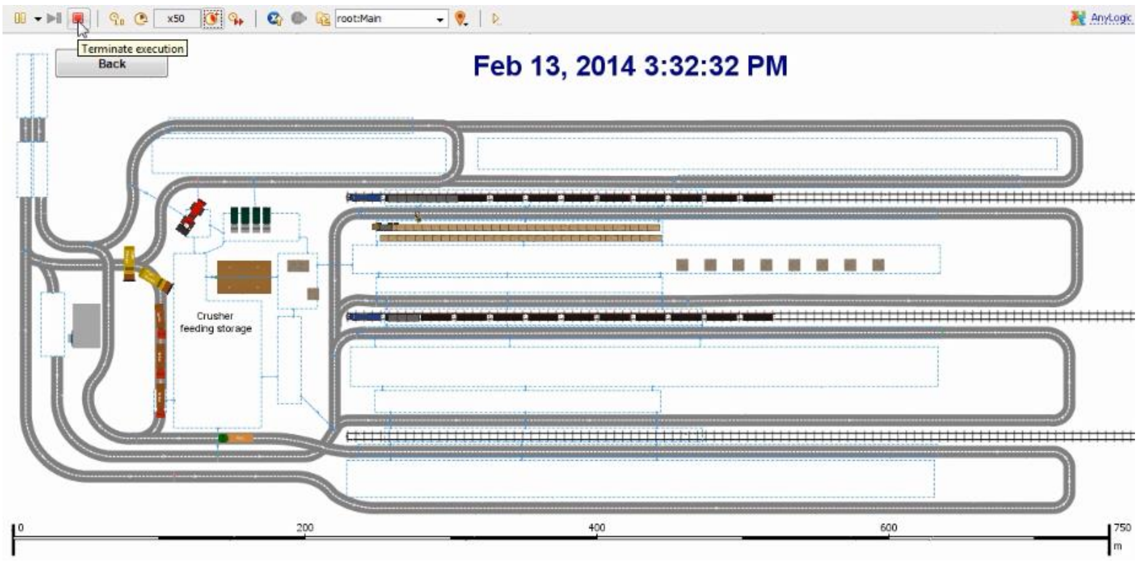

Figure 7. A snapshot from an animation of terminal operations. Grey “roads” represent the optimal vehicle trails. The actions are linked to the simulation of the entire supply chain.

3 Case II: Terminal network of a bioproduct mill

3.1 Case setup

The starting point of the case differed from Case I because the model was adapted to an existing logistics environment for feedstock supply. Furthermore, the supervising industrial partner, Metsä Group (MG), had extensive experience in logistics operations and was able to provide sufficient information about the essential parameters. The model application was designed so that it did not include a specific user interface for entering parameters. Instead, it was designed to import all required data from a database (MS Access) or a set of databases. The bioproduct mill (Metsä Group 2015) will most probably have a radical impact on the wood procurement streams and, supposedly, request for new terminal hubs. The main questions of the study were: 1) are the proposed new terminal hubs in the right place in terms of total logistics cost and 2) are they of sufficient capacity for storage? In this case, the focus was only on pine, spruce, and birch pulpwood transportation.

3.2 Model building

3.2.1 Origin points and terminal hubs

While the number of feedstock types was relatively small, the challenge of modelling the supply system came from a complex network of terminals and thus several possible solutions for transportation routes. Seasonal changes in both supply and demand were also accounted for. Total feedstock demand of the mill was assumed to be stable year round, but for downtimes of sawmilling industries the expected demand for roundwood was scaled up to compensate the lack of sawmilling residues. The harvest intensity was assumed to have similar seasonality to that of monthly logging statistics (Metsäntutkimuslaitos 2014).

Annual supply and demand were given as solid cubic meters (m^3) over bark by MG. It was assumed that the solid volumes did not change in any condition, but transportation capacity of trucks was decreased in the winter period from December to March (Korpilahti 2013). Supply volumes of the three feedstock types were connected to the origin point network in GIS where each point represented roadside storages that are usually operated by one transportation company. Additionally, MG gave 18 geographical locations for terminals that could be used for storage and transshipment of feedstock. Also, maximum storage capacities were given. A feed-in terminal was included in the study, but its location was not given, presuming that the terminal would be placed in close proximity of the mill. All the locations with geographical references were numbered with the following ID-numbers:

- 0 = bioproduct mill
- 1–7 = rail terminal
- 8–18 = highway terminal
- 66–759 = origin point representing a group of roadside storages

As may be observed, the numbering of origin points (498 points in total) was not consecutive. Highway terminal represents a hub where the load can be moved from a conventional truck onto a truck with higher transport capacity. Rail terminal represents a hub where the load can be moved from a conventional truck onto rail wagons. In this context, the mill was not considered a rail terminal, although it was the arrival station of rail deliveries. It was assumed that all the hubs have their own loading devices. The use of a truck's own crane loader was excluded from the study, assuming that it could leave the loading device to the area the origin point represents when hauling full loads.

Since data imports in this case were to be based on external database elements, information about of origin point and terminal hub properties was saved in database tables. The origin point table included the following data:

- Geographic coordinates
- Annual supply of pine, spruce, and birch, m^3
- Number of trucks operating from the point
- Truck availability, % of time

Truck availability was based on the assumption that each truck could deliver wood to several end-use locations, as well as power plants. In this case, the impact of this variable was that the truck was not always available to pick up the feedstock at the roadside but caused a delay in delivery. The higher availability the truck had, the better the punctuality of pick-up.

The terminal hub table included the following data:

- Geographic coordinates
- Storing capacity, m^3
- Annual cost, €
- Loading/unloading cost, €/m^3

Annual cost was applied to all terminal hubs. Nevertheless, it was ignored in the cost calculation of a terminal where no material flow was obtained during the simulation run.

3.2.2 Cost parameters

The simulation task was to fulfil the demand at the mill by minimizing total costs deriving from the supply chain. Theoretically, each entity ("payload") departing from an origin point had three alternatives about what kind of transport solution it would use: 1) direct truck transportation to the mill; 2) truck transportation to a rail terminal and further train transportation to the mill; or 3) truck transportation to a highway terminal and further transportation with a 76-t truck to the mill. The selection was based on a database query (MS Access) that gathered the information about the costs of each transport mode (vehicles), distances from origin points to the mill and other hubs (imported from GIS), and investment and material handling costs at terminal hubs (Fig. 8). The results of that query were imported to the simulation model.

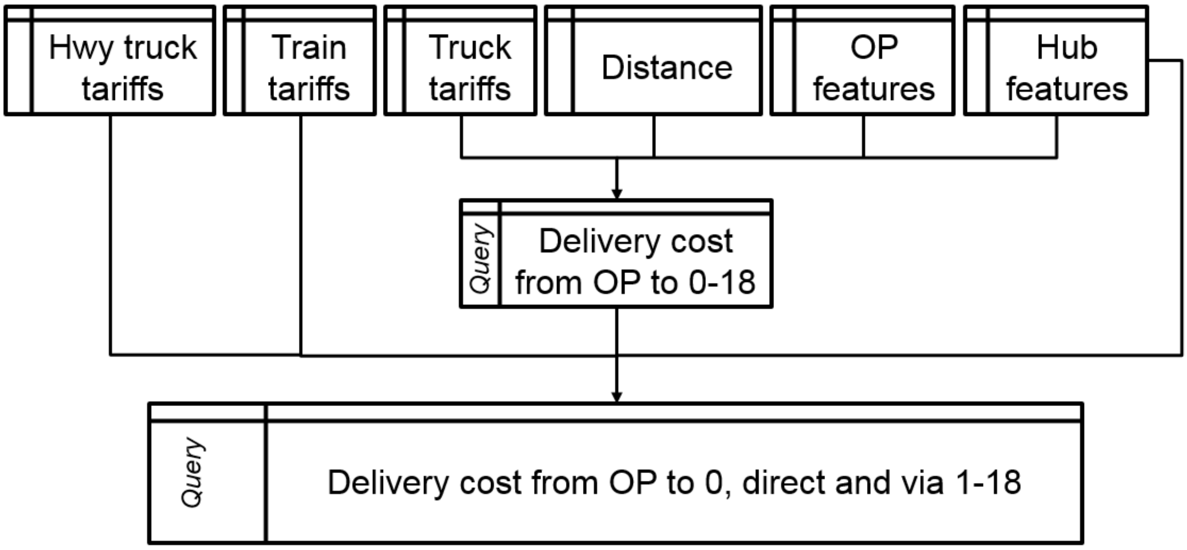

Figure 8. Database tables and queries that were used in aggregation of the cost matrix for decisions on transport solution. OP = origin point.

Entities' cost accumulation in the simulation runtime environment was not entirely based on the same procedure as the database query presented in Fig 8. Because the capacity of the mill yard was limited, it was assumed that the trucks approaching the mill gates were directed to the feed-in terminal if the stock at the mill met a predefined maximum limit. It was assumed that the feed-in terminal did not include rail sidings, and thus trains were given the priority to be unloaded at the mill yard. This was applied also for the trucks operating from highway terminals, as they were expected to hold the feedstock at highway terminals as long as the mill yard was empty enough. The procedure is illustrated in Fig 9. Costs "F" and "f" stand for additional costs that derive from using the feed-in terminal, and these costs were not included in the procedure for finding the optimal transport solution.

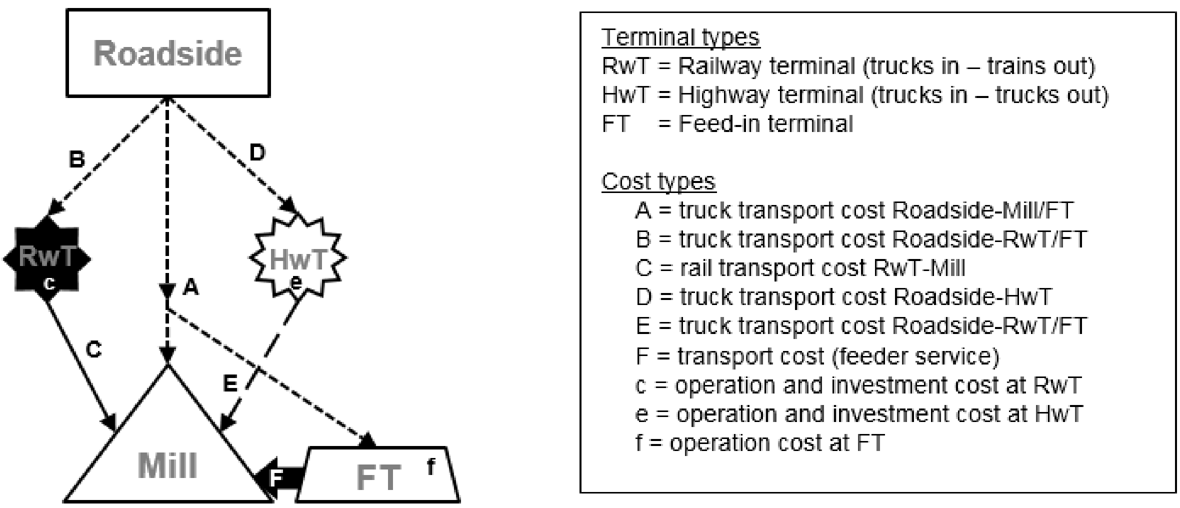

Figure 9. Runtime cost-calculation procedure for entities using different transport solutions. "Roadside" equals an origin point in the simulation environment.

The distance table (Fig. 8) included the shortest possible routes by road between the origin points (66–759) and the hubs (0–18). The maximum distances were 300 km when the destination was the mill (hub 0), 150 km when the destination was a rail terminal (1–7), and 100 km when the destination was a highway terminal (8–18). While the demand point was located in Central Finland and its supply area with a 300-km radius covered the most forested regions of the country, the majority of origin points (393 out of 498) were given a possibility for direct transportation to the mill. From these points there were at least 4 and at most 12 different transport solutions, while the average was 7. Deliveries from the remaining 105 points were to be carried out via rail or highway terminals in any case. For these points, there were on average three and at most five alternative terminals to be used. Only one solution was possible for 23 origin points. A graphical presentation concerning deliveries from three origin points in different parts of the study area is given in Fig. 10.

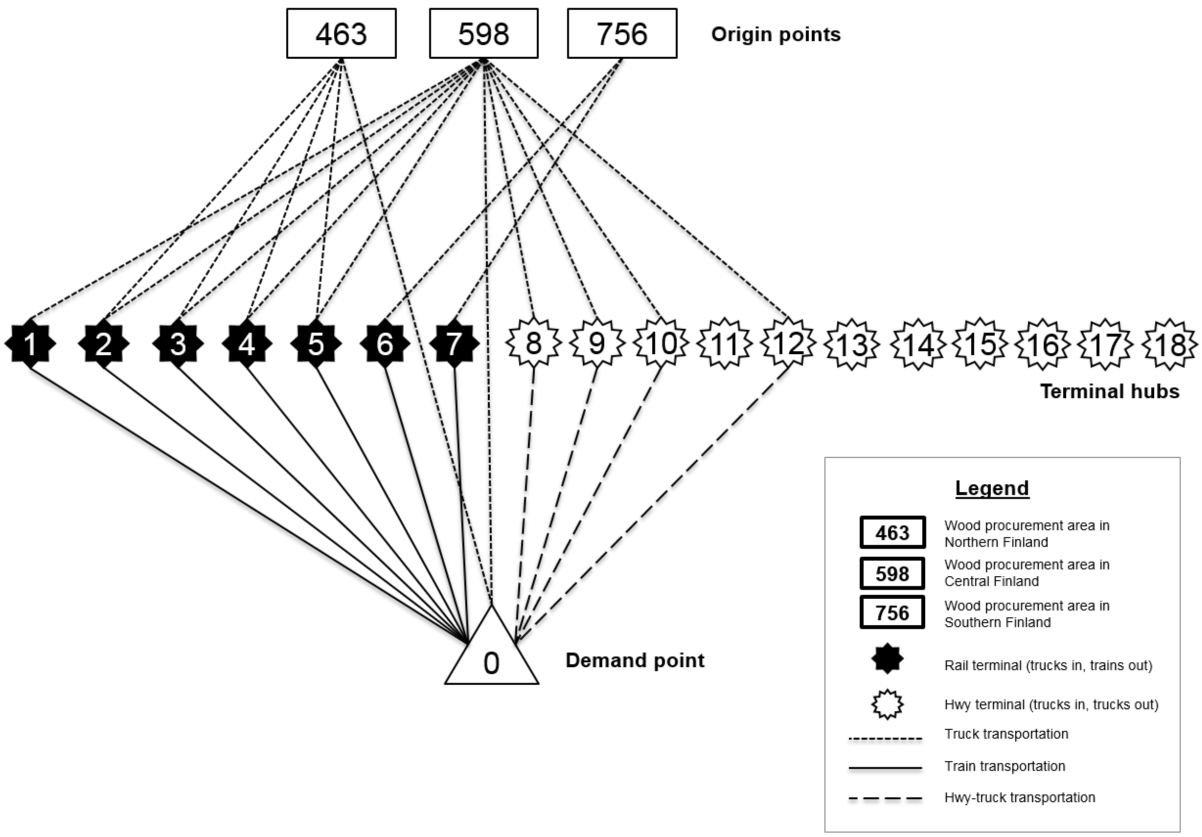

Figure 10. Example of transport solutions to the demand point from three origin points representing smaller supply areas in different parts of the country.

3.2.3 Temporal parameters

Time usage of each action in the simulation model did not have any direct impact on transport solutions or the costs deriving from the operations. In a discrete-event simulation it is, however, essential that delays (i.e. time used in operations) are defined as promptly as possible, because the purpose is to answer how significant the seasonal differences in supply and demand are and how they could be balanced.

The simulation run was programmed to start from 7 AM on 1 Jan 2015 and last until 7 AM on 26 Jan 2016. Because total volumes of supply at roadside and demand at the mill were equal and fulfilling the demand in the beginning takes time, two pre-adjustments were made in the model: 1) the mill had an initial stock of 80,000 m^3 to be used until the first deliveries arrive to the mill; and 2) the mill stopped at the end of 2015 but the simulation was still to be run for 25 days for procuring the remaining wood from terminals and roadside to the mill.

Both the available volumes at origin points and the feedstock demand at the mill were updated every day at 8 AM. The task for trucks was to begin loading of wood in the origin point at the same time and, after the loading phase, to make a decision about the optimal transport solution and transport the wood to the selected destination. A single truck was expected to repeat this procedure as long as there was at least one full truckload available at the origin point. If there was not a sufficient amount available, the truck should wait at the origin point until more wood was generated, usually until the next morning (8 AM). Time usage in loading, unloading, and feed-in-terminal operations was either universal or dependent on the size of the truckload (Table 1). For truck transportation, including highway trucks, time usage was based on route distances and road properties. Driving speeds were 70 km/h on the major highway network (speed limit of 80 km/h or more), 50 km/h on regional road network (speed limit of 50–70 km/h) and 20 km/h on the remaining roads. Trains were assumed to spend 150–450 min for a one-way trip, depending on the terminal hub of departure.

Table 1. Time usage parameters of loading and unloading actions and operations at the feed-in terminal. Hwy = highway.

Action	Vehicle	Place	Time usage
Loading	Truck	Origin point	72 s per m^3
	Train	Rail terminal (1–7)	20 s per m^3
	Hwy truck	Hwy terminal (8–18)	36 s per m^3
Unloading	Truck	Rail terminal (1–7)	20 s per m^3
	Truck	Hwy terminal (8–18)	20 s per m^3
	Truck/Hwy truck	Mill/feed-in terminal	19 min
	Train	Mill/feed-in terminal	334 min
Feeding	Feeder vehicle*	Mill environment	15 min

* e.g. a grab wheel loader or a special truck-trailer

3.2.4 Balancing supply and demand

The solution for balancing the differences in supply and demand was based on sufficient storage capacities at terminals. The mill yard was assumed to have a maximum storage capacity of a predefined amount. Storage capacities at rail terminals were smaller than the ones at highway terminals. The origin points and the feed-in terminal did not have limitations on storage space. The stock at the mill yard had also a minimum limit. If the stock was about to go below this limit, more feedstock was called in from the feed-in terminal. If the stock was about to exceed the maximum limit, trains and highway trucks were forced to hold the deliveries at terminals and other trucks were guided to drive to the feed-in terminal. To make this decision, the model summed up the prevailing stock volume and the volume being transported at the respective moment.

3.3 Simulation output

The simulation tool included five different interfaces for following a simulation run: 1) Stock levels at the mill and feed-in terminal; 2) stock levels at origin points and rail and highway terminals; 3) utilization of trucks and terminals; 4) cost accumulation; and 5) map-based follow-up.

3.3.1 Mill and feed-in terminal

A simulation run that was demonstrated in the study resulted in fluctuating stock levels at the mill and the feed-in terminal (Fig. 11). The mill used its initial stock in a few days and after that began to consume the feedstock that already arrived at the mill from the origin points. During spring the production at origin points exceeded the demand and thus the surplus feedstock was stored at the feed-in terminal. In the summer the production volumes decreased and the mill began to call in deliveries from the feed-in terminal. The feed-in terminal could not, however, fulfil all the demand, and, in late autumn, the mill faced a situation of unfulfilled demand. In December the increased deliveries from the origin points allowed the mill to recover from the feedstock shortage.

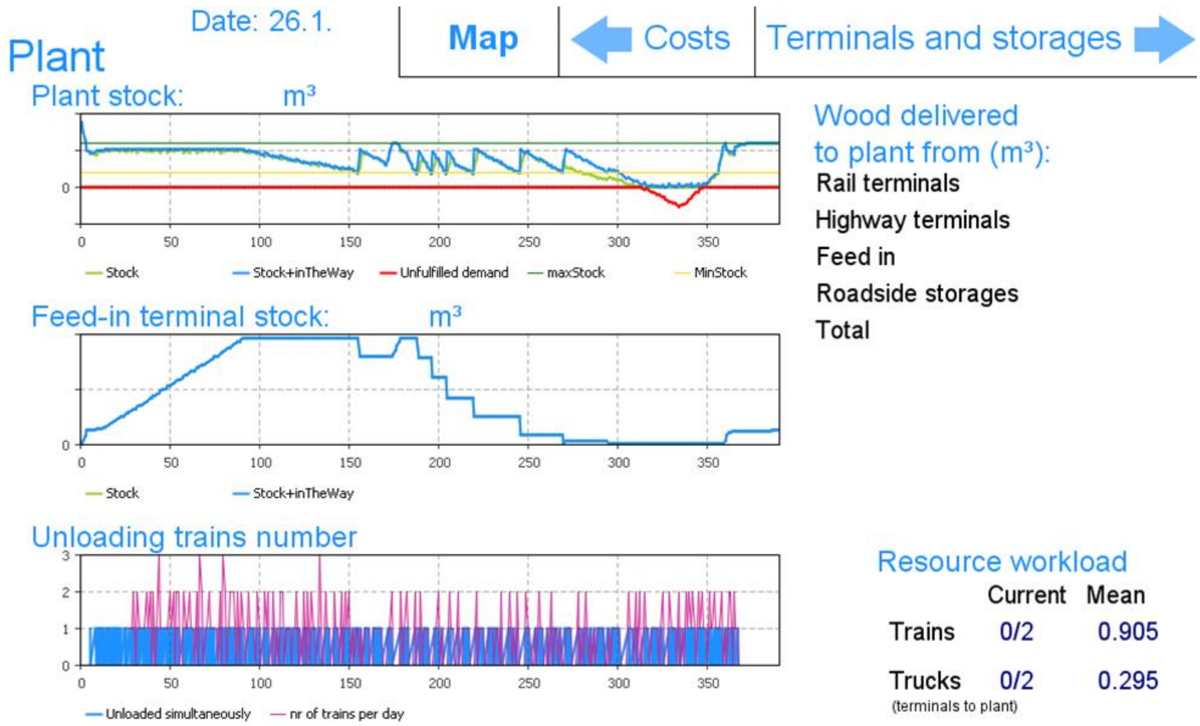

Figure 11. Feedstock levels at the mill and feed-in terminal and intensity of train deliveries during a simulation run. Graphics are partly hidden from the picture due to confidentiality.

3.3.2 Terminals and origin points

Feedstock levels at terminals and origin points could be followed as a whole or separately for each terminal, each origin point, and each wood type (Fig. 12). The workload of trucks was also reported as the number of trucks operating at the respective point of time and on average. The truck transportation cost from origin points directly to the mill or to the terminals was reported as the average of completed deliveries. It should be noted that because the truck was allowed to pick up only full truckloads, there was ca. 9,000 m³ of feedstock left at the origin points at the end of the simulation run. Respectively, ca. 7 000 m³ was not delivered from rail and highway terminals.

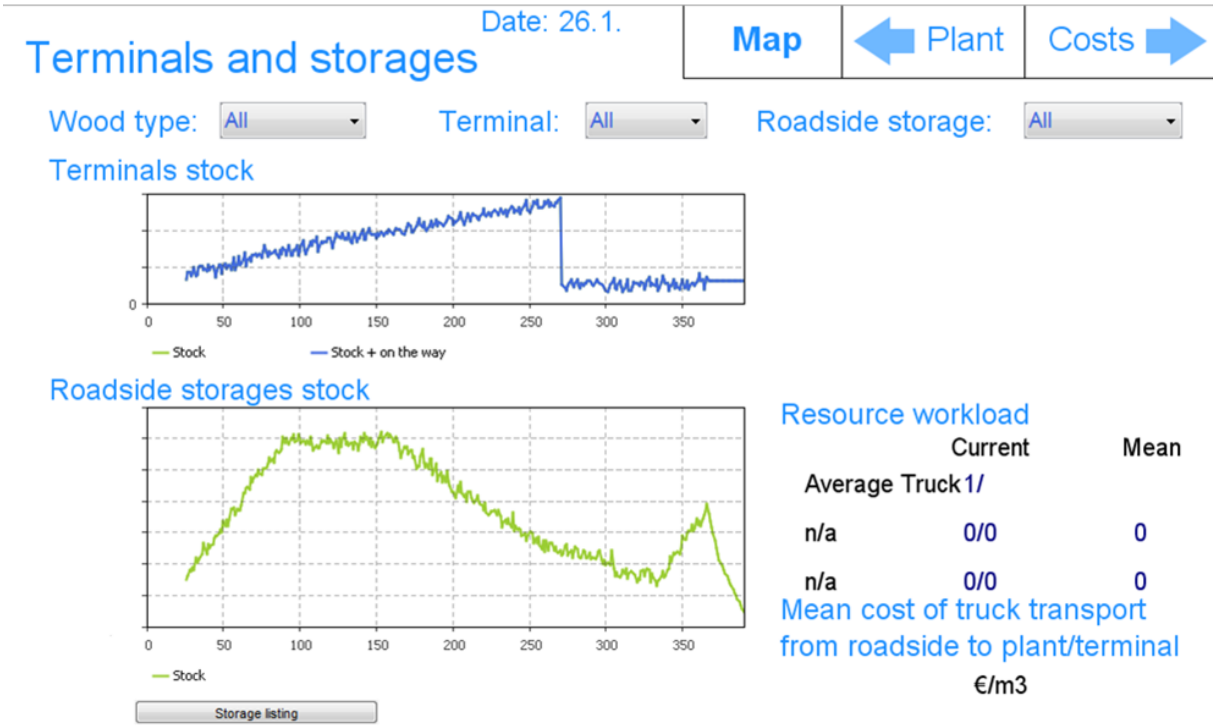

Figure 12. Feedstock levels at rail and highway terminals and origin points during a simulation run. Mean costs are hidden from the picture due to confidentiality.

In addition to the graphical presentation of storage levels, more detailed statistics regarding utilization rates and terminal capacity usage were presented in a separate storage listing view (Fig. 13). This information could, for example, support the decision-making of how large terminals should be built in relation to storage rotation or if additional trucks are needed to balance the oversupply of a certain origin point.

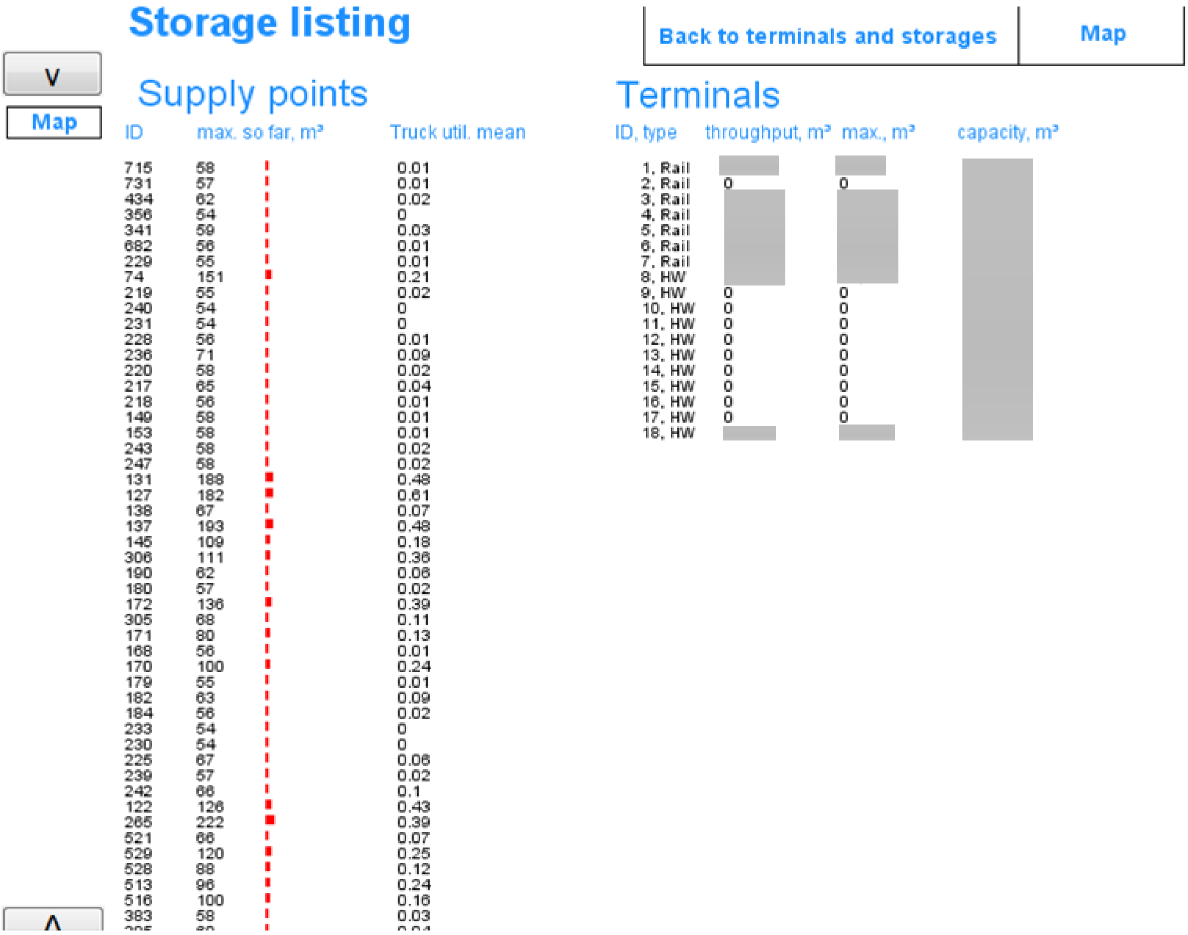

Figure 13. Utilization statistics of trucks per origin point and rail and highway terminals. Confidential data are covered with grey fields.

3.3.3 Cost accumulation

Cost statistics were collected as a cumulative sum during the simulation run. The figures have been hidden from Fig. 14 because initial cost data were confidential.

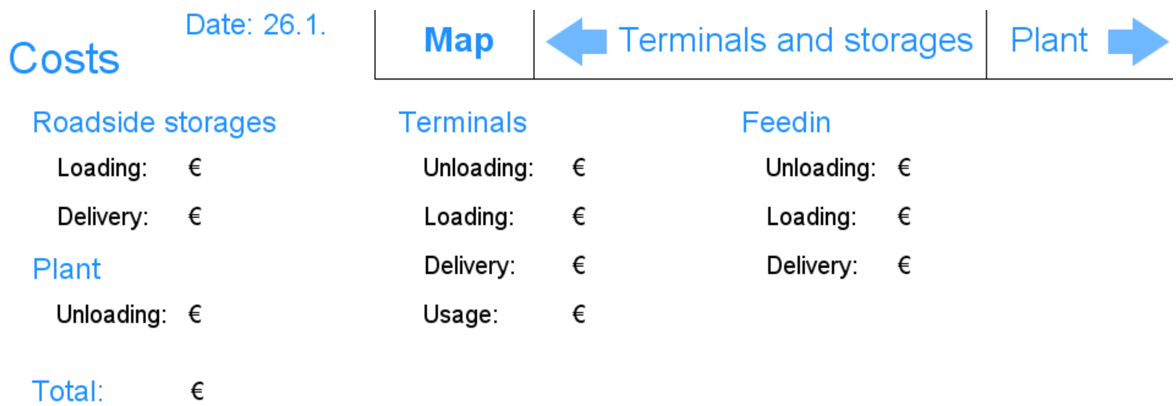

Figure 14. Cost breakdown statistics. The results of a simulation run are hidden from the picture due to confidentiality.

3.3.4 Map view

The map presentation included truck and train transportation between origin points, terminal hubs, and the mill. Empty returns were included in the presentation. Transportation routes were based on OpenStreetMap (2015) GIS platform, where the route network has been provided automatically. The route network for train transportation (Finnish Transport Agency 2014) was digitized manually onto the map layer. An interactive map view visualizing full-load trucks approaching the mill and an empty train moving away from the mill is presented in Fig. 15.

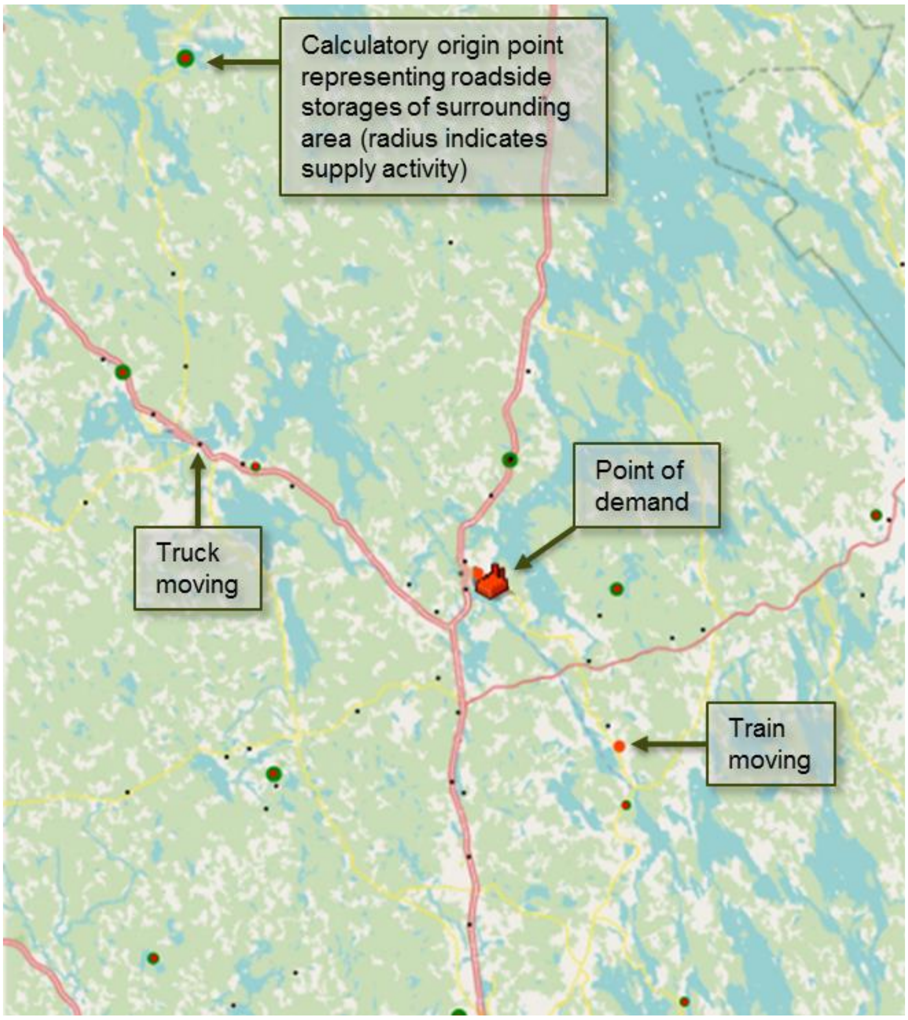

Figure 15. A screenshot from the map-based follow-up of the simulation run and explanations of the features included. The view has been zoomed in to the surroundings of the mill. Rail network, rural road network, and terminal locations are not included in this view, but can be observed with another zoom level.

4 Conclusions

Two dynamic simulation modelling tools were built for assessment and optimization of biomass logistics. They included all relevant steps of the supply chain and accounted for temporal variation in supply and demand. The models also included modules for spatial assessment of feedstock resources and a procedure explaining how to import spatial datasets into the model. This is important principally because spatial data are usually stored in large datasets in different formats, and it must be preprocessed into a format the simulation model can interpret. In Case I this was carried out by a separate feedstock availability and transport cost analysis, and it was imported to the model from an MS Excel spreadsheet file. In Case II, there were 11 different MS Access databases the model could import data from, and the transport cost analysis took place in those databases. The data processing methods of both cases are summarized in Fig. 16.

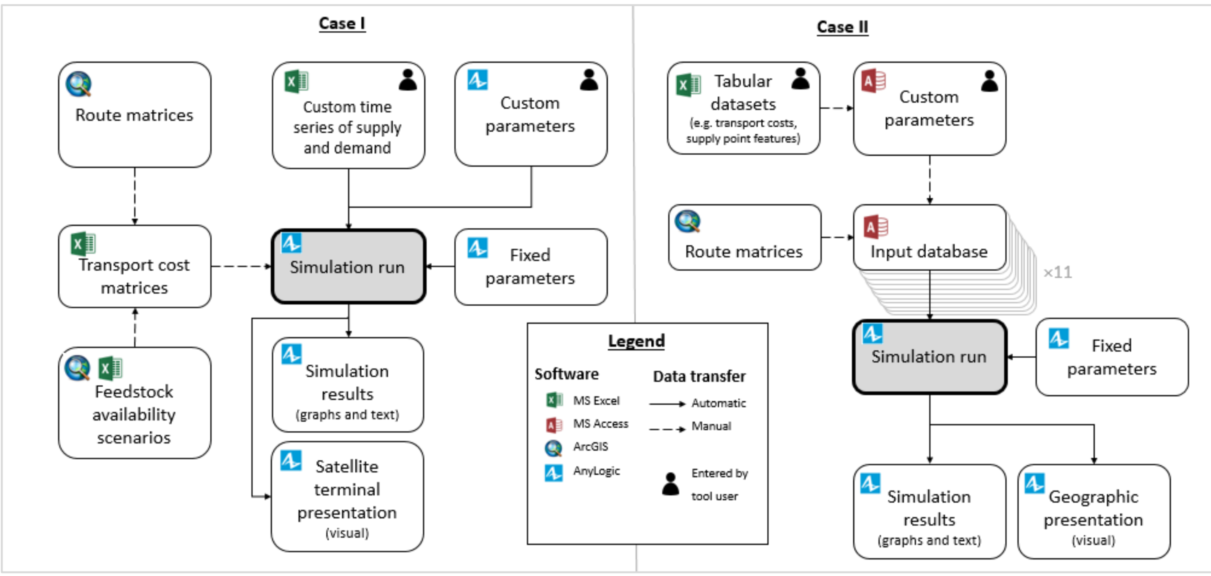

Figure 16. Data processing workflow in the study cases.

As previously underlined in Chapter 1, temporal variation should not be disregarded when analyzing large and complex supply systems. This was also indicated by the test run scenarios of both models. Feedstock shortage was very close in the summer in Case I (Fig. 5), and the simulation of Case II ran into a situation of unfulfilled demand (Fig. 11). The lessons learned for the next simulation run were that some parts of the logistics chain should be enhanced by increasing storage and transport capacities, for example.

Attention was also paid to how such a complex system can be presented in a concise view but still give a comprehensive impression about what happens in different parts of the supply chain during the run. In Case I this challenge was engaged by presenting the feedstock flow in a generalized process chart and additional information about the geographical extent of supply through a suggestive supply area map (Fig. 2). Moreover, internal operations of one terminal were presented in an animated view that was linked with the main menu (Fig. 7). In Case II the visualization was conducted on an interactive map with a direct connection to a GIS server (Fig. 15). This type of presentation could be informative not only for the industrial operator but also administrative organizations, such as municipal and regional construction and traffic planning authorities.

A distinctive need for improvement would be in the routing of trucks in Case II. Because the trucks' decision about where to drive was based only on the static calculation of logistics costs, the model did not take into account possible gains from choosing a more time-saving option that was second best in the static calculation. For example, if an origin point had a high biomass production and the most economical delivery method was direct transportation to the mill, one truck could probably not empty the storages in a given amount of time (i.e. 24 hours) if the transportation distance was too long. Instead, the truck could deliver the feedstock to a nearby terminal, saving delivery time and completing its daily task of emptying the roadside storages before new stocks are generated (Example 4 in Table 2). On the other hand, the number of trucks at the origin point could be increased, but that could also result in a poor performance rate for trucks in some cases.

Table 2. Examples of the truck number and transportation time affecting a truck's capacity to balance supply at two origin points (OP) of similar biomass production speed.

	Departure - destination	Biomass production at OP per day	Number of trucks at OP	Transport capacity per truck, m^3	Roundtrip per truck (incl. loadings), h	Supply in balance?
1	OP1 - mill	100	1	50	11	Yes
2	OP2 - mill	100	1	50	14	No
3	OP2 - mill	100	2	50	14	Yes
4	OP2 - terminal hub	100	1	50	7	Yes

From the tool user's point of view, data imports from spreadsheet files and databases to the models were undemanding to conduct, but a clear disadvantage was that the method could not be used for online model applications. The reason lies in the Java Applet protocol the online model service (AnyLogic 2015b) is using. It supports imports only from text files and MS Excel spreadsheet files. Even in spreadsheet imports the file should be saved on the user's computer before using the online application. This problem should be solved in the future, because the online application is the best way to share and disseminate the results of the modelling work without purchasing expensive software licences.

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Appendix I. Feed-in parameters of Case I.

Biofuel supply simulation

Click for further parameters

- Fuel properties
- Transportation fleet
- Comminution equipment
- Compaction
- Pick-up priorities at roadside
- Feedstock costs
- Train transportation
- Storage costs
- Feed-in truck costs
- Supply and demand timing
- Glossary and info

Annual demand (GWh) 1000

Share of supply by ship (% of total biomass use) 10 = 100.0 GWh/a

Set ship size in MWh 40000

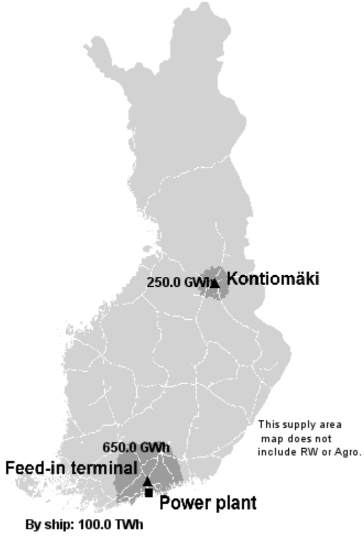
Ship size in m3 cargo space (updates automatically):
10000.0 loose m3 Note: max. ship size is 140 000 loose m3 to Vuosaari

Share of supply from satellite terminal in Satellite (%) 25 = 250.0 GWh/a

Share of different fuels (%, energy content, on annual basis)

	Southern Finland, %	Needed amount, GWh	Max. amount available, with 225 km driving radius, GWh
EW	17	110	31
HR	17	110	1,699
ST	17	110	848
DLEW	17	110	806
RW	16	104	9,197
Agro	16	104	2,191
SUM (must equal 100)	100 OK		

	Satellite terminal, %	Needed amount, GWh	Max. amount available, with 150 km driving radius, GWh
EW	20	50	694
HR	20	50	1,470
ST	20	50	321
DLEW	20	50	789
RW	20	50	4,417
Agro	0	0	0
Other fuel	0	0	0
SUM (must equal 100)	100 OK		



Run the model and switch to Main view

Fuel properties

Energy contents (MWh/m3solid)		Loose densities during first transport and storage (m3solid/m3loose)	
HR	2	HR, chipped	0.5
EW	2	EW, chipped	0.5
ST	2	ST, loose pieces	0.5
DLEW	2	DLEW, stems	0.5
RW	2	RW, stems	0.5
Agro	2	Agro, bales	0.5
Other fuel	2	Other fuel, chipped	0.5
Shipped fuel	2	Shipped fuel	0.5
Reserve fuel	2	Reserve fuel (eg. pellets)	0.5

Energy contents represent the feedstock properties at roadside.
The energy content may change due to drying or dry matter losses during the supply chain, these are modelled dynamically during simulation (not functional currently).

Loose density represents the density when loaded into truck at roadside.
For uncomminuted material, the density changes after comminution, which is modelled during simulation.

Loose densities after comminution (m3solid/m3loose)

HR	0.5
EW	0.5
ST	0.5
DLEW	0.5
RW	0.5
Agro	0.5
Other fuel	0.5
Shipped fuel	0.5
Reserve fuel	0.5

Truck fleet

	cargo space (loose m3)	number of units: Southern Finland	number of units: Satellite terminal
Chip trucks (EW and HR)	136	100	100
Stump trucks (ST and Agro)	164	100	100
Timber trucks (DLEW and RW)	119	100	100
Terminal trucks (from feed-in terminal to plant)	136	8	

Cargo space represents the maximum load volume.
In the current version, is is assumed that a truck will not pick up loads that are smaller than 50% of the maximum cargo space.
For smaller loads, the remaining amount is left to picked up the next working day.

Chip trains

Number of trains (1-3): 3
Number of containers per car: 4
Container volume m3 (accuracy 10m3): 70
number of cars: 8
Volume of chips in train: 2240.0 m3 loose

Total train cargo volume (in case of NOT using containers): 2300

Roundwood trains: 2300 | 2

Trucks run 08:00-17:00, Monday-Friday.
Terminal trucks run all the time,if needed (and their number is currently unlimited...).
Trains run all the time.

For deliveries from roadside, each truck gets a working order for each day, and it tries to fulfill the task. If the day's task was too much for one day, the remaining amount is left at the roadside for the next day.

Comminution

	Capacity (m3 loose/h)	Nr. of units
☑ Stationary crusher at feed-in terminal	300	
☑ Stationary crusher at Satellite	300	
Mobile chippers, feed-in terminal	111	20
Mobile chippers, Satellite terminal	111	8

If stationary crushers are not selected, mobile chippers are used.

Capacity (m3 loose/h) means the produced output.

Mobile chippers run 08:00-17:00, Monday-Friday.
Stationary crushers run all the time, if needed.

Compaction of chips during loading

☐ Compaction of chips when loading trucks at feed-in terminal
☐ Compaction of chips when loading the train at Satellite

Set compaction rate for chip trains (0.9 means that 1 loose m3 is squeezed into 0.9 m3 cargo space): 1
Cost of trainload compaction per m3 of cargo space: 0 €/m3 cargo space

Set compaction rate for terminal trucks: 1
Cost of truckload compaction per m3 of cargo space: 0 €/m3 cargo space

Compaction means pressing or squeezing comminuted fuel into the cargo space in order to increase payload.

Compaction rate represents the increased cargo density.
It is assumed that after unloading at destination, the fuel returns to its original loose density.

Priority for pick-up from roadside storages

Prioritization of feedstock pick-up and transportation from roadside storages for each fuel and truck type.

(●) weekly prioritization ( ) monthly prioritization ( ) always or not at all

Select the weeks/months when a given fuel type should be prioritized below.

Select the type that should always be prioritized.
If no prioritization is needed, select this and don't check any boxes.

Around plant and feed-in terminal
weeks

Chip trucks HR		EW		Energy wood and stump trucks Stumps		Agro		Timber trucks DLEW		RW	
1	27	1	27	1	27	1	27	1	27	1	27
2	28	2	28	2	28	2	28	2	28	2	28
3	29	3	29	3	29	3	29	3	29	3	29
4	30	4	30	4	30	4	30	4	30	4	30
5	31	5	31	5	31	5	31	5	31	5	31
6	32	6	32	6	32	6	32	6	32	6	32
7	33	7	33	7	33	7	33	7	33	7	33
8	34	8	34	8	34	8	34	8	34	8	34
9	35	9	35	9	35	9	35	9	35	9	35
10	36	10	36	10	36	10	36	10	36	10	36
11	37	11	37	11	37	11	37	11	37	11	37
12	38	12	38	12	38	12	38	12	38	12	38
13	39	13	39	13	39	13	39	13	39	13	39
14	40	14	40	14	40	14	40	14	40	14	40
15	41	15	41	15	41	15	41	15	41	15	41
16	42	16	42	16	42	16	42	16	42	16	42
17	43	17	43	17	43	17	43	17	43	17	43
18	44	18	44	18	44	18	44	18	44	18	44
19	45	19	45	19	45	19	45	19	45	19	45
20	46	20	46	20	46	20	46	20	46	20	46
21	47	21	47	21	47	21	47	21	47	21	47
22	48	22	48	22	48	22	48	22	48	22	48
23	49	23	49	23	49	23	49	23	49	23	49
24	50	24	50	24	50	24	50	24	50	24	50
25	51	25	51	25	51	25	51	25	51	25	51
26	52	26	52	26	52	26	52	26	52	26	52

Satellite terminal
weeks

Chip trucks HR		EW		Energy wood and stump trucks Stumps		Agro		Timber trucks DLEW		RW	
1	27	1	27	1	27	1	27	1	27	1	27
2	28	2	28	2	28	2	28	2	28	2	28
3	29	3	29	3	29	3	29	3	29	3	29
4	30	4	30	4	30	4	30	4	30	4	30
5	31	5	31	5	31	5	31	5	31	5	31
6	32	6	32	6	32	6	32	6	32	6	32
7	33	7	33	7	33	7	33	7	33	7	33
8	34	8	34	8	34	8	34	8	34	8	34
9	35	9	35	9	35	9	35	9	35	9	35
10	36	10	36	10	36	10	36	10	36	10	36
11	37	11	37	11	37	11	37	11	37	11	37
12	38	12	38	12	38	12	38	12	38	12	38
13	39	13	39	13	39	13	39	13	39	13	39
14	40	14	40	14	40	14	40	14	40	14	40
15	41	15	41	15	41	15	41	15	41	15	41
16	42	16	42	16	42	16	42	16	42	16	42
17	43	17	43	17	43	17	43	17	43	17	43
18	44	18	44	18	44	18	44	18	44	18	44
19	45	19	45	19	45	19	45	19	45	19	45
20	46	20	46	20	46	20	46	20	46	20	46
21	47	21	47	21	47	21	47	21	47	21	47
22	48	22	48	22	48	22	48	22	48	22	48
23	49	23	49	23	49	23	49	23	49	23	49
24	50	24	50	24	50	24	50	24	50	24	50
25	51	25	51	25	51	25	51	25	51	25	51
26	52	26	52	26	52	26	52	26	52	26	52

Feedstock supply chain costs, €/MWh

roadside cost, €/MWh

	Southern Finland	Satellite terminal
EW at roadside	1	1
HR at roadside	1	1
ST at roadside	1	1
DLEW at roadside	1	1
RW at roadside	1	1
Agro at roadside	1	1
Other fuel at roadside		1
Shipped fuel (CIF)	1	
Reserve fuel at plant	1	

unloading with material handling machine (i.e. not trucks own device) cost, €/MWh

	Southern Finland	Satellite terminal
EW unloading	1	1
HR unloading	1	1
ST unloading at terminal	1	1
DLEW unloading at terminal	1	1
RW unloading at terminal	1	1
Agro unloading	1	1
Other fuel unloading		1
Unloading of ships	1	

Discount-% in truck transport for stems, stumps and agro when unloaded with own Device (0-100): 0

comminution cost, €/MWh

	Southern Finland	Satellite terminal
EW chipping at roadside	1	1
HR chipping at roadside	1	1
ST crushing at terminal, stationary crusher	1	1
ST crushing at terminal, mobile chipper	1	1
DLEW chipping, stationary crusher	1	1
DLEW chipping, mobile chipper	1	1
RW chipping at terminal, stationary crusher	1	1
RW chipping at terminal, mobile chipper	1	1
Agro crushing at terminal, stationary crusher	1	1
Agro crushing at terminal, mobile chipper	1	1
Other fuel chipping, stationary crusher		1
Other fuel chipping, mobile chipper		1

EW = Small-diameter energy wood, chipped at roadside
HR = Harvesting residues, chipped at roadside
ST = Stumps, transported as loose stump pieces, crushed at terminals
DLEW = Delimbed small-diameter energy wood, transported as stems in timber truck and chipped at terminal
RW = Roundwood of traditional pulpwood size, transported as stems in timber truck and chipped at terminal
Agro= Agrobiomass such as straw, transported as bales and crushed at terminal
Other fuel = some other fuel from Satellite, such as sawdust

Add extra fixed costs for supply chains, e.g. organizational costs etc. (€/MWh):

Southern Finland | Satellite terminal

	Direct deliveries to plant	Via Feed-in terminal	Via Satellite terminal
EW chips	0	0	0
HR chips	0	0	0
ST, loose		0	0
DLEW, stems		0	0
RW, stems		0	0
Agro, bales		0	0
Other fuel		0	0
Other fuel transport to terminal			1

Train connection to feed-in terminal? ○ Yes ◉ No

☐ Roundwood trains used for DLEW and RW from Satellite to Feed-In Terminal

Train transportation and loading costs, €/m3 loose

	Southern Finland	Satellite terminal
Train loading of chips		1
Train loading of delimbed EW and RW		1
Train transportation of chips to terminal		1
Train transportation of chips to plant		1
Train transportation of DLEW and RW to terminal		1
Train unloading of chips at terminal	1	
Train unloading of DLEW and RW at terminal	1	
Train unloading of chips at plant	1	

☑ costs based on number of trains, not on transported amount of fuel

Storage costs, €/m3 loose

Satellite terminal

Storage of chips at terminals (for material coming in as chips)	1	

	Long term	Only through crusher near storage
Long term storage of DLEW and RW (as stems)	1	1
Long term storage of loose ST	1	1
Storage of agro (bales)	1	1

Feed-In terminal

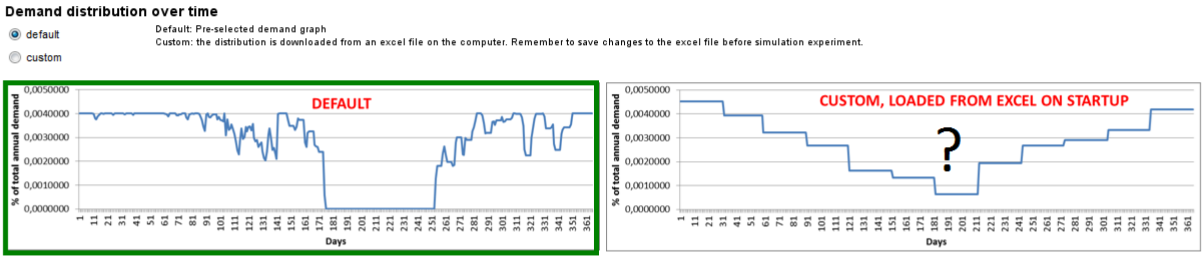
Storage of chips at terminals (for material coming in as chips)	1	☐ add storage costs as chips also to material that is crushed at terminal

	Long term	NOT IN USE NOW Only through crusher near storage
Long term storage of DLEW and RW (as stems)	1	1
Long term storage of loose ST	1	1
Storage of agro (bales)	1	1

Feed-in truck transportation costs, €/MWh

	Southern Finland
Loading of trucks at terminal	1
Transportation Feed-in terminal - plant	1
Unloading of truck at plant	1


default
steady year round
custom
Default: Pre-selected availability distribution for each feedstock-type over time
Steady-year-round: The availability of feedstocks at roadside storages does not differ between months
Custom: the distribution is downloaded from an excel file on the computer. Remember to save the excel file before the simulation experiment.
DEFAULT
STEADY YEAR ROUND
CUSTOM LOADED FROM EXCEL ON STARTUP
?
Energy wood chips
Harvesting residue chips
Stumps
Delimbed energy wood
Round wood (pulp wood size)
Agrobiomass


Demand distribution over time
default
custom
Default: Pre-selected demand graph
Custom: the distribution is downloaded from an excel file on the computer. Remember to save changes to the excel file before simulation experiment.
DEFAULT
CUSTOM, LOADED FROM EXCEL ON STARTUP
?
% of total annual demand
Days