Supplementary document

Lifecycle Assessment of Biomass Supply Chain with the Assistance of Agent-Based Modelling

Raghu KC[1]*, Mika Aalto[1], Olli-Jussi Korpinen[1], Tapio Ranta[1], and Svetlana Proskurina[2]

[1] Lappeenranta Lahti University of Technology LUT, School of Energy Systems, Lönnrotinkatu 7, 50100 Mikkeli, Finland
[2] Lappeenranta Lahti University of Technology LUT, School of Energy Systems, Yliopistonkatu 34, 53850 Lappeenranta
*Correspondence: Raghu.kc@lut.fi Tel.: +358504647457

1. General Information

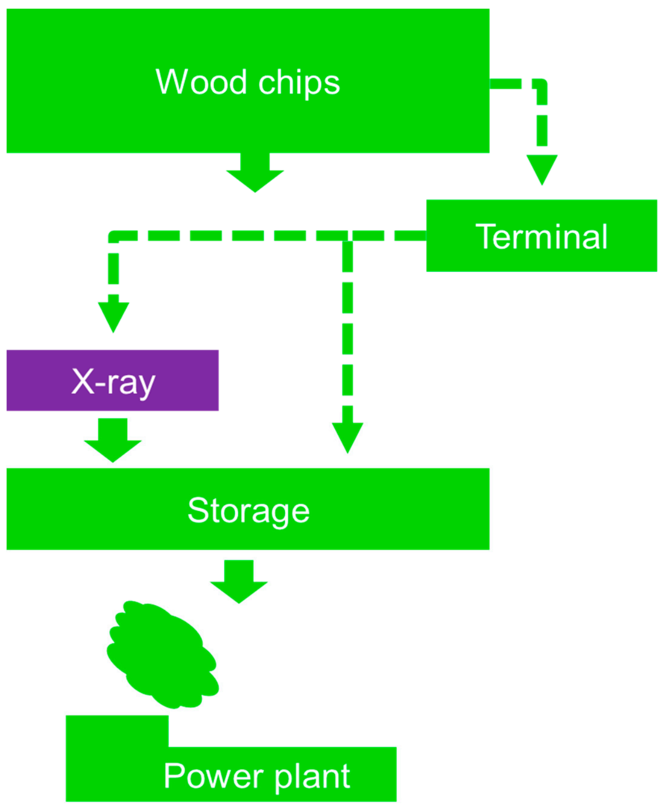

Figure 1. A schematic flow diagram of biomass flow with and without RTM

Table 1. The moisture content of biomasses at a forest roadside

Biomass types	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
WorD	55	55	55	52.5	50	45	40	40	55	55	55	55
HR	47.5	47.5	47.5	45	42.5	35	35	37.5	42.5	47.5	47.5	47.5

Table 2. Road types and their share in different scenarios

Scenarios	Road types and their share (%)		
	Urban road, ≤50 km/h	Rural road, 50–70 km/h	Rural road, ≥80 km/h
A	27 %	11 %	61 %
B	27 %	11 %	62 %
C	27 %	12 %	62 %

Table 3. Biomass properties in different scenarios

Feedstock	MWh/t	t/MWh
AD	2.991	0.334
ADI	2.989	0.335
BD	2.849	0.351
BDI	2.845	0.351
CD	2.751	0.363
CDI	2.746	0.364
BDRTM	2.802	0.357
BDIRTM	2.808	0.356

2. Agent-Based Modelling (ABM)

The purpose of the agent-based simulation model is to study the effect of introducing a real-time quality measurement system to a biomass supply system and how large-capacity marine transportation affects road transportation utilisation. The supply system includes the possibility of storing biomass near the power plant at the terminal. The supply system includes road-side chipping of the feedstocks that are possible to chip and transport logic for transporting stumps for comminuting at the terminal. The supply area of biomass is selected by the user, based on various scenarios, and the maximum supply area in the model is a 120 km radius from the demand point.

2.1. Entities, state variables and scales

The model has six agents that generate the supply system logic that lives in the main agent. The main agent has a map element that uses a geographical information system (GIS) to generate the road network that trucks and chippers use. Roadside, demand point and terminal locations are set based on user input coordinates by using the GIS. The model is capable of doing a multiyear simulation with a refreshed supply for every year.

2.1.1. The fuel entity

Fuel entity agents represent biomass and are generated by a roadside agent. The agent has a fuel type variable that dictates what type of biomass the agent represents. There are six different feedstock types: whole tree or delimbed (WorD), harvest-residue (HR), stump (ST), import, by-product and reserved feedstock. Biomass quality (moisture content and energy density) is set based on the creation month and normal distribution is based on user inputs. The volume that the agent presents is based on the value batch volume that is set to 1 m^3-loose.

2.1.2. Roadside

Roadside agents produce feedstocks. The feedstock is produced in one patch by a dynamic event that is set to be triggered based on harvesting times. Fuel entities are delayed in order to simulate the drying time at the stand and roadside. After the delay time, the roadside state changes from *created* to *available*, and the chipper or stump truck agent can reserve the roadside. After this, the feedstock is gathered and the roadside state changes to *empty,* and the roadside will be destroyed in the model at the start of the next year. Only one fuel type can be held at one roadside storage, but multiple roadside storages can have the same location.

2.1.3. Chippers

The chipper agent goes to an available roadside agent and calls truck agents to gather feedstock. The chipper can be in the states *moving*, *waiting*, *chipping* or *vacant*. The *moving* state is active when the chipper is going to the roadside. The *waiting* state occurs when the chipper is waiting for trucks to arrive, and when the trucks arrive, the chipper state changes to *chipping*. The *vacant* state is active based on a schedule and when in this state, no work is conducted. The chipper state changes based on whether it is moving, chipping or waiting for a truck. There are two states during the vacanct state of the chipper: ‘no work to do’ or ‘outside the work shift’.

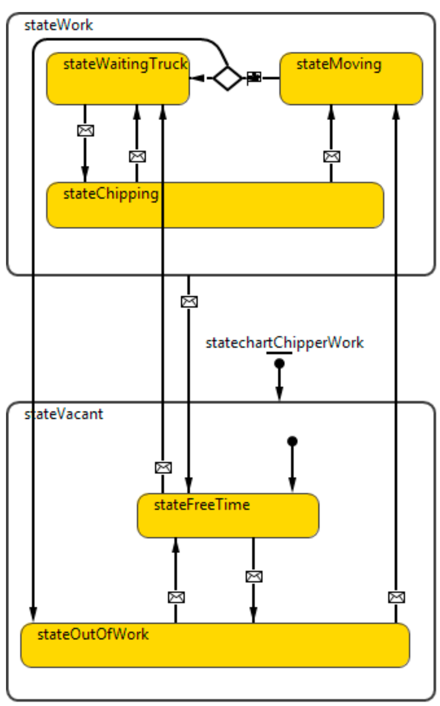

Figure 2. Chipper agent state chart.

2.1.4. Trucks

The trucks' main purpose is to move feedstock from one location to another. There are four different truck populations for different tasks and feedstocks. The properties of the different populations are described below:

- **Truck population:** Agents that move the chipped feedstock produced by the chipper. Change information with a chipper to estimate load time and transportation on the road network between the roadside, demand-point and terminal agents. Agents have their own capacity, set by the user.
- **Truck terminal population:** Agents that move chipped feedstock between the terminal and demand point. Agents have their own capacity, set by the user.
- **Truck stump population:** Agents that move stump feedstock between the roadside and terminal agents. This population's agents do not communicate with the chipper and have their own capacity, set by the user.
- **By-product truck population:** Agents that bring by-products to the plant. Their capacity and arrival are based on a by-product sub-model. This population's agents do not use the road network. Instead, the agents are created in the model at the demand point and destroyed after unloading.

Trucks have different states, based on if they moving, loading, unloading or waiting. There is also a *vacant* state, based on if the truck is not working or outside a work shift.

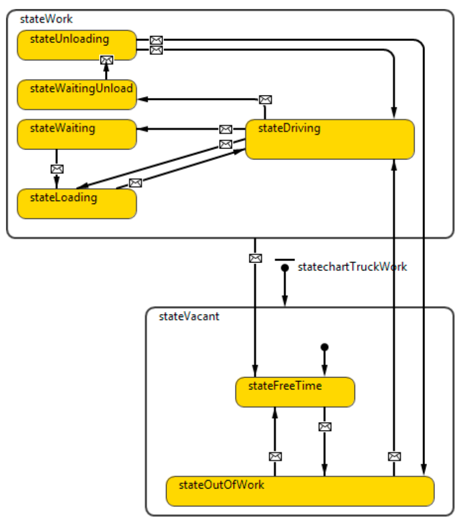

Figure 3. A truck agent's state chart.

2.1.5. The demand point

The demand-point agent produces demand based on user-selected distribution and annual demand. Demand is generated four times in an hour and fuel entities are destroyed in order to fulfil demand based on their energy content. Two queues are used to represent storage at the demand point. Fuel entities are moved to the first queue, main storage, from trucks in an unloading event. As fuel entities arrive, their moisture content is set to the average level for first storage in order to represent mixing of the fuel inside of the storage. Secondary storage, day storage, is first fulfilled at the start of the day or if its content drops below 50 fuel entities. The demand point has three unloading spaces and an unlimited waiting area.

2.2. Process overview and scheduling

Supply is generated by a theoretical value acquired from the Biomass Atlas database, and it is divided into centroids on a 2 km x 2 km grid. The model selects a user-set number of supply points randomly and elevates these points' supply by the total number of supply points divided by a selected number of supply points. A dynamic event is set to prompt, based on Finnish harvesting statistics using a road condition allocation to represent the harvesting of the stand.

When a roadside dynamic event is triggered, fuel entities are created and moisture content is set. A moisture content change-triggered function is used to estimate the energy content of the fuel entities. Fuel entities are then moved to the stand queue, where they are delayed to represent drying at the stand. Moisture estimation models are used to change fuel entities' moisture content and energy content during storage. After stand storage, fuel entities are moved to roadside storage and will be stored there for a user-set time period. Again, moisture is estimated and after the storage period, a roadside storage state change is available.

At the start of a shift, a chipper looks for available roadside storage if it does not already have one selected. The chipper moves to the selected roadside and then orders trucks. The trucks start their trip from the demand point if there is room in storage at the demand point or if the terminal is enabled and there is room for fuel. They travel to the roadside where the chipper is waiting. After arriving, the truck waits for its turn to load. During this event, both the chipper and truck agent have to be present. After loading, the truck will go to the demand point to unload. If the demand point storage is full, the truck will go to the terminal. The truck starts a new trip if there are more fuel entities to gather and if there is time in its shift. Truck and chipper logic are presented as a flowchart in 4.

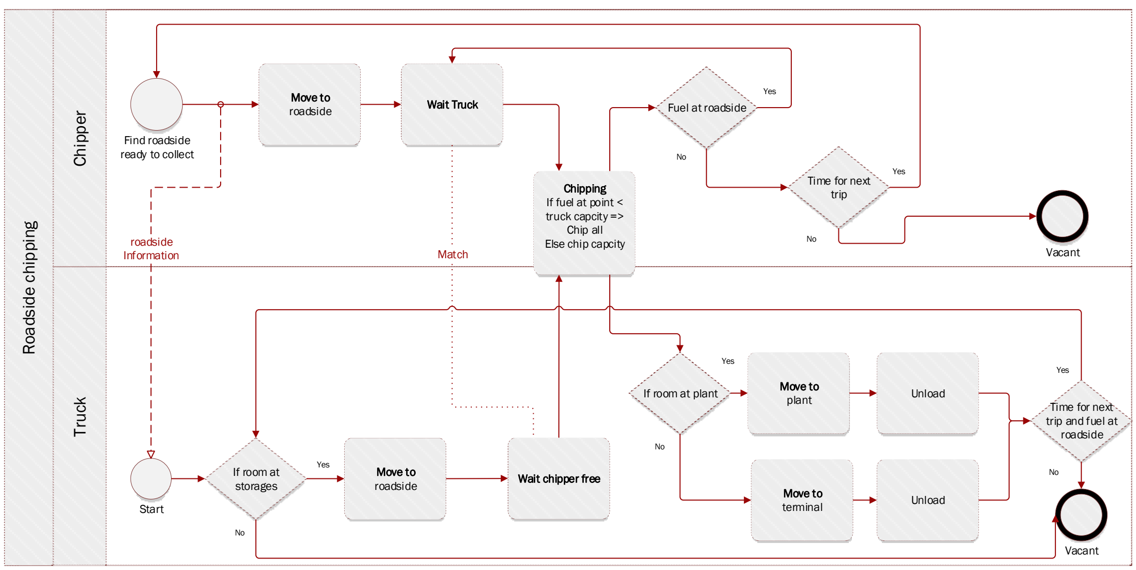

Figure 4. A flowchart of the truck and chipper logic used in the model.

A roadside that has an ST fuel type does not use a chipper for gathering fuel entities. Due to this, stump trucks look for available roadside storages at the start of their shift and start a trip to the roadside if there is storage room at the terminal. At the roadside, the stump truck loads fuel entities and delivers them to the terminal. At the terminal, stumps are assumed to be comminuted and stored until the demand point orders them. Stump truck logic is presented as a flowchart in Figure 5.

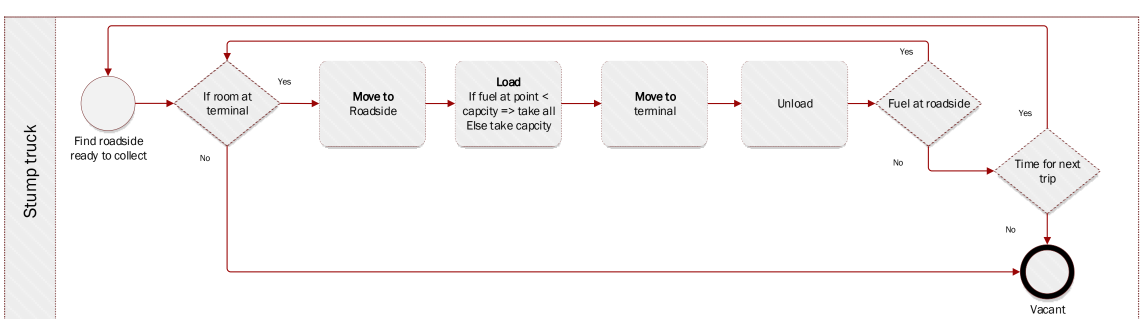

Figure 5. A flowchart of the stump truck logic used in the model.

2.4. The design concept

The model's basic concept is to represent a biomass supply system that includes a chipper hot chain. The road network, generated by the GIS, analyses and dictates trucks' movements between agents, including travel time. The moisture content of biomass is estimated by prediction based on the available literature, except for that of stumps which are assumed to have monthly distribution with a normal variation based on the month of usage. Moisture content is used to estimate the energy content of the fuel. At a demand site, the main storage is assumed to have perfect mixing of the fuel, and this is modelled by having all fuel at the same moisture content.

Marine transport and by-product deliveries are included in the model with a low abstraction level. Marine transports are ordered 2.75–3.25 days before arriving, and fuel is moved to the main storage. These do not directly affect the system, but there has to be room in the main storage. This leads to maximum storage being lower for road transportation during marine transportation ordering. By-product deliveries affect the demand site as trucks arrive and take up unloading space. Trucks are generated in a batches of three, based on the annual amount of the by-products. Trucks are created at the gate of the demand point and destroyed after unloading.

Marine transport affects the storage level, which leads to a momentary drop in the utilisation of road transportation. This means lowering the utilisation of trucks and chippers. Also, if the terminal is in use, fuel entities will be directed to the terminal, leading to higher usage of the terminal.

As roadsides are generated stochastically, the availability of the feedstock and transport distances varies annually. As supply varies, time in storage can change, leading to different amounts of drying the fuel. This and initial moisture content affect the end moisture of fuel entities at the plant.

The model gathered results which were transferred to spreadsheets for further analysis. During the run, plots and figures are drawn in order to see the values in the current situation. The following values are presented and written onto the spreadsheet: the utilisation of trucks and chippers, the distances driven by trucks and chippers, the usage of fuel, the needed amount of energy for the secondary feedstock and the arrived fuel's moisture content and volume. The values written onto the spreadsheet are monthly averages and sums. The generated roadside points' harvesting and gathering times are also recorded onto the spreadsheet in order to analyse the fuel's time in storage.

2.5 Initialisation

The model starts by initialising the first set of the roadside. As fuel needs time at stands and roadside storage before it becomes available, there is a two-month warm-up period where demand does not accumulate. During this time, marine transportation and by-product deliveries are disabled. The trucks and chippers work during the warm-up period, but the storage's fulfilment will stop them. All trucks and chippers are set to a demand point and all agents locations are set. It is recommended to run at least two simulation years in order to achieve a stable system and to use results from after that period.

2.6. Input data

Supply availability data is imported from the spreadsheet file. This file includes roadside locations, trip times between roadside and demand points, and harvesting time probabilities for every month. The file has all the data for the different availability scenarios and supply areas, and the user sets the wanted scenarios at the start of the simulation.

The user sets the trucks, demand points and initial moisture properties at the start of the simulation. Also, annual demand and the wanted distribution are selected by the user. The annual amount of by-product is set by the user and, for marine import, the annual amount of biomass and capacity of the vessel is set. Capacity affects the number of arrival deliveries, based on a sub-model. The user also has the possibility to force the storage times of the fuels by setting a minimal and maximal storage time at the start of the simulation or by importing values from the spreadsheet file. Weather data for years 2010–2017 are nested in the model and the user can select which years' data are used or set a random year to be used. Random year change used the weather data from the start of the simulation year.

As repeatability, with the same roadside storages, has to be ensured, the user can set a random-number generator seed that only affects the initialisation of roadsides and the used weather data if selected randomly.

2.7. Sub-models

The marine transportation sub-model includes two events. The first event, ordering marine delivery, triggers the second event 2.75–3.25 days after the first one in order to represent the travel time of the marine vessel. The first event is set to trigger recurrently, based on the annual amount of biomass and size of the vessel. The first event reserves room for fuel entities from the demand point to main storage. Marine transports are disabled between April and June as the assumption for demand is low and therefore it is assumed that no marine deliveries are needed. As the second event is triggered, fuel entities are created and sent to storage.

The by-products' sub-model also uses two events, but the transport vehicle's capacity is set to 150 m^3-loose and assumes that three vehicles arrive at the same time. The first event reserves room from demand-point storage, and the second event creates by-product trucks in the model at the demand point's enter element. From there, the trucks move to unloading and after that, they leave the demand point and are destroyed from the model.