

DYNAMIC SIMULATION OF BIOENERGY FACILITY LOCATIONS WITH LARGE GEOGRAPHICAL DATASETS - A CASE STUDY IN EUROPEAN REGION

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Abstract: *An agent-based simulation model was developed to account for the dynamic features of biomass feedstock logistics, including the large variation of supply and demand over time. The feedstock availability data is based on a geographical information system (GIS) analysis that covers 37 countries in Europe. The results may be used to optimize demand sites properties and compare the feasibility of different demand site locations. Out of eight locations, three were found have low fuel acquiring costs and other five could use long distance transportation to mitigate low supply of local biomass. Dynamic simulations flexibility makes it possible to integrate the model with a large database. The agent-based model with the large database from GIS provides a cost-efficient method to study and compare the geographical properties with a temporal factor of logistics, and it can be utilized as a tool for decision making of forest-based bioenergy facilities.*

Keywords: *forest biomass, agent-based, simulation, logistics, optimization.*

1. Introduction

The targets of reducing the use of fossil energy sources and replacing them with renewable energy sources have increased interest in new forest-based bioenergy and biorefining facilities. Before the facilities are built, analysis of feedstock availability and estimation of costs are carried out. There are many static analysis approaches (e.g. [5], [17]) that can be used for optimizing the location of the installation but, however, they usually exclude the dynamic elements of supply, demand, and logistics.

With dynamic simulation, a temporal factor of the demand-supply system can be included in the study. Agent-based simulation is a dynamic simulation method and it has been used for supply chain studies previously [8], [9] and [11].

Another reason to choose dynamic simulation is the flexible model design [3]. A disadvantage is the lower runtime performance that can be neglected to some extent by the model design or by increasing the computing capacity, which is nowadays relatively cheap. Due to complicated nature of the dynamic simulation, development and usage of the

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model requires an expert. The knowledge need of the model can be lowered by making the model easy to use, but the user has to have the ability to verify values that are used in the simulation.

Previous studies done with dynamic simulation approach have usually been location specific and only using local feedstock availability data. Location of the demand point in the model presented in this paper is user-defined showing how large database produced by GIS can be utilized with dynamic simulation study method allowing making comparisons between multiple locations.

The S2Biom project resulted in preparing a large database containing estimates of forest biomass availability in Europe [7], [8]. The database includes also estimated roadside costs for the available feedstock. The datasets cover EU28, Western Balkan Countries, Moldova, Turkey, and Ukraine.

During the designing phase of a new biomass utilization point, availability of the feedstock has to be counted but also logistics of acquiring the raw material have to be taken into account because logistics have a high impact on the operation costs of a biomass plant [13]. This factor can be included in a dynamic simulation model by using routing information that is, for example, provided by OpenStreetMap (OSM) [7].

This paper presents a dynamic simulation model that is developed by authors to solve the supply-demand problem. The model is based on a previous model that has been used for simulating agricultural feedstock logistics in India [8]. The same model concept is used for agricultural feedstock analysis [1].

The model has been modified to analyse forest-based bioenergy supply-demand problem and is still developed to count other feedstock types with needed operations. The model uses spreadsheet software for importing input values and

exporting the results for further analyses.

Used feedstock data include primary forest fuels and forest residues that can be used for heat or power generation or refined to advanced biofuels. Supply chains of these materials have many models and there have been studies to improve the formers [1], [14] and [15]. Previous studies have excluded long-distance transportation and have not been sensitive enough to the stochastic supply delays [14]. These factors can be taken into account in the presented agent-based model.

2. Material and Methods

Feedstock availability information used in this paper have been reported by the S2Biom project [4], [18] and this paper focus is on presenting a method to use this data by a dynamic simulation model that uses the agent-based modelling method.

2.1. Data Preparation

Data provided by S2Biom is spatially distributed corresponding to NUTS3 regions. The database includes an assessment for seven categories of lignocellulosic biomass feedstocks. This study focused on “Wood production and primary residues from forests” [18]. The availability has been estimated for years 2012, 2020 and 2030.

The data include also different levels of harvest potentials: Technical, Base, High as well as eight different user-defined potentials. The dataset projected for the Base potential in 2020 was chosen for this study, and the data was reprocessed into two datasets: “Production from forests” and “Primary residues from forests”.

The roadside costs were average weighted based on the availability of the biomass. Roadside costs include harvesting and forwarding feedstock to the roadside but exclude the contract costs.

The first reprocessed dataset, “Primary forest biomass”, is production from the forest that includes stem and crown biomass from felling and thinning. The second dataset is primary residues from the forest and it is called “forest residues”. This dataset includes logging residues from felling and thinning. The database includes also corresponding data for stumps, but it was excluded from the study due to different transportation and handling operations requirements.

For the simulation model, feedstock availability data had to be allocated to geographic supply points. This was done by creating a 5×5 km grid and using the centres of the grid cells as points of supply. The value of one point was the value of the respective NUTS3 region, divided by the total count of the grid points inside the region. Accordingly, all points inside the NUTS3 region got the roadside cost value of the region.

The computing power needed for the model running is relative to the amount of data imported to the model. To avoid unnecessary use of computing power, data from only one country per simulation run was used. Also, a maximum procurement radius was determined, lowering the number of points needed for the calculation process. Procurement radius was also used to determine the final proportions of biomass types. If the user-set portion of primary forest biomass from demand could not be fulfilled by the primary forest biomass, then the remaining demand was fulfilled by the available residues. If the share of residues could not be met, then the share was shifted to reserve fuel. Note that if residues could not be fulfilled and there are primary forest fuels available, the share wasn't shifted to primary forest fuels.

2.2. Description of the Simulation Model

The main purpose of the model was to produce location-specific data about feedstock logistics in different areas with multiple options for the location of utilization.

Agent-based modelling uses entities called agents to interact with each other and to create the simulation [12]. In the model, all agents are located in the Main-agent that includes the GIS-environment. There are: one demand point agent and multiple supply point agents set in this GIS-environment with agents called trucks that have the capacity to transport biomass with the later described as agent-called fuel entity.

Supply points accumulate fuel entities and call trucks to transport fuel entities to the demand point. The needed handling operations are performed at demand point on the fuel entities before they are used. An agent can carry information giving the possibility to have all costs of acquiring biomass carried by the fuel entity and add costs based on operations and fuel properties at the moment when the costs occur.

Input values are entered into the model through a spreadsheet file. There are two types of input values: values that are universal for all locations and location-specific values. Universal values include biomass properties and costs of the logistics operations. Location-specific values are coordinates of the utilization site, its annual demand (tonnes per year) and maximum procurement radius. These values are given in one row in the spreadsheet file.

The model imports the first row of the values to the model and runs a simulation. At the end of the simulation, the results are exported and the simulation run is repeated ten times with the same values so that the impact of stochastic events in the system can be discovered. Thereafter, new values

are imported from the next row of the input file and the process is reiterated. Simulation is ended after running the last row of the input file.

The simulation run starts by placing a demand point in the system according to the coordinates given in input file. The acquisition of the biomass availability data from the right country is also based on the coordinates. The supply points inside the procurement radius are sorted out according to their proximity to the demand point and the biomass accumulation is calculated starting from the closest supply point. The proximity is calculated as the distance along the road network. The accumulation is terminated when the annual feedstock demand or the maximum procurement radius is met.

Feedstock availability data does not include other properties than the biomass amount (tonnes). The user of the model determines the energy content of one tonne of biomass, density of biomass before comminution and density of biomass after comminution. These values are universal for all simulation runs. The biomass properties are used to batch biomass to fuel entities agents.

Unlike the initial values imported from the spreadsheet file, truck fleet properties are given through the graphic user interface (GUI) of the model. These values are also universal, and they include the number and payloads of trucks. Payload determines how many fuel entities one truck can carry and the number of trucks determines how many truck agents can perform transportation simultaneously.

Trucks are set to operate between 8 AM and 5 PM on weekdays. In the morning trucks are sent from the demand point to retrieve a biomass load from the supply point if there is biomass available. Random supply point is selected using feedstock availability as weighing factor. This means that point's probability to be selected is

point's supply amount divided by supply points' total availability in the system.

Trucks move to the supply point based on routing information (shortest route) and loads feedstock. Loading and slower speed of the forest road are considered to delay the truck for two hours at the supply point. After loading, truck returns to the demand point.

There is also a possibility to store feedstock at a buffer terminal next to the demand point. The user of the model defines the supply chain cases where trucks deliver their loads to the terminal instead of the demand point. When the truck has unloaded at a demand point or a terminal, the truck checks if there is more biomass at the supply point to retrieve. The truck operates also after 5 PM, but the trip has to begin latest at 5 PM.

Feedstock is comminuted at arrival to the demand point. The costs of comminution, purchasing and transportation are recorded and feedstock is stored in the storage. The amount of feedstock in the storage is recorded.

At the demand point, fuel is consumed every hour and the hourly consumption is based on monthly demand. If the storage goes below a defined level, more feedstock is called from the terminal. If there are no feedstock to fulfil the demand, reserve fuel is used. Reserve fuel's transportation or storing are not included in the model. Only energy content and price of reserve fuel is taken into account.

If the feedstock is transported to the terminal, it is comminuted to be ready for the use on short notice. When the demand point calls feedstock from the terminal, terminal trucks will transport fuel entities to the demand point for use. All costs of the terminal operations are included in the feedstock costs. Also, the annual cost of using the terminal is included in the result data if the terminal is used in the simulation.

The user may include transportation by other means than trucks (e.g. trains and vessels) in the input file. These deliveries are described in the system only as arrivals to the demand point or to the terminal. The properties of the arrivals by these means are set by defining the amount and biomass type that one delivery contains. The arrival frequency is set on a monthly basis. There may be as many transportation types as required.

The model keeps track on how much each feedstock type is used. Also, costs of feedstock procurement and reserve fuel use are recorded. These values are exported to an output spreadsheet file for further analysis.

3. Case Study

Eight locations where the International Symposium on Forestry Mechanization (FORMEC) meeting has been held were chosen for the case study (Fig. 1). In these locations, a biomass demand of 100000 tons was applied (Table 1). It was assumed that these demand points could represent combined heat and power CHP plants. From the total biomass demand 80% was targeted at primary forest biomass and 20% of residues.

Biomass properties and costs of operations selected for this study are presented in Table 2. Values of fuel properties are estimations from fuels used in Finland [2]. Estimations for comminution costs are from Virkkunen et.al. [16] and cost of the transportation is estimated from the study of Korpilahti [10]. Transport capacity for primary forest materials was estimated to 30 m³ loose and for residues to 20 m³ loose. In the model, there were 30 trucks for primary fuels and 10 for residues.



Fig. 1. *Locations of the demand points*

Input values of demand points

Table 1

id	Latitude	Longitude	Proce. radius [km]	Annual demand [tons]
1	45.37	11.54	150	100 000
2	47.92	14.10	150	100 000
3	45.06	15.18	150	100 000
4	48.60	8.54	150	100 000
5	48.04	6.84	150	100 000
6	48.31	14.67	150	100 000
7	52.27	20.80	150	100 000
8	45.58	25.45	150	100 000

Fuel properties and costs estimations [2], [6] and [12]

Table 2

Fuel type	Energy content of raw material [MWh/ton]	Truck transport cost [€/ton/km]	Comminution cost [€/ton]	Unloading costs [€/ton]	Density before comminution [ton/m ³ -loose]	Density after comminution [ton/m ³ -loose]
Primary	3,2	0,16	4,64	1,40	0,3	0,15
Residue	3,2	0,20	4,32	4,00	0,3	0,30

Forest biomass harvests vary over time and this was taken into account by using roundwood removal statistics from Finland [19] as seasonal supply distribution. Demand distribution was estimated to be highest during winter and lowest in the summer. This estimation was based on Finnish energy statistics [20]. For July, where maintenance of boilers usually takes place, demand was set to 0. Demand and supply distribution is presented in Fig 2.

Reserve fuel was assumed to be wood pellets with an energy content of 5 MWh/ton and with price 130 €/ton (Nordic Pellet Index PIX 18 Apr 2017).

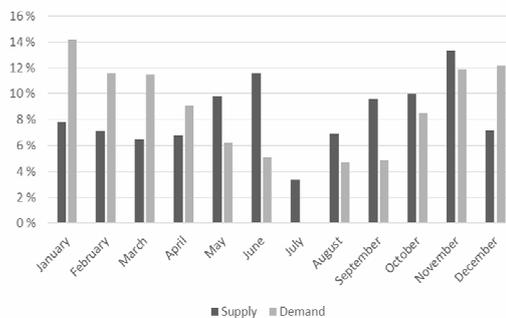


Fig. 2. Supply and demand distributions

4. Results and Revaluation

The case study was carried out in two simulation rounds. The results of the first round were used to estimate a better configuration of the demand points and simulation was run again with new values.

4.1. Results of Round 1

In three cases, less than 50% (i.e. less than 160 GWh/a) of the energy demand (320 GWh/a) was fulfilled by the biomass deliveries (Fig. 3). These locations have limited procurement area due to the proximity to shoreline (Fig. 1).

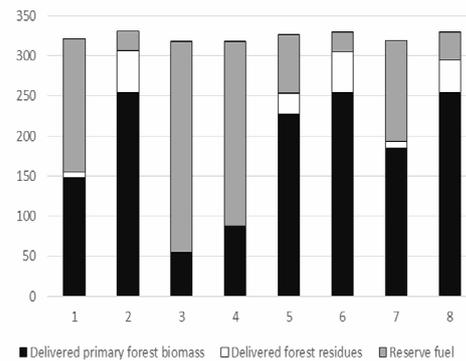


Fig. 3. Distribution of feedstock use in Round 1

The highest biomass shares were at demand points 2 and 6, which are both located in Austria. The third highest share was recorded at demand point 8, located in Romania. These locations have also the lowest average costs of feedstock supply (Fig. 4).

Due to the high price of the reserve fuel, locations with a low biomass shares had high costs. With current scenario needed storage for highest biomass share locations are over 60000 m³ loose.

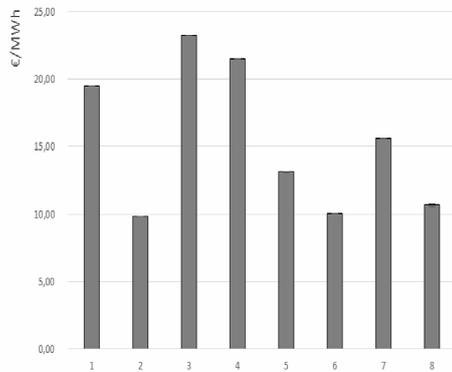


Fig. 4. Average supply costs of biomass feedstock in Round 1

4.2. Readjustment of Initial Data for Round 2

Based on the results of Round 1 it was assumed that supplementary deliveries by rail or waterway would benefit certain demand points in fulfilling the demand. It was also considered that this system would require a buffer terminal. The demand point was set a maximum biomass storage of 5000 m³ loose. The storage of the terminal was unlimited.

Terminal fixed costs were set to 0 €/a and terminal trucks capacity was assumed to be 80 m³ loose. There were three terminal trucks available and the cost of one trip was set to 3.00 €/ton.

Two long-distance vehicles, representing either train or vessel, were scheduled to arrive at all demand points. Both delivered primary forest biomass. The first transport type arrived four times every month and carried 500 tons of uncomminuted biomass. The second transport type arrived five times per month in high-demand season (October - March), carrying 1000 tons of uncomminuted biomass. Both transport types were defined to unload at the terminal. The price of the biomass arriving by these means was set to 50 €/ton.

4.3. Results and Conclusions of Round 2

Long-distance deliveries improved the use of biomass at locations where local supply had only a small share in fulfilling the demand in Round 1. However, there were still demand points where the use of reserve fuel remained high, such as locations 3 and 4 (Fig. 5).

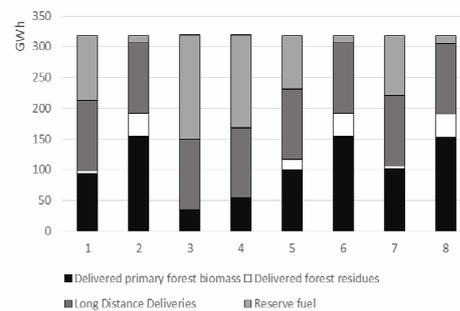


Fig. 5. Distribution of feedstock use in Round 2

In cases where local biomass supply mostly fulfilled the demand in Round 1, the local supply decreased. In these cases, also the average procurement costs increased from the results of Round 1 (Fig. 6). In cases where most of the demand was fulfilled with reserve fuel in Round 1, the costs decreased. Decrease resulted from shifting use of expensive reserve fuel to long distance deliveries.

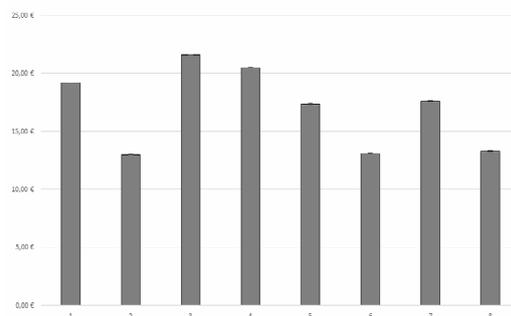


Fig. 6. Average supply costs of biomass feedstock in Round 1

Long-distance delivery price at the gate was slightly higher than that of local biomass but much lower than reserved fuel. In this study, the costs were crude assumptions and in the reality price would depend on many factors.

Terminal increased the cost of the supply chain but provided the possibility to have only 5000 m³ loose storage at demand site. The highest local biomass supply to demand points 2, 6 and 8 resulted in the highest utilization of the terminal. In those cases, 82% of the delivered feedstock, including the long-distance deliveries, was supplied through the buffer terminal. In locations with the lowest usage of biomass, the terminal was only used for unloading long distance deliveries.

5. Discussion

The results of the case study indicate that geographical factors have a significant impact on the logistical arrangements in different places. Rural areas and especially coastlines near the demand points affect greatly how much feedstock is available in the surroundings. If local biomass supply cannot fulfil demand, long distance deliveries may be used to support the biomass supply. The feasibility of long distance transportation method is also case-specific. With good availability of local biomass, long distance deliveries may increase the cost of feedstock supply.

Using results from the Round 1, justifications to initial settings were made. It can be seen that all eight point that were studied have a potential for forest biomass demand points, but in some locations, the actual energy demand in real life would be lower than that of other locations due to climatic factors. Also, locations 3 and 4 should rely on long distance transportation, which could be feasible due to onshore for supply. These locations were close to coastline so it is a possibility to have marine transportations to the demand site.

To fulfil a high demand, a storage area is needed. Depending on local land costs and possibilities to have the storing area at demand point, a terminal may be used. The terminal will increase costs but it also provides the possibility to have a small storing area at demand site with high usage of local biomass. In the case study, infrastructure costs were not considered. A terminal with fixed costs would naturally increase total costs of supply.

Many initial values in the case study were taken from Finnish literature, while the demand points were located mainly in Central Europe. Only roadside cost and feedstock availability were based on spatially analyzed data [4]. The quality of result data could be improved by complementing the initial values with local data about e.g. vehicle properties and variation of feedstock supply and demand.

In the model, demand point is only receiving and using biomass based on demand. With more complicated systems, like multipurpose use of biomass and delivery of refined production, model needs to be modified. This will lead to more case specific models developed that need more specific data.

Dynamic simulation requirements of computing power and experts to use the model can be mitigated by the model design. Combined with a flexible design of dynamic simulation model, large databases can be utilized in future studies.

6. Conclusions

Dynamic simulation can be used to support decision making about the location of a new demand point using biomass as its feedstock. It gives versatile results and initial values may be easily varied. Because the locations are not optimized in the model it is recommended to use another method for location optimization prior to the simulation study.

Simulation gives the option to study many different scenarios fast and cost-efficiently. Possibility to adjust initial values based on previous results provides a way to easily optimize settings. With dynamic simulation combined with a large database, supply-demand problems can be studied using temporal and spatial effects, giving a unique tool for decision makers to use.

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