Dissertationes Forestales 323

Spatial forest biomass supply chain analysis in Finland

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Academic dissertation

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ABSTRACT

The forest biomass supply represents an important part of the value chain for different wood-based products, and its environmental impacts are also frequently crucial. The performance of biomass supply chains (BSCs) can be assessed for various purposes and using a variety of methodological approaches, either including or excluding spatial properties. The purpose of this thesis was to investigate what kind of spatial data are required and available for case-specific BSC analyses in Finland, and what would be suitable levels of spatial precision for the various approaches. This thesis consists of five papers, one of which reviews case studies carried out in various geographical BSC environments around the world, while the remaining four are spatial case studies of BSC systems in Finland, three of them focusing on bioenergy production and one assessing the performance of a novel pulpwood transportation concept. A geographical information system (GIS) was used as the principal tool in one study, while in the other three the role of GIS was to produce spatially analysed data for life-cycle assessment and agent-based simulation. The main conclusion is that a spatial precision of between 1 km and 10 km, where each point of origin represents roughly an area of 1–100 km^2, is sufficient for forest biomass data in Finnish BSC systems. The final precision should be determined collectively by the setup of the case study, factors leading to complexity in the supply chain system and the geographical extent of the area concerned. Relative to many other parts of the world, Finland has a readily available high quality source of spatial data for BSC research. It is recommended that GIS-based research could be improved by adding dynamic properties and stochasticity to the models, because temporal variations in feedstock supply and demand will probably increase in the future.

Keywords: transportation, optimization, geographical information systems, logistics, life-cycle assessment, simulation

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Mikkeli, October 2021

Olli-Jussi Korpinen

LIST OF ORIGINAL PAPERS

This thesis is based on the original research papers listed below. The papers are reprinted with the permission of the publishers, and they are referred to in the text by the Roman numerals given here.

I Korpinen O-J, Aalto M, KC R, Tokola T, Ranta T (2021) Utilization of spatial data in energy biomass supply chain research - a review. Submitted manuscript.

II Korpinen O-J, Jäppinen E, Ranta T (2013) A geographical-origin–destination model for calculating the cost of multimodal forest-fuel transportation. J Geogr Inf Sys 5: 96–108. https://doi.org/10.4236/jgis.2013.51010

III Jäppinen E, Korpinen O-J, Ranta T (2013) GHG emissions of forest-biomass supply chains to commercial-scale liquid-biofuel production plants in Finland. GCB Bioenergy 6: 290-299. https://doi.org/10.1111/gcbb.12048

IV Korpinen O-J, Aalto M, Venäläinen P, Ranta T (2019) Impacts of a high-capacity truck transportation system on the economy and traffic intensity of pulpwood supply in Southeast Finland. Croat J For Eng 40(1): 89-105. https://hrcak.srce.hr/217400

V Aalto M, Korpinen O-J, Ranta T (2019) Feedstock availability and moisture content data processing for multi-year simulation of forest biomass supply in energy production. Silva Fenn 53(4): article id 10147. https://doi.org/10.14214/sf.10147

Olli-Jussi Korpinen was the principal author in Papers I, II and IV, while Eero Jäppinen and Mika Aalto conducted the major part of the research in Papers III and V, respectively. Olli-Jussi Korpinen was responsible for collecting the spatial data and running the GIS analyses that produced the input data for LCA in Paper III and the simulation case studies in Paper V. The other co-authors helped with the conception and design of the respective papers and participated in writing and reviewing the manuscripts.

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ABBREVIATIONS

ABS	Agent-based simulation
BSC	Biomass supply chain
CHM	Canopy height model
CHP	Combined heat and power
DES	Discrete-event simulation
FFC	Finnish Forest Centre
GHG	Greenhouse gas
GIS	Geographical information system
HCT	High-capacity transportation
LCA	Life-cycle assessment
LCP	Least-cost path
LiDAR	Light detection and ranging
MS-NFI	Multi-source national forest inventory
MOO	Multi-objective optimization
NFI	National forest inventory
P2X	Power to X

1 INTRODUCTION

1.1 Background

Bioenergy production in Finland underwent a transition from traditional to modern (Kampman et al. 2010) primarily in the twentieth century, in response to industrialization and the resulting rise in society's energy demands. Until the Second World War the main source of bioenergy was firewood, although this was quickly replaced by fossil fuels such as oil and coal, and later peat and natural gas, in industry and other centralized heating systems (Kuitto 2005; Statistics Finland 2007). Under post-war conditions the forest industries grew in size, as did the volumes of process by-products such as wood chips, sawdust and black liquor (Natural Resources Institute Finland 2021a). Wood fuels nowadays account for the largest proportion of final energy consumption in Finland (ca. 380 PJ in 2019, amounting to 28%), surpassing fossil fuels (288 PJ, 22%) (Statistics Finland 2021). Not all wood energy is used on a large scale, however, as small-scale firewood consumption accounts for about 60 PJ annually.

Relative to European countries with larger areas of cultivated land, the use of forms of biomass other than wood is marginal in Finnish energy plants (Eurostat 2015), so that only about 220 TJ of plant (non-wood) and animal-based biomass was used in Finnish combined heat and power (CHP) plants in 2019 (Finnish Energy 2020). Rather than direct combustion in power plants, agricultural biomasses such as grass, straw and manure are more commonly refined into gaseous fuel products (Winquist et al. 2019).

Forest fuels are a subcategory of wood fuels that includes biomass harvested and supplied from the forest for energy production directly, without processing in sawmills or pulp and paper mills (Alakangas 2015). Consequently, the feedstock is not available at industrial sites and the logistics framework includes supply chains that connect a variety of forest stands to an energy conversion facility. Forest fuels are more expensive at their destination than other wood chips (Ylitalo 2007), which are typically delivered by standard truck-trailers operating between wood processing sites and energy facilities. Forest-fuel supply chains include forwarding (i.e. off-road transportation), comminution (i.e. chipping or grinding), and road transportation. Even the road transportation takes place under more difficult driving conditions than conventional transportation. Because of the predominance of comminution, forest fuels are also known in Finland as forest chips. Firewood is not classified as a forest fuel fraction (Alakangas 2015).

On a national scale, the use of forest fuels has steadily increased, but the proportion of forest fuels among the energy sources has increased relatively rapidly in the last 20 years (Natural Resources Institute Finland 2021b and 2021c). The most obvious driver has been the replacement of fossil fuels in heat and power production. Following the oil crisis of the 1970s, forest chips were used to increase the domestic content of energy sources, but as the price of oil fell, forest chips became uncompetitive again in many places (Hakkila 2005). Much stronger growth started in the late 1990s, when climate-based policies pushed heat and power plants into using renewable energy sources instead of fossil fuels. In addition to the numerous boiler investments in smaller heating plants, large heat and power plants underwent modifications that enabled the replacement of major fossil fuels such as coal, natural gas, and peat. The consequence was that a demand for forest fuels began to emerge in areas where the demand for wood fuels exceeded the supply of wood-processing by-products.

In 2000 the amount of forest fuels used was 5.8 PJ (Natural Resources Institute Finland 2021c), with much of the use concentrated in the sawmills and paper mills of Central Finland (Natural Resources Institute Finland 2021d; Ranta 2002). Also, forest fuels have gradually become a significant fuel fraction in the district heating systems of Finland's largest cities, their use having increased almost tenfold in the last two decades and become concentrated in the country's most densely populated regions. The two southern regions, Uusimaa (7.2 PJ) and Varsinais-Suomi (6.8 PJ), account for more than a quarter of the country's annual forest fuel use (54.4 PJ) (Natural Resources Institute Finland 2021d), in spite of the fact that the proportions of forest land in these regions are among the lowest in Finland (Natural Resources Institute Finland 2020), posing obvious supply chain challenges. The Naantali power plant, for example, which uses more than 3.5 PJ of forest fuels annually, receives deliveries by truck from up to 150 kilometres away, and a significant proportion of the chips (up to 25%) is delivered by sea (Kjellberg 2020). In such a case, the power plant must have a large storage capacity and the truck transportation system must be able to adapt to significant changes in the plant's available storage space.

1.2 Forest fuel availability, supply chains and their stakeholders

Since forest fuels are principally delivered to the plant directly from forest stands, the supply logistics characteristics are more similar to roundwood procurement than to the supply chains for other fuel fractions. Forest fuels are primarily a by-product of forestry operations that are aimed at roundwood production, and as a result, their availability is heavily reliant on the market conditions prevailing in the forest industries. Harvest residues from regeneration fellings together with small-diameter wood extracted as whole trees or delimbed stems from younger stands are the main forest fuel fractions in Finland.

Forest fuel supplies differ from roundwood procurement principally in terms of their supply chain lifetimes, as roundwood should be fresh on arrival at its end-use location (Rikala et al. 2015) whereas forest chips should be dry (Röser et al. 2011). Forest fuels are intended to be dried at the stand immediately following felling and later in a roadside storage stack prior to delivery to the destination. The roadside chipping method, in which the fuel is chipped at the roadside stack and transported directly to the energy plant, is the most common arrangement nowadays, accounting for approximately 60% of all forest fuel by volume in Finland (Strandström 2020), while the second most common is the terminal chipping method (ca. 30%), in which fuel from various roadside stacks is collected and comminuted at a cost-effective location between these points of origin and the destination. Comminution at the destination has become less common (ca. 10%), partly because not all power plants have stationary grinders and suitable yards for comminution, and also because uncomminuted material has a lower density and therefore a negative impact on transport economy over longer distances. The terminal chipping method nevertheless has the advantage of increased operational reliability (Virkkunen et al. 2015), in that large volumes of uncomminuted forest fuels can be stored at many terminal sites, allowing the fuel supplier to respond to a rapidly increasing demand for fuel, e.g. during the winter. In the last ten years, the proportion of terminal chipping in the supply of small-diameter wood has increased from 10% to 30% (Strandström 2020), expressing an increased interest in supply security within feedstock logistics. It has been observed that delimbed stemwood, in particular, retains its heating value even after extended storage (Aalto 2015), which is beneficial from the stockpiling point of view.

In business terms, supply chains are a network of customers, fuel-suppliers and contractors performing harvesting and transportation operations and comminution. At the energy plant, forest chips can be the primary fuel type or possibly only a minor component of a feedstock mix. Similarly, a single supplying organization may have multiple delivery destinations or customer enterprises. The supplier could be the wood procurement department of a forest company, for example, or simply a dealer focusing on the forest fuel trade. But regardless of the business model, it is critical that the supplying organization should compile information on its raw material resources (e.g. fuel volumes available for delivery), supply chain components (available vehicles, machines and workforce), and energy plant preferences (e.g. fuel quality criteria, supply contracts, orders and feedback).

Geographical information is important for the supplying organization at all levels of business planning. The locations and extents of supply areas, which are determined by the positions of the delivery destinations, terminals and transportation routes, are essential in strategic planning, while the list should be accompanied by the locations of roadside stacks in tactical planning and by the locations of machines and vehicles in operative planning. A geographical information system (GIS) is a vital tool for managing such vast amounts of data, since it can enable the performing of location-based mathematical calculations (at the strategic level), for example, or provide a map-based interface for heuristic supply chain management (at the operative level).

1.3 Research into the development of biomass supply chains

Research into biomass logistics has played a critical role in the development of the competitiveness of forest fuels (vis-à-vis other feedstock types) because harvesting, storage and transport costs account for approximately 80-90% of the value of a fuel at the plant gate (Laitila et al. 2010a; Laitila et al. 2017). Literature reviews (e.g. Wolfsmayr and Rauch 2014; Cambero and Sowlati 2014; Kogler and Rauch 2018) suggest that the published research contains numerous examples supporting all levels of business planning. The publications involved are frequently case studies that cannot be applied elsewhere due to geographical constraints (Kogler and Rauch 2018), whereas the methods, and possibly also the data sources, can be used in other operational environments.

Another important goal of research is to assess the environmental or sustainability impacts of biomass supplies. The environmental impacts are typically examined using a life-cycle assessment (LCA) method, which yields a numerical estimate of the impact that each functional unit (e.g. volume, mass or energy content unit) running through the system exerts on the environment (Schweinle et al. 2015). In supply chain systems the impact is typically measured in terms of greenhouse gas (GHG) emissions. The system under consideration can be limited to supply chain stages that are economically more important (harvesting, comminution and transport) (de la Fuente et al. 2017), or it can be more comprehensive, including impacts on the carbon balance of the growing stock and the soil of the forest stand as well as the greenhouse gases emitted from biomass stocks during storage (Jäppinen et al. 2014). Some studies have limited the system in other ways while still covering a longer time frame in the analysis, including biomass production, supply and utilization. Werhahn-Mees et al. (2011), for instance, focused on only one of the main tree species yielding biomass for energy purposes in the Nordic countries, which simplified the production part of the model in particular, because different species require different management plans in the region.

Their model was also non-spatial, as fixed transport distances were used instead of a GIS-based analysis.

Despite the understanding that biomass supply chains (BSC) can frequently be studied using a spatial approach and with assistance from GIS (Zahraee et al. 2020), there is still room for non-spatial research. If, for example, the focus is solely on the arrangement of business processes and the information flows between stakeholders in the supply chain (Windisch et al. 2013), spatial data and methods are not needed. On the other hand, GIS is most beneficial when the system includes the mobilization of geographically scattered physical objects, such as biomass located in numerous fields or forests. In the context of forest biomass, this is especially the case in studies corresponding to the strategic level of real-world business planning, where biomass availability, supply costs and other procurement impacts, for example, are analysed on an annual basis. Nationwide analyses of the geospatial balance between supply and demand have also been published, based on large forest inventory databases and spatial information regarding heating and power plants (Nivala et al. 2016; Athanassiadis and Nordfjell 2017; Anttila et al. 2018). In the most basic GIS-based case studies the supply chain modelling consists of resource data for one type of feedstock and the calculation of transport distances for one type of vehicle, without any location-specific factors limiting the logistics (see Jäppinen et al. 2011). As business has grown and competition for feedstock has increased in the real world, so the research methods and the quality of the data have been refined. Today at least the following factors which are likely to have a significant impact on the results of the analysis are likely to be included whenever they are assumed to have spatial variation within the area concerned:

- Technical and ecological constraints on harvesting of the stands
- Competition between demand points and their varying abilities to pay for feedstock
- Willingness of different forest owners to sell biomass
- Fuel mixes and technical constraints at the plants
- Supply chain resources (machines, vehicles, workforce)
- Technical and environmental constraints affecting the supply chains (e.g. permitted locations for storage and comminution)

Furthermore, the numbers of fuel fractions and the varieties of rolling stock, comminution machines and storing methods have increased (Spinelli et al. 2020), as has the diversity of end products made manufactured from forest chips. Forest fuels can be refined to a standardized solid fuel product such as pellets, for example, or they can be used as a component of a liquid or gaseous fuel product (Yu et al. 2021). Additionally, since there are nowadays hundreds of energy plants using forest biomass in Finland (Nivala et al. 2016), there could be also opportunities to benefit from backhauling options and multi-way transportation models (Palander et al. 2004; Venäläinen and Poikela 2016).

1.4 Spatial data in BSC studies

When biomass resources are procured from various distant locations using alternative vehicles, it is advantageous to have GIS tools for planning purposes. In GIS-based modelling of transport systems, both raster data (also referred as “grid-based data”) and vector data (“line-based data”) can be used (Rodrigue 2020). Vector data are not necessary for modelling the transportation network in GIS, since transport distances, times and costs can also be assessed using raster data and raster calculation tools, but it can be difficult to account for dense network areas if too small a scale (i.e. a coarse grid) is used. Also, the modelling of multilevel objects (e.g. highway interchanges) and the identification of one-way traffic zones will obviously be more straightforward in a vector-based system than in a set of raster layers. Raster data models are typically used in analyses of the static “cost-path” type (de Smith et al. 2018), while vector data are required for dynamic systems that call for complex connectivity and shared attributes between spatial objects. Sufficient road network data is available nowadays in vector format, even free of charge (e.g. OpenStreetMap data (OSM 2021)) that it is convenient to model a supply chain network as a line-based system. For this purpose, biomass resource data should be converted from area-based data (raster cells or vector polygons) to vector points, as transport routes and their properties are calculated between objects (i.e. lines or nodes) in a network. One common method is to extract the centroids of raster cells and their values, or vector polygons and their attributes, and to move the data to the closest object along the network. Sometimes, particularly if a feedstock supplier’s data on roadside storage sites is used, the format of the biomass data may already consist of vector points and no conversion from a raster format or extraction of polygon centroids will be needed.

Accuracy in GIS indicates how well the object in the model matches the location or attributes of the corresponding object in the real world (Li 2017). In a spatial BSC case, data accuracy can be assessed, for example, by comparing the location of a line segment representing a road in the GIS context with the reckoned real-world location (e.g. based on some form of remote sensing method), or by comparing the attribute of a segment with the corresponding observation in the field (e.g. the pavement type of a road). There is usually some degree of inaccuracy, for example, between the data location of a static road network and the locations of roadside storage sites if these are stored in GIS by several operators in the supply system. Consequently, the storage points need to be moved to the nearest object in the transport network. GIS software may have built-in algorithms for finding the closest point or line in the network automatically (Esri 2021a).

Precision refers to the minimum geographical scale for a raster cell or vector object (Fisher et al. 2006). In a raster dataset this means that the cell value indicates a certain statistical value (e.g. a count, sum, mean, mode, median or standard deviation) for the physical quantity (e.g. tree volume). However, a cell cannot contain data for each individual object found in the area that it covers, so that individual objects and their properties can be presented more precisely in a vector layer. The challenge of generalization and reasonable precision for each dataset nevertheless still exists, and minimum size of an object should be decided upon when forest stands are to be represented by vector polygons in GIS.

1.5 Data sources, system abstraction and spatial aggregation in Finnish biomass data

Geographical information on forest resources in Finland has been collected systematically for a relatively long time. The first National Forest Inventory (NFI) started 100 years ago (Ilvessalo 1927), and the inventory has been repeated 12 times since then (Natural Resources Institute Finland 2021e). Developments in data processing, computerization and, certainly, GIS have increased the possibilities for exploiting NFI data in various forest-related research projects and developing new calculation and estimation models and dataset exports from the NFI database. The multi-source National Forest Inventory (MS-NFI) database has been generated by combining field measurement-based NFI data with data from satellite images and estimating given forest and forest-land attributes (44 thematic datasets) in a continuous raster layer covering the entire country (Mäkisara et al. 2019). The resolution of the raster grid is 16 m, and a new version has been published every second year. This data collection is most useful in supply chain studies at a strategic level, due to the greater estimation errors in smaller areas and the fact that the material dates back to about two years before the publication of the last dataset (Natural Resources Institute Finland 2021f). In addition to georeferenced raster images, the same data are also available as municipality-level estimates in a table format that can be imported into GIS by combining the data with vector polygons representing the areas of the municipalities concerned (Mäkisara et al. 2019).

Another important provider of public forest data is the Finnish Forest Centre (FFC), which has the statutory task of enforcing the Forest Act (1093/1996) and maintaining an information system that contains data on forest properties and forest owners (Forest Data Act 419/2011). The system includes GIS data on forest resources in a raster format (16 m resolution, similar to the MS-NFI data) and as vector polygons representing either forest stands (principally in private forests) or intended cutting areas (Finnish Forest Centre 2021). Unlike NFI data, where the backbone is a systematic nationwide network of field plots (Mäkisara et al. 2019), FFC products are based on light detection and ranging (LiDAR) data and aerial images, which are interpreted and processed to final datasets with support from field assessments. The resulting polygons contain more than 100 attributes describing the growing stock, soil type and other characteristics of the forest stand concerned. LiDAR data are used to generate the growing stock raster cells (16 m × 16 m) and to delineate the stands. A canopy height model (CHM) is also available as raster data with 1 m resolution for further data processing (e.g. single-tree maps). The datasets can vary in geographical coverage and age according to their regions and themes, so that the coverage of forest stand data is better in Southern Finland, for example, where the proportion of private forest ownership is higher than in the north. Cutting intent is the most up-to-date and uniform dataset, as it is based on the legal obligation to announce forthcoming commercial cuttings (Forest Act 1996), and it can also be considered the public dataset that corresponds most closely with the operational-level forest data owned and controlled by various companies that are active in the forest and energy industries.

The road network is the most important transport network in biomass logistics in Finland, as most supply chains are totally based on truck transportation (Strandström 2021) and, quite obviously, transportation by road is included in all chains that start out from a roadside stack. Digiroad is a national GIS database containing vector data on all roads and streets in Finland and is available free of charge (Finnish Transport Infrastructure Agency 2021a). Its spatial precision is high and the geometry and attributes of the public roads and streets is checked and updated regularly. Attribute data concerning private forest roads (e.g. width, surface, obstacles, and turning points) are seldom provided at present, although improvements in this respect are currently under way (Venäläinen and Nousiainen 2021). As far as other transportation modes, vector lines of railways and fairways of maritime transport are also available as public data (Finnish Transport Infrastructure Agency 2021b).

Abstraction is an important part of the modelling of real-life objects and events. The higher the level of abstraction, the more the contents of the model are generalized. In GIS-based BSC research, abstraction can refer to both the spatial precision of the GIS data and the operations included in the supply chains. Based on the public data available in Finland, Figure 1 demonstrates the scale of spatial abstraction with datasets in which biomass and transportation are modelled as data objects at different levels of precision. The geographical extent of the system and the available computing capacity will principally determine how low a level of abstraction can be applied in practice. Also, any increase in the alternative transport methods and node points in the supply chain network (i.e. plants and terminals) will increase the complexity of the model and limit the number of points representing biomass sources.

Single trees are included in Figure 1 as an example of the lowest level of abstraction, but because the number of trees grows rapidly as the area concerned expands, their use as potential starting points in BSC studies is mostly theoretical. Furthermore, the lowest level of abstraction presented here would obviously necessitate the inclusion of forwarding tracks in the transport network, and data of this kind are not publicly available. Instead, it is convenient to use roadside storage locations as the starting points for supply chains, or, if the locations are unknown, to choose a spatial precision that corresponds sufficiently well to the distribution of roadside storage sites in the real world. Of the public datasets including attribute data on growing stock properties, forest-stand polygons are probably the most suitable, because in Finnish forestry the individual cutting areas are commonly defined in accordance with the forest stand patterns. Nevertheless, roadside storage sites represent only a small proportion of all forest stands when a biomass supply is analysed in the short term, e.g. on an annual basis. In strategic-level research it might be more advantageous to use a static network of starting points (e.g. representing the centroids of a raster layer) with suitable geographical precision (e.g. where hundreds of forest stands are covered by a single raster cell). The most significant advantage of this method is that transportation routes would only need to be estimated once, provided that the other locations in the supply chain network (such as roads and biomass destinations), as well as the network itself, remain unchanged during the model's lifespan.

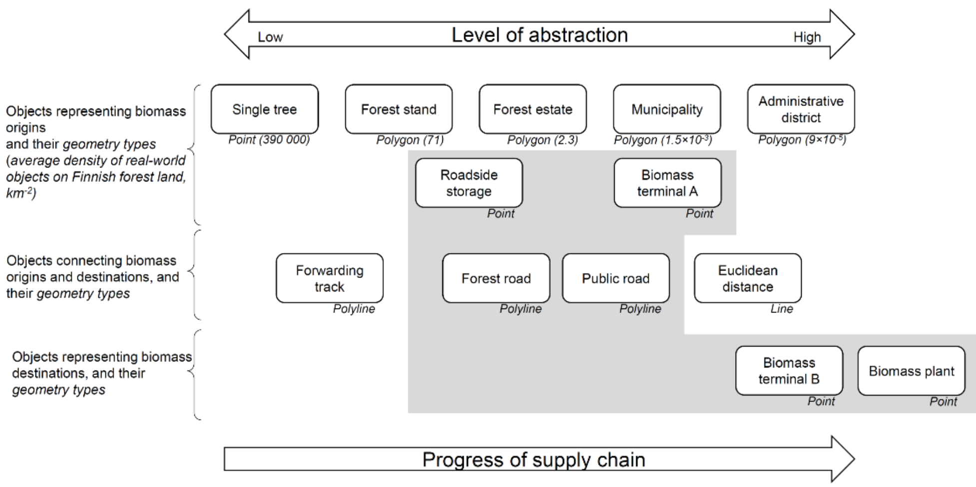


Figure 1. An overview of the abstraction possibilities in a GIS model that represents a forest BSC system based on road transport with alternative datasets available in Finland. The most common datasets used by transport operators in practice have a grey background. Biomass terminal A denotes a point where biomass can be collected and stored close to the origin. Biomass terminal B is a buffer terminal near the mill or plant or a point where biomass can be transshipped to another mode of transportation. The densities of real-world objects are based on information published by Finnish Forest Centre (2021) and Natural Resources Institute Finland (2020, 2021e).

Spatial aggregation (Esri 2021b) is required when the level of abstraction is raised so that the precision of the biomass data declines. The available forest datasets that may be used in supply chain analyses at different abstraction levels in Finland are summarized in Figure 2, which also explains how the data can be processed in GIS to enable a further transportation analysis to be performed starting out from the same points of origin. In addition to the aggregation performed during vector-to-raster conversions (and vice versa), data will be aggregated when a new, coarser raster is formed from a higher-resolution one (such as the FFC and MS-NFI grids with 16 m resolution), and sometimes even disaggregation (Spiekermann and Wegener 2000) may be appropriate if, for example, data from large vector polygons are transferred to a systematic grid with relatively high precision.

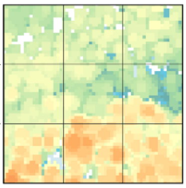
1.6 Outline of the thesis and objectives

This thesis is based on experience with spatial data collection from various sources over a number of years, with regard to multiple research and development projects concerned with biomass supplies. Research methods, data formats, quality requirements and levels of abstraction played important roles in the evaluation and dissemination of the results of these projects.

Although the most useful approach in principle would be to opt for the most precise and reliable material available, it is the case in practice that information systems include procedures for which a decrease in spatial precision is needed to speed up data management and processing. The researcher has therefore been obliged to assess the impacts of the selected level of data abstraction and the resulting spatial uncertainty on the final results of the research in each case separately. If the profitability of a planned biomass terminal is to be assessed, a higher spatial precision will obviously be required than in a study focusing on the entire supply area of a biomass plant, for example, or an even larger area. On the other hand, the spatial precision of biomass resource data does not necessarily play a very important role, if the main focus of a case study is on some other specific part of the supply chain, such as transportation between biomass terminals and plants, or selection between alternative comminution methods.

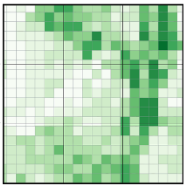
The main motivation was a need to identify the best sources of spatial BSC data and to increase our understanding of such matters as data quality (including spatial precision), coverage and the feasibility of different approaches. The idea was that, regardless of the biomass types, procurement methods or the global location of the area concerned, each geographical dataset has an optimal spatial precision, although this may depend on many factors, such as the aims of the research and the intended level of abstraction to be aimed at in the model.

Single tree level

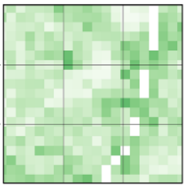


Dataset name	**Canopy height model**
Geometry	Raster (1 m × 1 m)
Source	Finnish Forest Centre
Attribute data	1 raster layer representing canopy height
Spatial processing methods	Crown delineation to polygons and estimation of treetop location inside polygon
Processing result	Vector points representing single trees
Adjacent object in transport network	Forwarding track (no public data available)

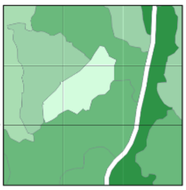
Stand level



Dataset name	**LiDAR based grid layers**
Geometry	Vector polygons (16 m × 16 m squares)
Source	Finnish Forest Centre
Attribute data	27 attributes of growing stock 8 attributes of forest ground
Spatial processing methods	Aggregation of grid data to 1) forest stand polygons 2) a coarser grid
Processing result	Vector points (polygon/cell centroids) representing possible harvest sites
Adjacent object in transport network	Forest road



Dataset name	**NFI grid layers**
Geometry	Raster (16 m × 16 m)
Source	Natural Resources Institute Finland
Attribute data	40 raster layers of growing stock 4 raster layers of forest ground
Spatial processing methods	Aggregation of grid data to 1) forest stand polygons 2) a coarser grid
Processing result	Vector points (polygon/cell centroids) representing possible harvest sites
Adjacent object in transport network	Forest road



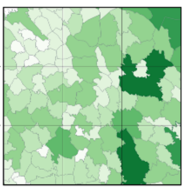
Dataset name	**Forest resource patterns**
Geometry	Vector polygons
Source	Finnish Forest Centre
Attribute data	15 attributes of growing stock 7 attributes of forest ground
Spatial processing methods	Polygon to point conversion Optional (dis)aggregation to a grid
Processing result	Vector points (polygon or grid cell centroids)
Adjacent object in transport network	Forest road

Forest estate level

Dataset name	**Cadastral units**
Geometry	Vector polygons
Source	National Land Survey of Finland
Attribute data	N/A*
Spatial processing methods	Aggregation of data from external datasets (e.g. FFC or MS-NFI data) Optional (dis)aggregation to a grid
Processing result	Vector points (polygon centroids) representing forest estates
Adjacent object in transport network	Public road

*) Access to land ownership data is limited by the Personal Data Act, and only the property ID is included as attribute data. This level of abstraction is rarely used in supply-chain oriented studies in Finland.

Municipality level



Dataset names	**Municipalities, Forest resources by municipalities**
Geometry	Vector polygons
Sources	Statistics Finland (geometry), Natural Resources Institute Finland (attribute data)
Attribute data	4 forest ground tables, 24 growing stock table and forest ground and growing stock table
Spatial processing methods	Combining of datasets by municipality ID (IDs in polygons and spreadsheet tables) Optional (dis)aggregation to a grid
Processing result	Vector points (polygon/cell centroids) representing forests within municipalities
Adjacent object in transport network	Public road

Figure 2. Map examples and information on Finnish datasets that can be used in GIS to model forest biomass origins. Required or optional processing methods for linking biomass data with the transport network layer in a BSC system analysis are also presented.

The main purpose of this thesis was to assess the applicability of different levels of spatial abstraction in case-specific BSC system studies that represent different objectives and methods. The focus was on supply chain systems providing feedstock to conventional Finnish CHP plants, a conventional Finnish pulp mill and a possible industrial-scale biomass-to-liquid refinery using forest fuels as its main input. Another aim was to review similar BSC studies performed in other regions of the world, as international references for the materials and methods applied in Finland. The questions that this thesis set out to answer were the following:

1) What kind of spatial data is needed when BSC systems are studied case-specifically from different perspectives?
   - How are the most economic solutions for supply chains in a GIS model to be found when different feedstock types, vehicle types and transport networks are included in the system?
   - How are the GHG emissions arising from the biomass supply to be assessed with the aid of GIS? What are the impacts of plant locations on the total GHG emitted from a supply chain system?
2) What is the appropriate precision for spatial forest biomass data in order to represent the biomass origins of real-world cases of biomass supply and logistics in Finland,
   - when parallel transport systems are studied with a simulation approach?
   - when randomness is added to the determination of points of origin and dynamic changes in the attributes of these are accounted for in the GIS data?
3) How do the data specifications compare with similar BSC case studies in bioenergy research worldwide?
   - How much spatial data and of what kind have BSC case studies used in recent decades?
   - How do the research objectives and methods, and the geographical region affect the selection and processing of spatial data?

2 MATERIALS AND METHODS

2.1 Research framework

This thesis covers the framework of BSCs and the use of spatial data and methods in related research (Figure 3). First, a review will be presented of the global situation and recent methodological developments in this field of research, covering a wide range of biomass logistics and end-product types (Paper I). The scope will then be narrowed to forest biomass as feedstock and Finland as the geographical region in focus. The research will include static supply chain analyses (Papers II and III) and dynamic supply chain models (Papers IV and V). In this context a model refers to a representation of a real-world system in a computer environment, while dynamic and static, respectively, stand for the inclusion and exclusion of time-based variables in the model. These variables may be of minor importance in strategic management, but they are already essential in situations that involve the tactical planning of BSCs (Palander 1995).

This work represents a combination of a literature review, theoretical methodological development and experimental case studies, where the latter included varying logistical setups for BSCs covering different geographical regions in Finland (Table 1). The biomass datasets, which were collected from different sources and processed using different aggregation methods, were deployed in a systematic grid of vector points in all the cases. The spatial resolution of the grid was 2, 4 or 5 km and the supply areas ranged between 200 km² and 85 900 km².

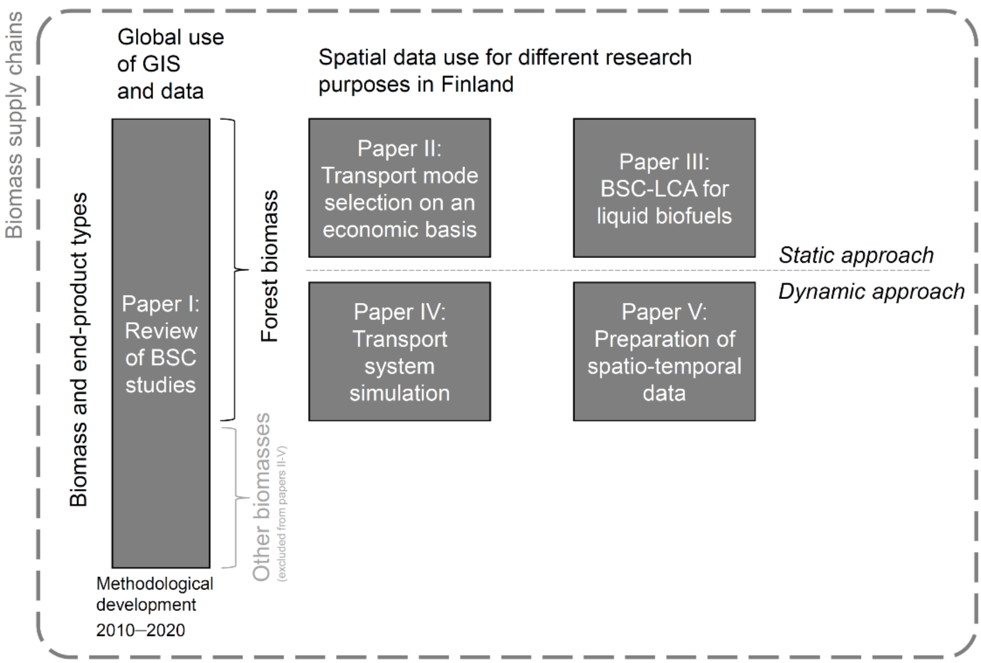


Figure 3. The framework for the research.

Table 1. Geographical properties of the supply areas included in the GIS models in Papers II-V.

Paper	Demand point / area studied	Grid resolution	Supply points	Supply area, km² (ca.)
II	Jyväskylä	2 km	9 414 – 20 626	39 500 – 85 900
II	Haapajärvi	2 km	53 – 659	200 – 2 900
III	PRV (Porvoo)	4 km	310 – 1 478	5 400 – 24 900
III	RMA (Rauma)	4 km	333 – 1 831	5 900 – 32 000
III	AJO (Ajos, Kemi)	4 km	592 – 3 755	11 700 – 73 000
III	PIE (Pieksämäki)	4 km	103 – 416	1 700 – 6 800
III	PKO (Parkano)	4 km	150 – 655	2 500 – 10 800
III	KON (Kontiomäki)	4 km	234 – 987	4 000 – 17 400
III	KJÄ (Kemijärvi)	4 km	431 – 1 717	9 200 – 39 700
IV	Southeast Finland (7 points)	5 km	532	11 800
V	Southern Finland (1 point)	2 km	3883	17 500

2.2 Assessment of biomass supply chain studies (Paper I)

The material for the literature review was collected from scientific peer-reviewed papers that included a case study concerned with biomass supplies. The collection method was an automated bibliographic analysis based on an earlier study in the same field that had a different objective but had carried out a search for a similar set of publications as a starting point (Aalto et al. 2019). As the purpose of this review was to extract case studies with a certain content, the papers were accepted or dismissed on a manual basis (i.e. by reading them) applying the following screening protocol. An answer "no" to any of the questions below would lead to elimination of the paper from the review:

1) Does the article include a case study where
   a) biomass is considered as a source of energy, and
   b) biomass is procured from several geographical locations and transported to one or many end-use or intermediate storage locations?
2) Does the case study focus on an area smaller than or equal to 10 000 000 km²?
3) Is biomass transportation by road, rail, waterway or pipelines from the origin to the destination or intermediate location mentioned in the case study?

The following stage was to assess the properties of the spatial data and GIS-based analysis methods by comparing them with the objectives and methods of the present work and with the features of supply chain systems that the case studies represent. The review also focused on how GIS methods and data have developed in time and to what extent studies from different parts of the world apply them in different ways. This stage involved classifying the studies into 16 thematic categories (Table 2) and then examining correlations that were of interest in a cross-classification analysis of these categories, principally highlighting their spatial properties.

Table 2. Classification of the case studies reviewed in Paper I.

Group 1: General information
a) Year of publication
b) Region
c) Target country

Group 2: Biomass origins and destinations
a) Biomass origin
- Forests and tree plantations
- Farms and fields
- (Other sources)

b) End product
- Heat and/or electricity
- Gaseous fuels
- Liquid fuels
- Solid fuels
- (Other products)

Group 3: Methodology
a) Method
- Regression analysis
- Optimization
- Life-cycle analysis
- Discrete time simulation
- (Other approach)

b) Objective
- Economic performance
- Energy balance and emissions
- Social impacts
- (Other impacts)

Group 4: Spatial framework
a) Area
- 1 – 100 km²
- 101 – 1 000 km²
- 1 001 – 10 000 km²
- 10 001 – 100 000 km²
- 100 001 – 1 000 000 km²
- 1 000 001 – 10 000 000 km²

b) GIS data format
- Raster
- Vector
- (Other)

c) Transport network data source
- Authority or enterprise
- OpenStreetMap
- (Other sources)

Group 5: Supply system complexity
a) Points of origin
- 1 – 100
- 101 – 1 000
- 1 001 – 10 000
- 10 001 –

b) Destinations
- 1
- 2 – 10
- 11 – 100
- 101 –

c) Multi-stage network (Yes/No)
d) Multi-modal network (Yes/No)
e) Biomass property changes (Yes/No)
f) Transport cost basis
- Distance
- Time
- (Other)

2.3 Static modelling of supply chains in GIS (Papers II and III)

2.3.1 Economic optimization on a GIS platform (Paper II)

A GIS-based calculation model for analysing the economy of supply chains may include additional transport modes such as rail or water transportation. Paper II consists of two parts: 1) description of the design of the model, its analysis methods and data sources, and 2) a case study demonstrating selection of the economically optimal transport solution for each individual pair of origins (representing roadside storage points) and destinations (representing a power plant).

The design of the model was based on several spatial datasets representing the biomass supply at harvesting stands, transportation network and locations where distance-independent costs, such as biomass comminution or transhipment, were added to the supply chain. For the supply of two forest-fuel types (logging residues and stumps), the theoretical potential was extrapolated from the harvest statistics and NFI-based estimates at the municipality level to a fixed spatial grid with a cell size of 2 km × 2 km. The volume was thereafter limited to a techno-economic harvest potential with universal conversion factors. For one fuel type (small-diameter energy wood) the data was already provided in the form of the techno-economic harvest potential. Land use data were used as a weighing factor so that the cells including high forest coverage were allocated higher supply volumes than those with low forest coverage. The cell centroids were used as the starting points for transportation and the routes between all possible origin-destination pairs were calculated during the construction of the model. The closest line segment representing a trafficable road was linked to the centroid automatically by the software, so that manual offsetting of the centroids was not compulsory.

The model accounted for the given local or universal limitations applying to the theoretical potential and calculated the accumulation of available biomass as a function of transport distances around the power plant or transhipment points. Another output of the model was the optimal transport mode from each point of origin, calculated separately for each biomass type. This was determined by the spatial point barrier method as provided by the GIS software extension (Network Analyst of ArcGIS Professional), so that the entire analysis could be run within the GIS environment. The procedure for finding the most economic route is presented in Figure 4.

The performance of the model was tested in a case study in Central Finland in which a combination of truck and train transportation represented the multimodal option. The supply potentials were deducted from the techno-economic harvest potential by an amount corresponding to the assumed market share of the power plant. The grade of reduction varied spatially, as it was assumed that there is less competition for the feedstock further away from the power plant.

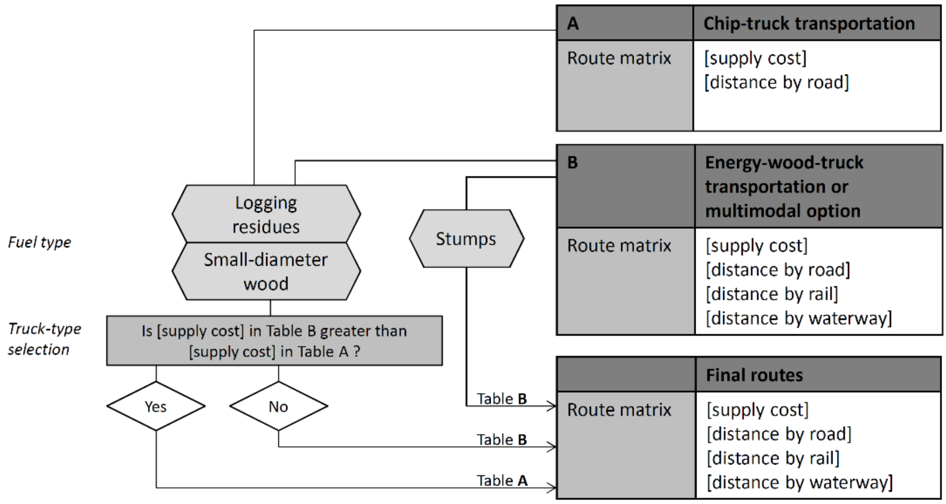


Figure 4. Determination of the most economic routes in the supply chain model of Paper II. (Figure originally published by Korpinen et al. (2013), J Geogr Inf Sys 5: 96-108. DOI: 10.4236/jgis.2013.51010. Licence CC-BY 4.0)

2.3.2 GIS-assisted LCA for GHG emission assessment (Paper III)

In addition to the economic impacts, it is also important to assess greenhouse gas emission impacts of the supply chain when deciding between alternative locations for a new biofuel refinery. The framework of Paper III included two models, a GIS model and an LCA model, where the function of the former was to produce all the necessary spatial input data for the latter.

The estimated annual feedstock demand for liquid biofuel production was significant, ca. 1 million m^3_{solid} of forest biomass for producing the planned volume, 250 000 t of biodiesel. The scale of the plant was such that a resolution of 4 km × 4 km was applied for the grid representing the biomass sources and instead of cost-based determination of the optimal transport modes, alternative ways of delivery were studied by means of four scenarios including fixed transport mode proportions (0%, 33%, 50% or 67% of feedstock delivered by a truck system and the remaining proportion by a railway system).

As the system boundaries (Figure 5) included all the supply chain operations between roadside storage and the plant yard, biomass comminution emissions were also analysed. Given that roadside chipping was included as a comminution method for the harvest residues and small-diameter energy wood, the movement of the chipper truck was modelled by the Travelling Salesman Problem solver included in the GIS software extension (ArcGIS Network Analyst).

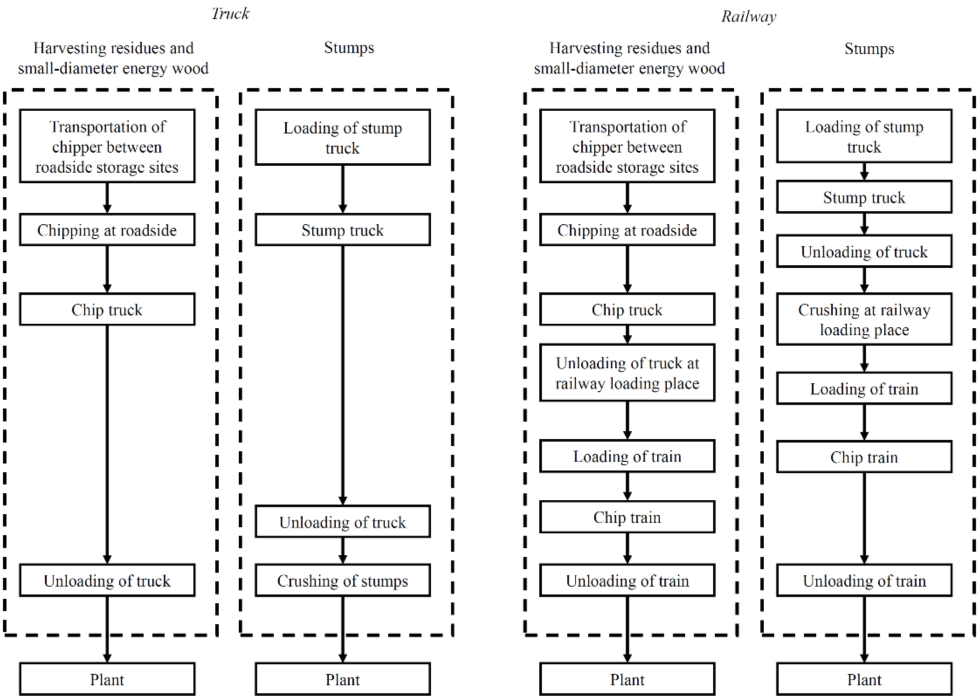


Figure 5. Supply chains and system boundaries in Paper III. (Figure originally published by Jäppinen et al. (2013), GCB Bioenergy 6: 290-299. DOI: 10.1111/gcbb.12048. Licence CC-BY 4.0)

2.4 GIS for dynamic modelling of supply chains (Papers IV and V)

2.4.1 GIS-assisted agent-based simulation (Paper IV)

Dynamic simulation is a viable method for studying logistics in detail when the timing of deliveries, scheduling and alternative "what-if" scenarios are important factors (Saad 2003). Simulation can also be beneficial when it is too expensive, or even impossible, to experiment with a new system in real life. The logistic setup in Paper IV included a task of delivering feedstock to several pulp mills in South-eastern Finland, which was assigned to a combination of a conventional truck transportation system and a system based on high-capacity transportation (HCT). Individual trials with HCT trucks exceeding the maximum gross weight of 76 metric tons (payload ca. 52 t) were underway in Finland at the time when this research was conducted, and these produced some experimental data concerning the activities and impacts of such trucks (e.g. fuel consumption), thereby supporting the profitability calculations for truck investments. The need for a comprehensive analysis of the impacts of HCT in a broader context nevertheless called for a holistic simulation of a larger transportation system.

An agent-based simulation (ABS) model was designed to meet the demand for such a holistic system approach. The model is a spatio-temporal one, meaning that it accounts for the geographical properties of the system and time-dependent factors, such as the sufficiency of the transport fleet (i.e. HCT and regular trucks), seasonal variations in the supply at the biomass origins, and feedstock inventory levels at the transhipment terminals (i.e. HCT terminals) and mill yards.

The decision-making process used in the model, as summarized in Figure 6, is based on four agent types, each containing a given population of units capable of interacting with other agent types. By contrast with discrete-event simulation (DES), a popular approach in the modelling of logistics, the product of interest (i.e. roundwood) was not modelled as an entity flowing through a process chart but was "moved" towards the destination as information defined for the agents and as interaction between the agents.

The role of GIS was to feed the ABM with source datasets that were indicated by "tables" in the operation principles for the supply and demand points (Figure 6). In addition to the spatial distribution of three pulpwood types according to species, the spatial source data contained two route matrices: one for regular trucks and the other for HCT trucks. This was based on the assumption that the dimensions and structure of the HCT trucks concerned are not suitable for most forest roads. Unlike the static GIS analyses, the routing was not definitively based on the shortest distance or the lowest cost of delivery, but rather the simulation procedure was to go through a table of destinations (ranked in order of supply costs) and send the truck to the first destination accepting feedstock at that time.

The locations of demand points were based on the existing pulp mills, since at the time of the research there were no specific HCT terminals other than the mill yards in the area concerned. The placement of terminals was therefore based on a visual inspection of the map displaying the traffic intensity of regular trucks. The pulpwood harvest potential was extrapolated from municipality-level estimates, and a MS-NFI raster dataset (presented in Figure 2) was used for weighting the harvest potential of the grid cells within each municipality. The dataset contained pulpwood volume estimates for each of the tree species in cells of size 16 m × 16 m.

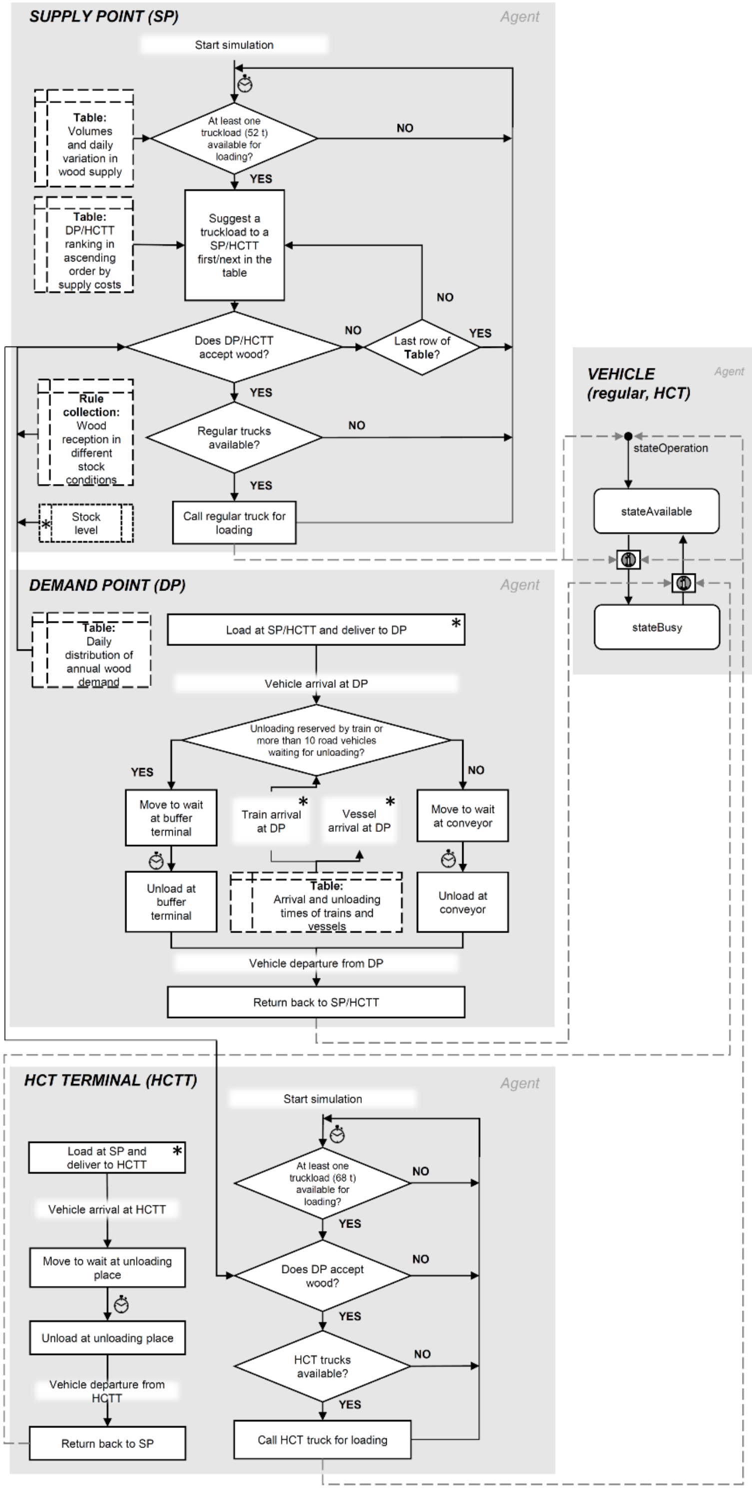


Figure 6. Decision-making process in the multi-modal supply chain model designed with an agent-based simulation approach in Paper IV. * indicates randomness relative to an event and a stopwatch represents possible time delays. (Figure originally published by Korpinen et al. (2019), Croat J For Eng 40(1): 89-105. Licence CC-BY 4.0)

The ABM included three levels of system abstraction, the lowest level being used for representing truck transport operations and the highest level for pulpwood deliveries by rail or waterways. The purpose of the latter deliveries was to affect the demand at the mill and temporarily reserve the mill yard unloading capacity (Figure 6). Between these levels, regular truck transportation to and from the surrounding area (i.e. the rest of Finland and Russian Federation) was taken into account by generating supply and demand at the borders of the area considered here.

Since the system had not been demonstrated in practice, many parameters affecting its performance had to be estimated by means of a sensitivity analysis that included the number of HCT terminals in the network (0, 7 or 14) and the expected unit costs resulting from the use of a particular terminal (similar to the barriers of the loading points in Paper II). One critical question was how many trucks were needed to keep the system in balance. The case study had a total of 64 scenarios to be simulated, with varying numbers of regular and HCT trucks (Figure 7). Seven out of these were reference scenarios with an unlimited number of vehicles, setting the level of eligible system balance. Moreover, all the scenarios were replicated eight times to show the impact of the stochastic variables in the system (e.g. the arrival times of trains and vessels at the pulp mills). Scenarios that were incapable of delivering enough feedstock to the mills due to an excessively short transport capacity were disqualified from the final evaluation.

After the resolution of the supply point grid had been adjusted to 5 km × 5 km, yielding 532 origins of biomass, 491 in the grid and 41 border transit points, test runs were performed with the ABM. As the feedstock demand was represented by seven pulp mills, the feedstock supply by 491 points, while the 14 HCT terminals and 41 transit points represented both supply and demand, the set of supply cost tables theoretically included 75 991 different transport routes (directly to the destination or via a terminal). In practice, however, the demand at the transit points was excluded, as it is known that pulpwood is not actually transported out of the region, so that the number of individual transport routes in the simulation was reduced to 55 860.

2.4.2 GIS generating spatial and temporal uncertainty (Paper V)

Substantial variation in biomass supply and demand can be observed between years in Finland, especially in the case of heat production, principally due to long-term natural anomalies in weather conditions. Since it has been assumed that a simulation model will become more realistic when uncertainties related to operational resources (e.g. machines and vehicles) and feedstock sufficiency at different times can be taken into account, the purpose of Paper V was to develop a method for acquiring and processing biomass source data so that a supply chain system can be simulated over a multi-year period together with the uncertainty factors that may affect the performance of the system. The paper focuses on the stochastic variations in roadside storage locations (spatial variation) and harvesting events (temporal variation), and the process of drying the harvested biomass at the roadside (temporal variation). Further operations in the supply chain following roadside storage were excluded from consideration, as they were meant to be included in the simulation model.

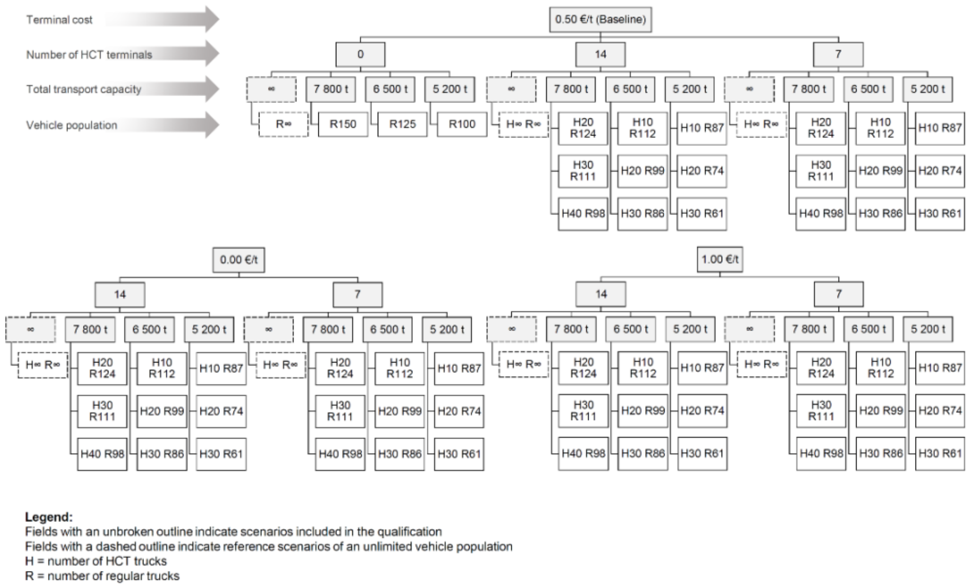
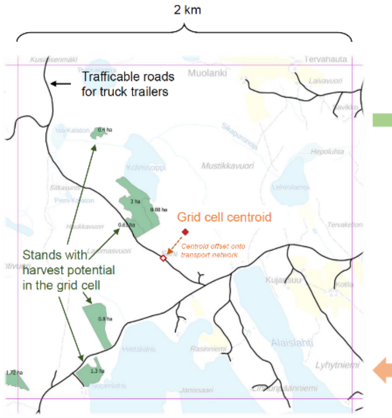


Figure 7. The configuration of simulation scenarios in Paper IV (white fields). Total transport capacity indicates the approximate sum of the payloads of the trucks in the scenario. (Figure originally published by Korpinen et al. (2019), Croat J For Eng 40(1): 89-105. Licence CC-BY 4.0)

The paper also presents a case study of a forest biomass supply area at a maximum distance of 120 km by road from the central demand point in the area and representing a total feedstock supply of 78 500 m^3/a on average. The spatial biomass source grid was adjusted to 2 km × 2 km and the original biomass availability data was imported into the grid from the national Biomass Atlas data service (Natural Resources Institute Finland 2021g). The allocation of the availability estimates from the original dataset to the grid followed the same principle as in Papers II-IV. To fulfil the need for a realistic number of points of origin in the area, it was determined that for a simulation run of one calendar year only ca. 5.15 % of the points (i.e. 200 per 3883 points) should be randomly selected to represent the year's biomass supply. Simultaneously, the available feedstock volume was multiplied by 19.415 (i.e. 3883 per 200), in order to create supply point datasets for supply chain simulations representing consecutive years, so that the yearly total volumes of available feedstock, transport distances and, thus costs, would deviate from the average estimates.

We then examined the possibilities for generating random variation in the monthly harvesting volumes, which were based on the national statistics for forestry operations. For this purpose the supply points were assigned proportional values for each month (totalling 100%), indicating the probability of the stand (or stands) in the grid cell being harvested in the respective month. After the month was determined the simulation model was to select the final time of harvesting within the month using a uniform random distribution. In addition, the probability distributions can be weighted at the supply point level by means of location-specific factors such as stand accessibility at different seasons (Finnish Forest Centre 2021). The weights should be finally adjusted, however, so that the monthly averages for the total population of points correspond to the statistical distribution of harvesting months (Figure 8).



The map contains data from the National Land Survey of Finland and the Finnish Forest Centre, 2021

Cell specific

Stand ID	Area, ha	Harvest months	1	2	3	4	5	6	7	8	9	10	11	12
1180854	0.40	12 – 3	0.250	0.250	0.250	0	0	0	0	0	0	0	0	0.250
24272787	3.00	4 – 11	0	0	0	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0
27427286	0.88	12 – 3	0.250	0.250	0.250	0	0	0	0	0	0	0	0	0.250
1181400	0.61	4 – 11	0	0	0	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0
24274075	0.80	4 - 5, 10 – 11	0	0	0	0.250	0.250	0	0	0	0	0.250	0.250	0
24272804	1.30	4 - 11	0	0	0	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0
Total	6.99	Average (weighted by area)	0.046	0.046	0.046	0.116	0.116	0.088	0.088	0.088	0.088	0.116	0.116	0.046

Supply area specific

	1	2	3	4	5	6	7	8	9	10	11	12
Average of all cells in the supply area	0.081	0.081	0.081	0.096	0.098	0.073	0.073	0.073	0.073	0.096	0.098	0.081
Statistical proportion of harvest operations (national level)	0.118	0.107	0.134	0.088	0.063	0.079	0.057	0.062	0.072	0.069	0.081	0.070
Coeffient to adjust grid cell probability values	1.560	1.414	1.771	0.981	0.703	1.159	0.836	0.909	1.056	0.770	0.903	0.925

Cell specific

	1	2	3	4	5	6	7	8	9	10	11	12
Adjusted probability values for grid cell	0.072	0.065	0.081	0.114	0.082	0.102	0.073	0.080	0.093	0.090	0.105	0.043

Figure 8. An example of determining the probability distribution of the month of harvesting in a grid cell, based on the stand data (Finnish Forest Centre 2021) and the statistical proportions of harvest months at the national level (Natural Resources Institute Finland 2021h).

While the above-mentioned method expressed the temporal distribution of the harvesting time, another important data processing stage for the simulation of a supply chain is the determination of the optimal storing time before transportation to the plant. The second part of the study focused on this time and the associated weather-dependent decision procedure by comparing different moisture estimation models. This analysis was also spatially referenced, as the models were tested using experimental weather data from a known location. Despite the fact that historical weather data are nowadays also available in spatial grid form, i.e. spatially interpolated data from weather station observations (Finnish Meteorological Institute 2021), the models were not analysed at the grid point level. Furthermore, moisture estimation is not considered here, as it lies outside the scope of this thesis.

3 RESULTS

3.1 The use of GIS in BSC case studies of bioenergy research (Paper I)

The bibliometric analysis yielded 180 publications, 94 of which qualified for further review. North America and Europe are the main regions where spatial BSC case studies have been published, and the number of published studies has increased steadily from year to year, 2020 being the record year, with 21 papers in the review (Figure 9). At the same time the proportion of large areas studied (more than 100 000 km^2) has increased.

While North America and Europe are the main regions where supply chains have been studied, the end-products of biomass conversion differ significantly (Figure 10). In Europe the case studies have focused principally on heat and power generation, while in North America the supply chains have provided feedstock for liquid biofuel plants. From the spatial abstraction point of view, many US-based case studies have used county-level data on biomass resources and thus county centroids as points of origin. On the other hand, the US-based studies often had several optional destinations in the supply chain network, in some cases represented by the same county centroids as the origins. The areas concerned were also larger than in Europe on average, and the systems usually included intermediate terminals, making them more complex in terms of routing. Economic optimization of the system was the most common research method worldwide, and it was this that was used in all the most complex supply chain analyses (i.e. those with large numbers of origins and destinations).

There was great variation in both the sizes of areas studied and the spatial precision of biomass data. In general, similar approaches were applied in quite diverse geographical environments with different types of spatial datasets. The number of points of origin, for example, ranged from three points to over eight billion, with the three points representing the centroids of extensive macroalgae harvesting areas in the ocean and the case with the most points being a raster data-based least-cost path (LCP) analysis of the profitability of forest biomass supplies. The resolution of the raster in the LCP analysis was 10 m and off-road skidding tracks were included in the supply chain network. Hence this was the most spatially precise case study regarding forest biomass supplies among all the papers reviewed here. Raster data were also used in other studies where the number of individual biomass origins was high. In general, a vector was the most commonly used data format, found in ca. 61% of the papers, although unfortunately, as many as ca. 27% of the studies did not report the GIS data format at all.

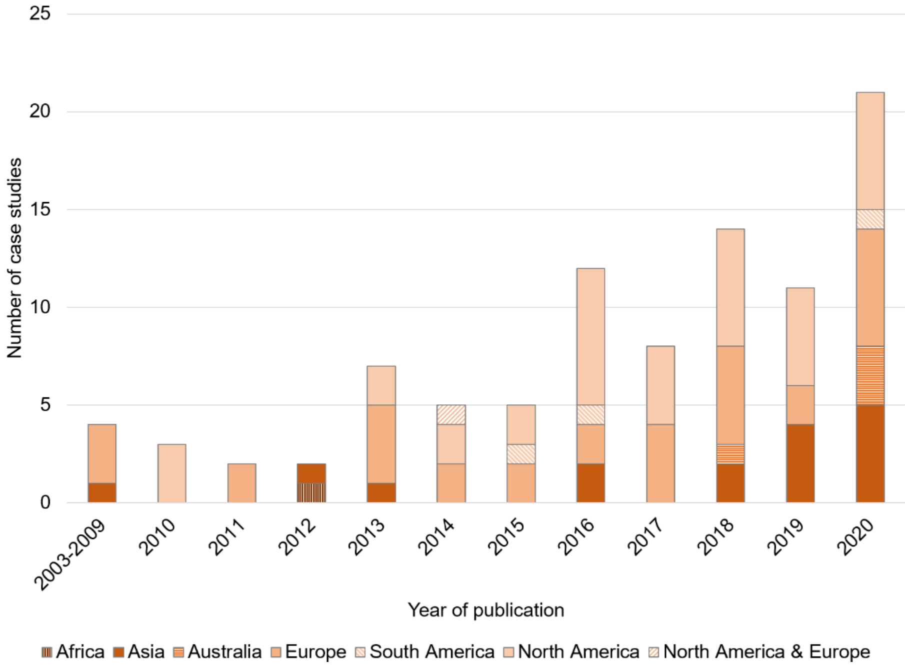


Figure 9. Case studies reviewed in Paper I, classified by year of publication and region of the world.

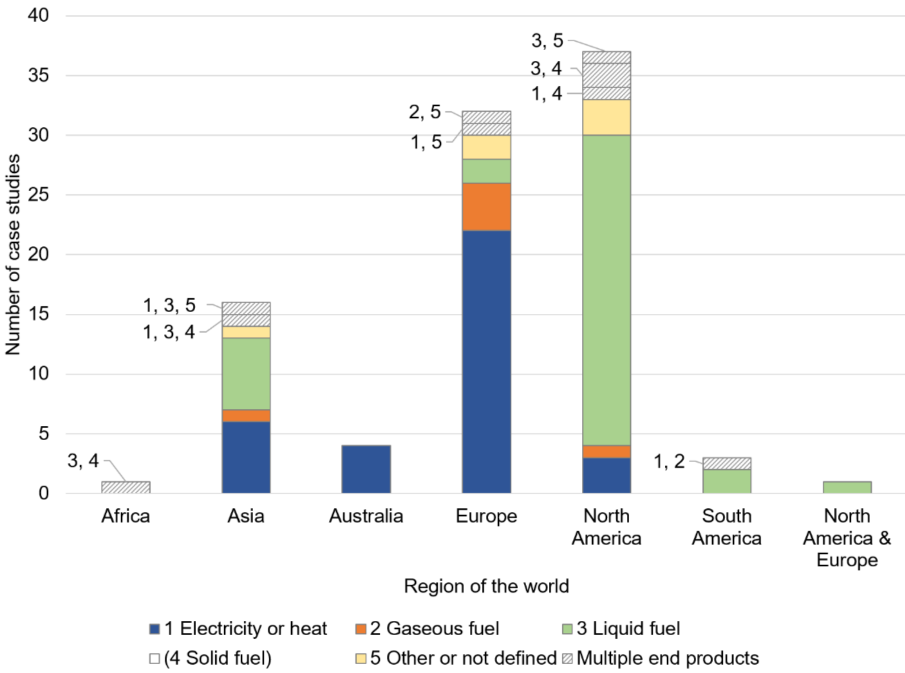


Figure 10. Case studies reviewed in Paper I, classified by the region of the world and the end product of biomass conversion.

3.2 GIS for studying economic and environmental BSC impacts (Papers II and III)

Although the objectives and analytical methods of Papers II and III were different, they used very similar methods for modelling the biomass supply at the origins. The results of the case study in Paper II showed how competitive a truck transportation chain from roadside storage directly to the plant can be relative to other transport modes. Out of the scenarios constructed for three annual volumes of total feedstock demand, the rail transport chain was the most economic option only for a marginal proportion of the routes from forests to a power plant. This can be seen from the map in Figure 11, which shows that a demand of 2500 TJ a^{-1} or less is not high enough for considering transportation by vehicles other than truck trailers. Furthermore, an even higher demand results in direct truck transportation from origins very close to the selected railway loading point.

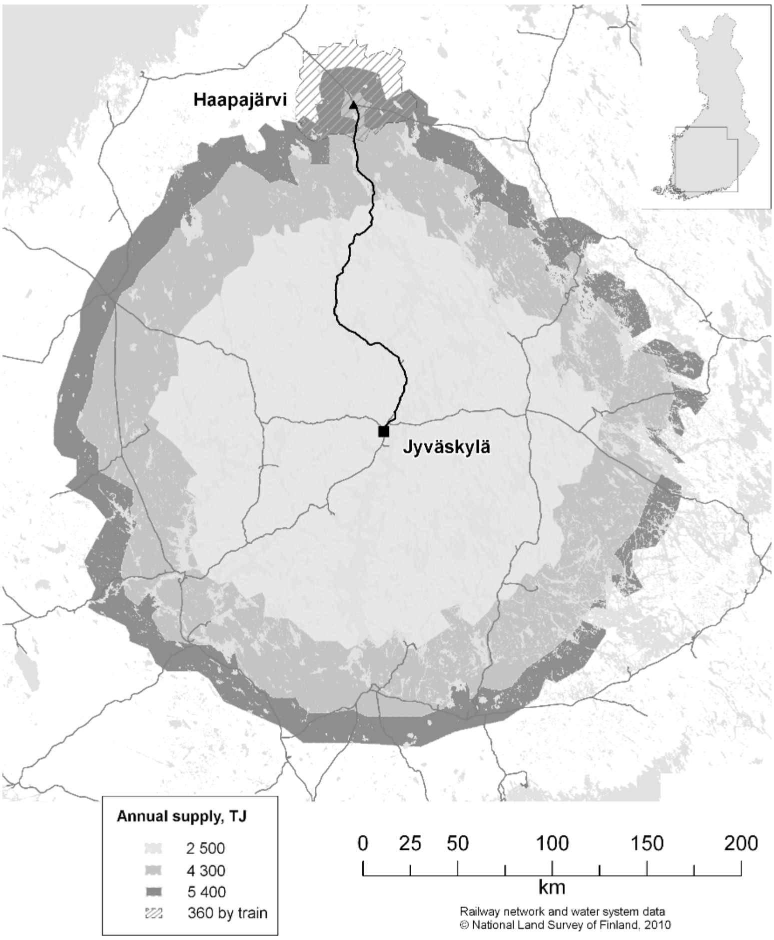


Figure 11. Forest fuel supply areas in the scenarios of Paper II. Black square: a demand point representing two closely located power plants, Black triangle: railway loading point. (Figure originally published by Korpinen et al. (2013), J Geogr Inf Sys 5: 96-108. DOI: 10.4236/jgis.2013.51010. Licence CC-BY 4.0)

The case study also revealed a problem related to the static modelling approach in such a spatio-economic optimization, because the unit costs applied for the point barrier at the railway loading point assumed a higher utilization rate for the biomass comminution machine than was achieved in any of the three scenarios. A scenario using a fixed volume for routing through the loading point (equalling 360 TJ a^{-1}) was therefore added to enable a sensitivity analysis, but the result of this scenario indicated that the additional cost of moving the required volume of biomass by rail was marginal.

From the GIS modelling point of view, the paper discussed the spatial abstraction challenges posed by the two supply areas (i.e. surroundings of the power plant and railway loading point), which differed considerably in extent, the supply area surrounding the power plant being large in this geographical system while the area around the railway loading point was very small. In one scenario the average transport distance from a supply point to the loading point was 8 km and the number of supply points modelled was only 53, resulting in a supply area of ca. 200 km^2. This is only ca. 0.2% of the largest possible supply area in the study concerned, ca. 85 900 km^2 (Table 1).

A similar conflict between supply areas around the plants and railway loading points existed in Paper III, but with less contrast in terms of size. The smallest supply area included 103 supply points and covered ca. 1 700 km^2, which is ca. 2.3% of the largest supply area in the study (Table 1). On the other hand, the spatial abstraction level for biomass supplies in Paper III was higher, due to the sparser supply point network. In theory, a grid cell in Paper III represented four times the number of real-world roadside sites relative to a cell in Paper II. The use of a sparser resolution in Paper III was not critical, however, because the objective was to calculate the accumulation of emissions from pre-selected supply-system settings and not to optimize spatial break-even points as was the case in Paper II.

The case studies focusing on three biomass plant locations (PRV, RMA and AJO) in Paper III indicated that the most important decisions in terms of GHG emissions are 1) prioritizing railway-based supply chains, 2) using electric trains for railway transportation and 3) building the plant in one or other of the southern locations, PRV or RMA. The differences between north (AJO) and south (PRV and RMA) were significant with regard to emissions from truck transportation, especially when no railway route was used at all. The location-based differences in biomass comminution, on the other hand, were marginal, as the average GHG emission was slightly less than 1.0 gCO_2eq MJ^{-1} in all the scenarios. Nevertheless, comminution represented ca. 25 – 60% of the total supply chain emissions, which, alongside the comminution process, also indicates the significance of accounting for the travelling of roadside chippers in one way or another. In this case it took ca. 95 hours (on a standard laptop computer) to solve the optimal route visiting all 3 755 supply points in the largest supply area (AJO) included in the GIS model.

3.3 GIS for BSC simulation (Papers IV and V)

Since the purpose of a dynamic simulation modelling approach is to imitate processes as they occur in real life (or as they are believed to occur in the future), validation of the model is an important part of the research prior to analysis of the output from the model. This was done first in Paper IV, by following up the traffic flows on the map-based display of the simulation software (AnyLogic 2021). It was then possible to check that the points of origin were supplying wood as they were intended to do and that the pulp mills' storage levels were fluctuating in a reasonable manner. As far as the balance in the transport system was concerned, the scenario criterion in the case study guaranteed that the model was run with a suitable combination of HCT and regular trucks, at least in certain scenarios.

The scenario criterion dropped 19 scenarios out because their simulations ended in an excessive feedstock shortage at the mills. In the remaining scenarios it was found that a total transport capacity of 6500 t was enough to supply the necessary pulpwood volumes in time. With the highest capacity used in the comparison (i.e. 7 800 t), the task was also accomplished successfully, but without any significant improvement in supply costs. The main finding of the case study was that the use of an HCT system could reduce total transport distances significantly with just 10 HCT trucks involved (Figure 12). The savings in supply costs were proportionally smaller, but they would also have become evident with a small number of HCT trucks in the system.

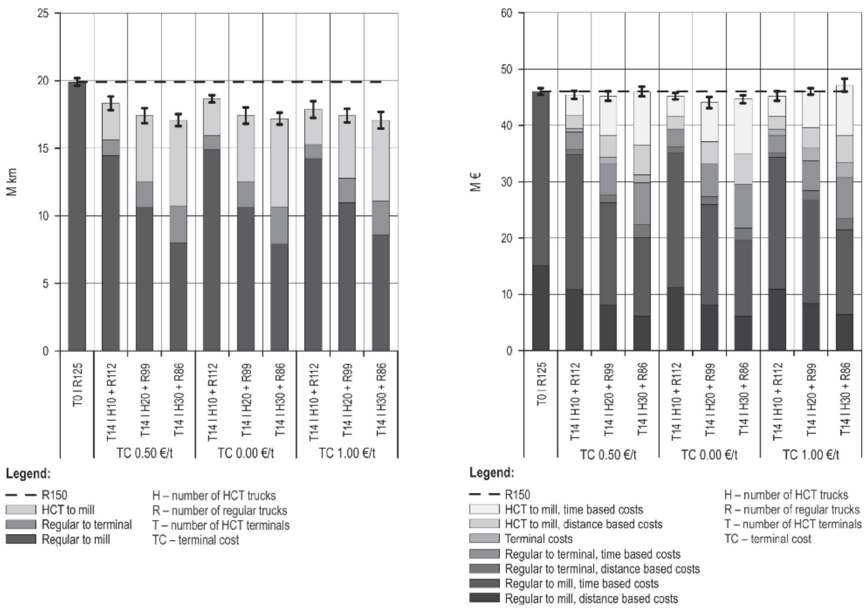


Figure 12. Transport distances, including empty returns (left) and transport costs (right), according to transport modes, and their cost bases in scenarios having a total transport capacity of ca. 6500 t and 0 or 14 HCT terminals. Error bars represent the range of total distances (left) or costs (right) in 8 simulation runs. (Figure originally published by Korpinen et al. (2019), Croat J For Eng 40(1): 89-105. Licence CC-BY 4.0)

Based on an examination of the resulting data and a map-based follow-up of the simulation run, it was discovered that transhipment at HCT terminals resulted in two-way transportation of the same wood stacks in the surroundings of the terminals on certain occasions. Depending on the locations of the origin and demand points and the terminals in each routing task, there were two alternative explanations for this behaviour: a) routing via terminals was still found to be the most profitable solution despite this transportation back and forth, or b) limited receiving capacity at the pulp mills forced the model to steer deliveries to HCT terminals, at times, although still prioritizing the most profitable options available.

The generation of temporal variations in the statistical biomass data and a means of accounting for uncertainty in certain system events brought the simulation model in Paper V closer to real-world experiences of biomass supplies for energy production purposes. The data processing method succeeded in this task in three senses. Given a random selection of 200 points of origin out of the population of 3883 points (Table 1), the simulation model produced 30 output datasets (representing 30 separate simulation years), where the maximum deviation from the statistical average transport distance was ca. 4.4% (Figure 13). This result indicated mostly the variation in transport economy between years, as distance is the main factor determining transport costs. The next quantity to be analysed was the total volume of harvested biomass in the 30 repetitions of the simulation, which, by contrast, is a good indicator of feedstock sufficiency and the need for buffer storage in the system. The model resulted in a deviation of 22% at most from the statistical average (i.e. the volume of the total stand population divided by a coefficient of $3883 * 200^{-1}$). As the third indicator, the number of stands generated in each month of the year, can be used to forecast the need for work resources in the system throughout the year, for example, the combination of cell-specific and supply area-specific probability values for harvesting (example presented in Figure 8) appeared to result in the desired variation as well.

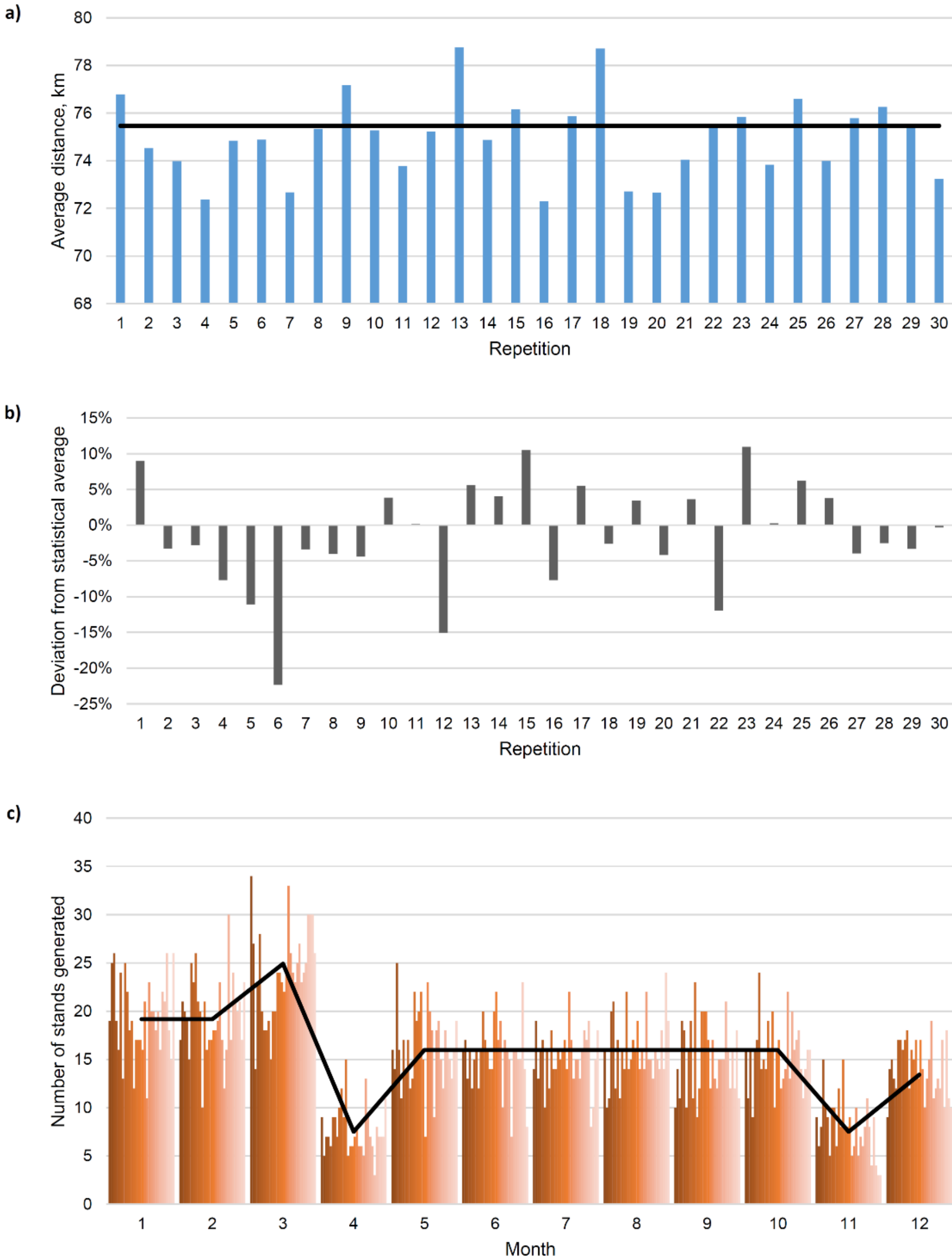


Figure 13. Annual average transport distances from supply points to a destination point (a), deviations from the statistical average for annual biomass supplies in the area studied (b), and monthly variations in the numbers of harvest stands created by the model (c) in 30 repetitions of the simulation run in Paper V. Black lines (a, c) represent the statistical averages of the total supply point population in the model. (Figure contents originally published by Aalto et al. (2019), Silva Fenn 53(4): article id 10147. DOI: 10.14214/sf.10147. Licence CC-BY-SA 4.0)

4 DISCUSSION

4.1 Development of GIS and quality and availability of spatial data for supply chain analysis

Bodies of spatial data concerning biomass resources and transportation networks form the cornerstones of successful GIS-based research into BSC systems, but the quality and availability of suitable datasets vary globally. Despite the fact that global coverage in terms of spatial transport network data (e.g. OpenStreetMap) and access to satellite images that can be used for various land cover assessments (e.g. Landsat or Sentinel) are nowadays achievable free of charge (USGS 2021), they are seldom used as the primary data sources in case-specific research. The publications reviewed in Paper I indicate how versatile the need for spatial data can be in different systems where the final form of biomass use is energy generation. The results of Paper I also indicate that GIS has gained ground in research during the last decade, as the number of GIS-based supply chain studies has increased steadily. Simultaneously, GIS applications have developed from individual computer programs towards multi-platform software, and the potential for storing and sharing geospatial data online has been realized.

In general, more biomass studies utilizing spatial data seem to be published in regions where data are already available in abundance. The governments of Canada and the US, for example, provide access to numerous datasets of high resolution (Thompson 2021; Esri 2021c) which can be of benefit to many research fields, including GIS-based research into supply chains. The situation is somewhat similar in the European Union, although the member states vary greatly in their data sharing policies and practices (Minghini et al. 2021). In Finland the public authorities today provide a good coverage and easy access for forest biomass, land survey and transport network data (as discussed above in section 1.5.2), but this positive state of affairs is relatively new. The contents of the national road and street database Digiroad were released for public distribution in 2013, for example, and MS-NFI data became available in 2012 (Natural Resources Institute Finland 2021f), real estate boundaries of the cadastral index in 2017 (National Land Survey of Finland 2017) and FFC data as late as in 2018 (Valonen et al. 2019). Of these data sources, only Digiroad was used in Papers II and III (published in 2013), as it was available for research purposes prior to its general release. An important political decision paving the way towards the current situation in Finland was the government resolution for improving the accessibility of public information resources in digital format (Ministry of Transport and Communications 2011). Today such authorities as the Finnish Environment Institute (providing spatial data on nature conservation, for example), the Finnish Transport and Communications Agency (e.g. municipality-level data on vehicles and their motive power) and the Finnish Meteorological Institute (e.g. spatial grids of weather observations and predictions) also share data that can be advantageous for research and development purposes in the forest biomass sector.

4.2 System complexity in spatial BSC analysis

Based on experiences from the papers in this thesis it can be concluded that there are several factors that contribute to system complexity and collectively determine the spatial precision of the supply chain model. These are summarized in Figure 14 in terms of three hierarchical categories, the first of which includes factors related to the purposes of the research and the setting up of the logistics framework, i.e. it is the dominant group of factors affecting the settings in which the other categories operate. The second category includes factors that increase the complexity of the supply chain network, and the third category represents the spatial datasets used in the GIS model. For most factors a growing number of discrete elements or parameters can be shown to increase the complexity of the whole system. Thus, multiple objectives can be chosen to fulfil particular purposes, for example, or several constraints based on natural conditions or technical properties can be applied in order to gain reliable estimates of harvesting potentials.

4.2.1 Setup of the study

In general terms, increasing the number of objectives in a mathematical problem-solving exercise (e.g. optimization) will increase the number of target functions, and thus the complexity of the calculation model. Focusing on one essential problem in logistics, vehicle routing, Jozefowiez et al. (2008) emphasize that the motivation for multi-objective optimization (MOO) arises from the need for reacting to more real-life situations than can be done using an academic model with a single objective. In addition to minimizing the total distance travelled (e.g. in Papers II and III), there can be several parallel objectives, including but not limited to the minimizing of vehicle travel times or idle times, the minimizing of logistic risks, the maximizing of freight loads, or the maximizing of the profits for one or more of the stakeholders in the system. As an example from forest biomass logistics, Palander (2015) introduces a non-spatial MOO model of a supply system that includes several biomass power plants and a rail freight company as the logistics operator. The objective is not only to minimize the sum of the various cost components but also to optimize the time consumption of the trains, because time is an important factor for both the power plants concerned (lead times) and the transport operator (wagon rotation). Moreover, many constraints that bring the study closer to real-world circumstances are included, e.g. limitations on vehicle and storage capacities and the regulations governing timber trading between Finland and Russia.

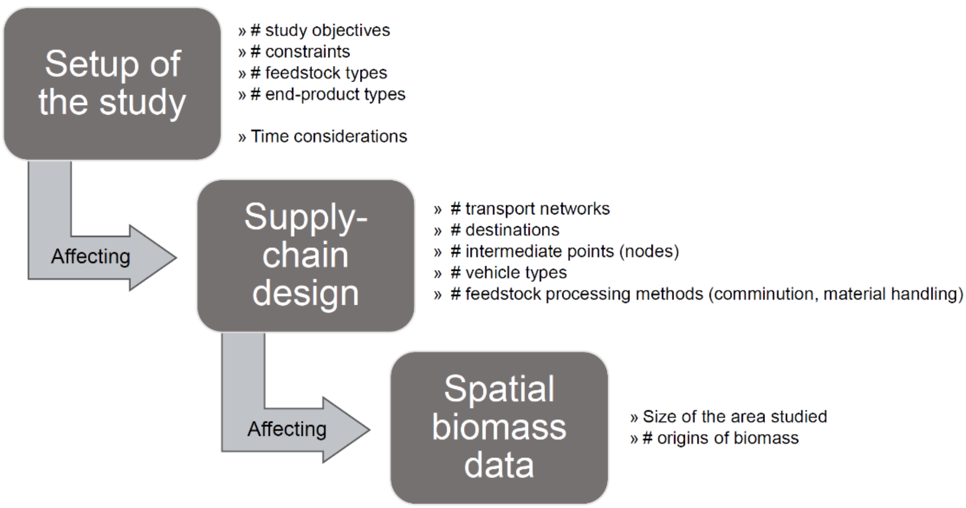


Figure 14. A hierarchical presentation of factors affecting the complexity of GIS-based models of biomass supply chains. # = number of.

In spatial models any increase of the objectives of the research will usually result in the acquisition or production of more GIS data. In cases where the performance of the transportation provided is assessed in terms of time, the transport network dataset in vector format should not only include the distances as cost attributes but also travel-time estimates for the line segments. These can certainly be added to the model simply by means of a conversion based on universal driving speeds, but a more advanced dataset is recommended when the purpose is to come closer to real-life transport conditions. Sosa et al. (2015), for example, used the road type attributes quoted in the national road network data to support their estimates of travel times and the costs of biomass transportation in Ireland. Svenson and Fjeld (2017) examined even more factors predictive of speed, such as the road surface and its curvature and vehicle weight. A classification by types of road was also applied in the road network assessment in Paper III, where the objective was to analyse the GHG emissions of the transport used in an LCA framework, including functions for three road type categories. Furthermore, there can be even more targets in the analysis, although these will increase the potential workload caused by data acquisition and processing. Woo et al. (2018) included objectives of three kinds (economic, environmental and social) in their GIS-based assessment of bioenergy facilities and reported that they had collected spatial data from numerous private and institutional sources.

While constraints in general are important for solving an optimization problem, they can also be spatial constraints in a GIS analysis, as is the case with regionally specific factors that limit the supply potential, such as the rough market share estimates quoted in Paper II. Geographical variations in these constraints can also be modelled with the same spatial resolution as the biomass dataset. Verkerk et al. (2011), for example, filtered the theoretical forest biomass potentials of Europe to more realizable levels of harvest potential in a raster analysis that accounted for several spatial datasets (e.g. site productivity, soil bearing capacity, slopes and nature protection areas). The constraints can even be spatio-temporal, such as those limiting access to forest stands at different seasons in Paper V.

4.2.2 BSC system design

Temporal factors such as supply and demand fluctuations and the seasonal nature of the feedstock are important considerations in biomass logistics for energy production and should thus be taken into account at least in studies supporting tactical and operational planning. A similar conclusion was reached by Kogler and Rauch (2018), who highlighted DES as an appropriate method for wood supply chain research on these levels. Among the factors identified as generating complexity in GIS-based models (Figure 14) these are arguably the most decisive for the design of the supply chain system. Consequently, a spatio-temporal model usually includes a modest number of nodes in the network structure, or the model boundaries are limited to a subsystem only. In the data resulting from Paper I only two out of nine case studies accounting for biomass property changes during the supply chain featured a multi-stage (or multi-echelon) system. The same implication is also supported by Kogler and Rauch (2018), who did not find any spatial or non-spatial DES studies with an operational-level approach that included multimodal properties and a detailed system abstraction at the same time. The spatio-temporal investigation in Paper IV resulted in a large number of routing problems with a relatively low number of transhipment points in the system as compared with the potential locations along highways in real life. A pre-selective analysis of traffic flows in the area concerned was required in order to restrict the number of system nodes and, accordingly, to indicate the potential locations that ought to be included.

It is significant that the computational demand of the ABS method used here is higher than of DES (Majid et al. 2016), which argues for higher abstraction in the supply-chain network when a vast number of agents are used. In addition to a simulation approach, time-based elements can be included in optimization models where the temporal abstraction level is indicated by the number of time periods or their length in real life. Gunnarson et al. (2004), for example, used 12 time periods (each representing a month) to take into account the varying fuel demands of heating plants in the course of a year. Van Dyken et al. (2010) also included 12 periods in their model, but as the focus was on operational planning of supplies, the overall time horizon was only 12 weeks (with each week represented by one time period). By contrast, Palander (2015) split a one-year planning horizon into as many as 26 time periods (each representing 2 weeks) and modelled a supply chain network that excluded truck transportation, despite the fact that this was included in the system in real life. The approach was reasonable, however, because the focus was on the performance of trains. Furthermore, the inclusion of truck transportation would have resulted in increased network complexity and, obviously, a need for spatial biomass data for the Russian territory.

4.2.3 Points of origin and spatial biomass data

The case studies presented in Papers II-IV were all based on a systematic spatial grid of biomass origins, but the designs of the GIS models varied significantly because of the different approaches and objectives. The case study in Paper II, for example, used the densest network of origins (a 2 km grid) covering a relatively large area (Table 1), but in other parts the static optimization model was fairly plain. Thus the railway transport option included only one route instead of a network of multiple origins and destinations. Paper III included more railway lines, but they were added to the LCA framework as individual objects with no connection to the road network, and moreover, the approach used fixed scenarios of rail transport volume instead of optimized transport mode determinations. The lower origin density (4 km grid) did not result from the design of a multi-modal transport network but rather from the complex problem of routing the chipper truck, which apparently represented a more important contributor to the GHG emissions than to the economic performance of the system. In Paper IV the number of origins was relatively low, but the inclusion of several feedstock destinations, intermediate terminals and, on particular, a parallel HCT transport network increased the complexity substantially. One notable shortcoming in this case was that the relatively small area involved (Table 1), representing only ca. 4% of Finnish territory, did not enable very much longer transport routes, where HCT trucks would have been the most competitive alternative. It was also suggested that extending the area would have resulted in a greater number of supply points and accordingly an exponential increase in alternative origin-destination pairs with a supply point network of the same spatial precision. This fundamentally computational challenge could have been tackled with a sparser network, but on the other hand, much higher spatial abstraction would have led to difficulties in the validation of the model, and obviously less precise results regarding the usability of the various means of transportation.

Solutions other than a systematic vector-point network seem to be dominant in the earlier GIS-based biomass supply analyses performed in Finland. Ranta (2002) for example, used Voronoi polygons for aggregating roadside storage data in their centroids, and proceeded with the transportation analysis by using a commercial dataset as the road network data source. Nivala et al. (2016) employed unprotected forest land patterns from land cover datasets as biomass origins and preferred a high abstraction level for transportation by using

Euclidean distances instead of road network distances. Laitila et al. (2010b), used road network-based data to estimate transport costs, but instead of more detailed spatial precision, they allocated equal transport cost estimates to all the forest stands within the same municipality. In contrast to vector-based transport network analysis, Vainio et al. (2009) introduced a GIS model in which both the harvesting and transport cost analyses were based on raster datasets having a spatial resolution of 10 m.

The use of a systematic network of biomass origins has clearly become more popular during the last decade as more forest biomass datasets (e.g. MS-NFI and FFC) have been published in grid format. The grid system is beneficial when forest data are to be analysed together with other grid-based datasets (e.g. weather or population data), as long as the spatial resolution of the layers and the coordinate systems are consistent. Furthermore, Anttila et al. (2018) reported that both the computing and the visual map-based presentation of the results improved when the model presented by Nivala et al. (2016) was converted to a 1 km × 1 km grid-based system. Natarajan et al. (2012) used a 0.1° × 0.1° grid (equal to ca. 5 km × 11 km) in a multimodal GIS-based optimization model covering Eastern Finland, and the method was later extended to the whole of mainland Finland with a 10 km × 10 km grid of biomass origins (Natarajan et al. 2014). This may be assumed to be the coarsest resolution used for a systematic point grid in a GIS-based analysis of forest biomass supply in Finland. The choice of this resolution was undoubtedly determined by the research framework (biodiesel production calls for large feedstock volumes, and thus increases in the area studied), changes in the objectives and methods of the research (minimization of total supply costs and supply chain emissions with mixed-integer linear programming) and a complex supply chain network (including roads and railways for feedstock collection and biodiesel distribution, and a large number of connecting nodes).

4.3 The role and significance of GIS in bioenergy research

In addition to the availability of spatial data, one considerable motive for the adoption of GIS in bioenergy research is the sheer extent of business taking place in the real world. We are speaking of high supply volumes and thus large amounts of capital that are bound up in biomass before its conversion to merchandise at various mills and plants. Based on the findings in Paper IV, even marginal savings (of a few percent) in supply costs can already be worth millions of euros. In a globally competitive business such as pulp and paper production (Karikallio et al. 2011) even such a marginal improvement in a BSC system can be considered a serious competitive advantage. It is not evident that a spatial system approach would always be more credible than a non-spatial one or a much more abstract one, but still it is reasonable to ask whether any latent potential for business improvement can be found if spatial properties are left outside the design of the system? In pursuance of this question, the maturity of the business sector is an evident contributor to the interest in supply chains and the significance of GIS and spatial data. Sawnwood and pulp and paper production are old industries in this context, as also is biomass-based CHP production in Finland. By contrast, the large-scale manufacture of advanced products from biomass, i.e. biorefining, is a relatively new concept (FitzPatrick et al. 2010; De Bhomwick et al. 2018), and the developing markets for various bio-based end products are based on global targets for reducing the global dependence on fossil resources. Obviously the primary focus of research should be on the technological and economic prospects of different conversion technologies and the system outside the industrial process should be of secondary importance. It is only thereafter that research should begin to take on a more case-specific character, extending the scope to supply chains that can be examined with a GIS approach. The research and development in the field of wood-based diesel production in Finland is a good example of such evolution: 1) the suitability of the Fischer-Tropsch process integrated into the Finnish forest industries was first investigated from a technological angle (Rantanen et al. 2005; Gust 2009; Mponzi 2011), 2) the impacts of commercial production on the economy and the environment were assessed at the national level (Heinimö et al. 2011, Forsström et al. 2012, Soimakallio 2014), and 3) the BSC systems involved were studied more closely using GIS methods (Paper III, Natarajan et al. 2014). Nowadays the “Power-to-X" (P2X) concept covering various energy conversion technologies is in focus as a promising innovation on the path towards a low-carbon world, and biomass is seen as an important energy source for balancing energy systems (Wang et al. 2020). In Finland, P2X is expected in particular to decarbonize energy-intensive industries in a low-carbon scenario (Afry 2020) where the proportion of wood fuels used in district heating and power production is at the same time predicted to increase significantly at the national level. No GIS-based case studies on this topic are yet to be found in the literature, but their time will most probably come soon as a consequence of advancements in non-spatial research. Wang et al. (2020) have also detected this research gap in a global context and have emphasized that geographical case studies are needed for identifying the potential future business opportunities for system-balancing plants using biomass as a fuel.

Hence we can argue that, as far as biomass-based innovations (e.g. new products or technologies) are concerned, spatial BSC case studies usually become relevant with a small delay, while the role of spatial data and GIS methods is much more important when new concepts are introduced within existing BSC systems. Such cases include, for example, new feedstock types (Laitila et al. 2016a; Laasasenaho 2019) or changes in vehicles (Laitila et al. 2016b; Paper IV), processing methods (Laitila et al. 2015; Agar et al. 2020), BSC network design (Kanzian et al. 2009; Cavalli et al. 2012; Athanassiadis and Nordfjell 2017; Berg and Athanassiadis 2019), or decision-making strategies (Windisch et al. 2015; Eriksson et al. 2017; Laurén et al. 2018).

According to Väätäinen et al. (2021), high volumes and long transport distances between biomass origins and destinations, together with similar policies and practices in the management and use of forests, are good reasons to examine biomass logistics in Finland and Sweden independently of research taking place elsewhere in the world. On account of their northern location, these countries face challenges of their own in balancing the seasonality of biomass supply and demand, and a strong linkage between timber supplies based on the cut-to-length-method and the use of forest biomass for energy production purposes. Besides the spatial approach motivated by the large volumes and long distances, the above-mentioned factors argue for temporal research methods, especially at the tactical and operational levels. Therefore a simulation approach has frequently been used in Finnish and Swedish case studies (Kogler and Rauch 2018), and circumstances accounting for the interconnections between timber and forest fuel supply systems have been widely studied as well (see Asikainen 2004; Palander and Vesa 2009; Lindholm 2010; Kärhä 2011; Routa et al. 2013; Karttunen and Laitila 2015; Ovaskainen 2017; Kons 2019; Palander and Takkinen 2021).

Despite the complex characteristics of many BSC systems that include both timber and forest fuel assortments, the feasible options of preserving or upgrading forest biomass properties within individual supply chains are fairly straightforward and constrained. Fresh roundwood is supplied to the mill yards directly or via transhipment terminals soon after harvesting, and forest fuels are stored for drying purposes and comminuted at some stage in the supply chain, primarily in order to meet the particle size criteria and secondarily to optimize the bulk density of the remaining transport stages in the supply chain. From the value-added point of view, the principal location of biomass processing is a large-scale industrial facility that represents the final stage of the BSC. The configuration may change in the future, however, if industrial processing is brought closer to the biomass origins. Such a setting has been proposed by Agar et al. (2020), for example, who used GIS to examine the impacts of wood torrefaction to pellets in a network of biomass terminals. In addition, network systems of this kind could be studied with a temporal supply-demand balance approach, employing dynamic optimization or simulation, because the utilization rates of the torrefaction units are obviously key factors determining the overall profitability of the system. This is one more example of how BSC systems are developing towards more complex frameworks for both researchers and decision makers, and also highlights the demand for illustrative and, if possible, geographically specified case studies. In the broader context of transportation, Loidl et al. (2020) have reported that, due to the increasing availability of high-precision spatial data and the development of interactive visualization concepts in geography, geo-visualization of traffic would be an important method for strengthening the field of transport research. Despite the challenges of balancing between spatial abstraction, the extent of the system and computing capacity for geo-visualization that faced the authors of Paper IV, it is highly recommended that BSC researchers should increasingly make use of this approach and concurrently develop more efficient techniques for data management in computer-intensive GIS models.

4.4 Conclusions

In the light of the studies referred to above and of Papers II-V of this thesis it can be concluded that a sufficient distance between points of origin for forest biomass in GIS-based supply chain models in Finland would range approximately from 1 km to 10 km. Figure 15 summarizes the spatial properties and the most critical complexity issues of these studies, as well as how the chosen precision determines the number of origins, when the study area is set up to cover the entire Finland. When detailed transport-network data are used, 10 km precision is more suitable for national-level analyses and for more complex system design purposes, while 1 km precision suits well for local or regional levels and simpler design tasks. A greater density of origins is not necessary if the purpose is to procure feedstock for a typical biomass energy plant in Finland. It must be noticed, however, that doubling the precision leads to approximately quadrupling the GIS computational requirements (i.e. for transport route calculation) given the same area. Conversely, it could be more advantageous to halve the precision in order to achieve computational benefits in certain cases. For example, the online tool for assessing the availability of numerous biomass types in Finland, Biomass Atlas, is currently based on a grid with 1 km resolution (Natural Resources Institute Finland 2021g). Despite its usefulness for spatial analyses in general, the tool can calculate road transport distances only up to 65 km. Without significantly increasing the computational requirements, a grid resolution of 2 km would obviously extend the maximum distance by road to over 100 km, which is closer to the maximum biomass procurement distances of many larger forest biomass plants in Finland.

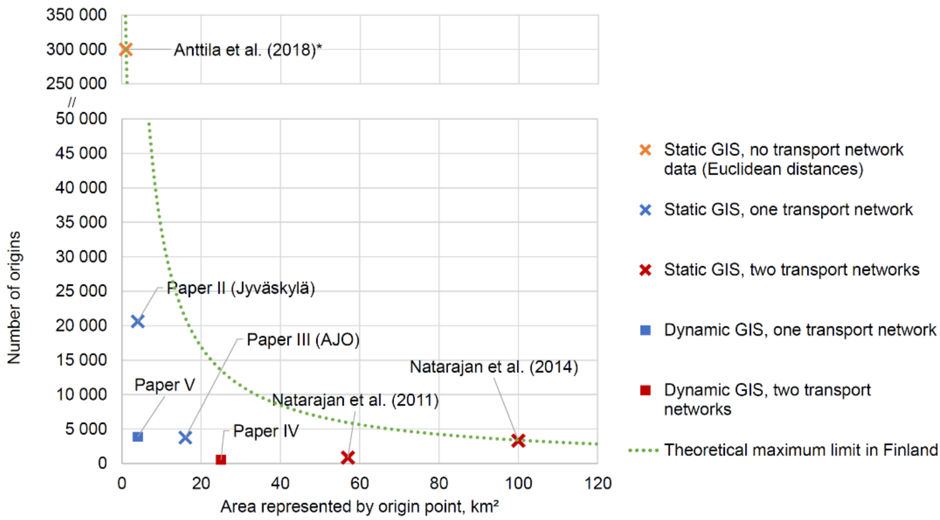


Figure 15. The spatial extent and precision of the case studies in Papers II-V and selected GIS studies in Finland based on a systematic grid of forest-biomass origins. Only the largest supply areas of Papers II and III are presented. *) The number of origins was approximated from the maps of the article, because exact number has not been reported.

Within the suggested range, the final precision will be determined by many case-dependent factors, as conceptualized in Figure 14. These factors do not have equal impacts on the complexity of the system, however. For example, an increment of one in the comminution methods results in additional calculations in the model, but it does not change the structure of the system as the addition of one destination or intermediate terminal does. In GIS-based research such structural change means recalculation of the transport routes, which is time-consuming if the network is already extensive. Another significant impact is the inclusion of time. In this context there is a significant contrast between a static calculation model producing results on an annual basis and a discrete time simulation (e.g. ABS or DES) model that, subject to the level of abstraction, may contain millions of calculation steps in a simulation run. Temporal aspects can also be taken into account with a higher level of abstraction in the more static approaches, such as optimization or LCA. Harvesting potentials, and consequently the appearance of available roadside storage sites, can be assessed on a monthly basis, as suggested in Paper V (Figure 8), and thereafter the outputs of 12 assessments can be summed up at the annual level.

Possible threats and challenges related to the topic of this thesis include tightening of the sustainability criteria for forest biomass use (European Commission 2021) and the gradual concentration of the population of Finland into the largest urban areas in the extreme south (MDI 2019). Both can be assumed to increase average transport distances in the future, creating more space for BSC research in the following ways, at least.

There will be:

– a need for new multi-modal supply chain models that include both rail and marine transport for long distances and deliveries from abroad
– a need for more temporal GIS-based optimization models that include stochasticity

  - Minimization of transport costs and optimization of the use of vehicles throughout the planning horizon will become more important factors in terms of competitiveness.
  - Climate change and the increase in extreme weather conditions (Kirkinen et al 2005) will call for more spatially explicit risk assessments with regard to energy, its production and distribution, and feedstock procurement (e.g. access to rural and forest roads during floods and storms).
- a need for new multi-echelon studies, as more buffer terminals close to urban areas will be needed to ensure supplies (given longer distances from forest sites and the increased weather hazards)
  - In the long term, following the projected impacts of low-carbon technologies in energy-intensive industries on the national energy system (Afry 2020), spatio-temporal case studies of the impacts of the altered (low-carbon) energy system on the operation and profitability of biomass plants will be called for.
- a need for advanced spatial modelling of biomass market dynamics, especially in the regions with the most competition for biomass feedstock
  - "What-if" prospective studies of the starting up of new plants or the conversion of existing ones to new feedstock types will be needed and new regulations concerning biomass production and use will have to be implemented.

In view of the growing availability and improved precision of spatial data (incl. "big data") in Finland and the rapidly expanding computing capacity, there are no technical obstacles to tackling the above topics in BSC research. The widely important biomass logistics designs presented in the case study alternatives described here offer a good starting point for next-level technological and methodological solutions, and accordingly this thesis provides ideas and support for decision-making with respect to current and future biomass logistic systems.

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