Digital Technologies for Forest Supply Chain Optimization: Existing Solutions and Future Trends

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Abstract

The role of digital technologies for fostering sustainability and efficiency in forest-based supply chains is well acknowledged and motivated several studies in the scope of precision forestry. Sensor technologies can collect relevant data in forest-based supply chains, comprising all activities from within forests and the production of the woody raw material to its transformation into marketable forest-based products. Advanced planning systems can help to support decisions of the various entities in the supply chain, e.g. forest owners, harvest companies, haulage companies, forest product processing industry. Such tools can help to deal with the complex interdependencies between different entities, often with opposing objectives and actions – which may increase efficiency of forest-based supply chains.

This paper analyzes contemporary literature dealing with digital technologies in forest-based supply chains and summarizes the state-of-the-art digital technologies for real-time data collection on forests, product flows and forest operations, as well as planning systems and other decision support systems in use by supply chain actors. Higher sustainability and efficiency of forest-based supply chains require a seamless information flow to foster integrated planning of the activities over the supply chain - thereby facilitating seamless data exchange between the supply chain entities and foster new forms of collaboration. Therefore, this paper deals with data exchange and multi-entity collaboration aspects in combination with interoperability challenges related with the integration among multiple process data collection tools and advanced planning systems. Finally, this interdisciplinary review leads to the discussion of relevant guidelines that can guide future research and integration projects in this domain.

Keywords

Digital technologies, Planning systems, Sensors, Interoperability and information exchange, Optimization, Collaboration

1. Introduction

The Forest-based Supply Chain (FbSC) comprises a temporal sequence of spatially referenced activities from the forest to the customer that transform the woody raw material to marketable forest-based products (e.g. D’Amours *et al.* 2008). The FbSC is commonly structured into four distinct processes: Procurement, Production, Distribution and Sales to final clients. Procurement describes the production of raw timber by harvesting activities. This includes the temporary storage of the raw material at the forest roadside and subsequent transportation to the production facilities. Production encompasses the processes that transform the raw timber into different marketable intermediate or final products. Finally, these products are distributed to the market and sold to the clients. The activities are performed by different stakeholders of the FbSC, like forest owners, harvesting enterprises, haulage companies or forest industry in general. These actors are connected by material, monetary and information flows. In respect to material flows, authors usually distinguish between lumber, pulp and paper, biomass and other forest products (D’Amours *et al*. 2008; Scholz 2015; Cambero & Sowlati 2014; De Meyer *et al*. 2014; Mafakheri & Nasiri 2014).

The scope of this research is focused on the digital technologies that have been developed over recent years to support the management of FbSCs. In recent years, a wide range of digital technologies such as RFID, GPS-based tracking devices, light detection and ranging (LIDAR) were successfully applied to collect data about forest characterization and operations monitoring, remotely and as un-expensive as possible. Advanced planning systems and similar software solutions provide support to planners and decision makers.

Yet, in many cases, these technologies remain as singular solutions that apply to an isolated forest, process or machine, and are tailored to case-specific applications (Rönnqvist *et al.* 2015). One of the main reasons is that the nature of supply chain activities, their planning and control processes and the relationships between the supply chain actors varies greatly among countries and regions. So, generalization requires caution. For example, in Scandinavia (e.g. Sweden and Finland), medium to large forest enterprises manage the whole supply chain from procurement, transport and distribution to sales. While in Austria forest ownership is dominated by small privately owned forests. Only a minor proportion of the forested land is owned by the state and big forest enterprises. Typically, procurement, transport and sales are done by independent entities of the FbSC – i.e. forest owner, haulage company, forest industry.

Higher sustainability and efficiency in FbSCs poses new challenges to the research and development of digital technologies (e.g. Forest Platform Vision 2030, Digitizing Europe Industry Initiative). One key aspect is to integrate multiple process data collection solutions to reach a value-chain coverage (D'Amours *et al*. 2008). This poses new research challenges related with software interoperability, i.e. how to assure efficient and seamless data exchange between devices from different providers. Another key aspect is to increase the scaling capabilities of existing singular solutions for wider application (e.g. to other countries and regions) while still being able to cope with local specificities. This aspect is a must to reach economies of scale in the development of digital technologies and to lower development and utilization costs. Further research is needed to show how advanced planning systems can better utilize the large amount of data that becomes available to improve the dynamics of planning and operations control processes (D'Amours *et al*. 2008; Rönnqvist 2003). Furthermore, the social dimension of supply chains needs to be investigated further and efforts should be made to enhance data sharing among multiple companies of the supply chain and foster collaborative business opportunities (Audy *et al*. 2012b; Beaudoin *et al*. 2010; Frisk *et al.*, 2010; Holweg *et al*. 2005).

This framework leads to the research questions tackled in this paper:

Question 1: Which are the most promising digital technologies for improving efficiency in managing operations in the forest-based supply chains, retrieved from the literature?

Question 2: Which guidelines can be taken from the literature and the researchers past experience, to guide future research and development towards a seamless information flow for integrated management of FbSCs, facilitating data exchange and collaboration?

To answer these questions, this article highlights relevant literature concerning planning in FbSCs, collaboration in SCs and technological solutions having potential to contribute to solve the identified missing links in the FbSC. This implies that the authors do not claim to provide an exhaustive list of developments. The article does not cover developments in remote sensing, as this is out of the technological scope of this article. Hence, we provide references to relevant papers in the field of remote sensing in forestry.

In Chapter 2, the methodological approaches for identifying and classifying the publications considered in this paper as well as for defining guidelines, has been described. Based on the classification approach, Chapter 3 covers the publications divided in three sections: (1) Digitizing technologies for process data collection over the FbSCs (Section 3.2), (2) Advanced planning systems for FbSCs (Section 3.3) and (3) Technologies to support collaboration in SCs (Section 3.4). Chapter 4 presents guidelines to guide future research and development towards a seamless information flow for integrated management of FbSCs, facilitating data exchange and collaboration.

2. Methodology

The methodological approach to identify and classify the publications considered in this review is based on 4 steps, as described in Seuring and Müller (2008). The first step is literature collection. The literature search was done in Thomson Reuter's Web of Science database in January 2014 and updated in March 2017. The search terms used for Topic were "forest" AND "supply chain" AND ("planning" OR "sensors" OR "technology" OR “Interoperability”). Additional search criteria are publications written in English and published between 1995 and 2017. Since information on new software tools and ongoing research projects is not always available as peer reviewed articles, other types of publications have been considered as well, including reports of EU projects such as the EFORWOOD project and the FOCUS project. The second step is the descriptive analysis. In several iterations, the authors evaluated formal aspects of the publications list, including the publication type (e.g. Journal paper, Conference paper, Report, Book, Other), year of publication and journal type. The third step is category selection. The authors convey to a 3-dimensional classification schema (Figure 1), representing (1) the FbSC processes (i.e. Procurement, Production, Distribution, Sales, Entire supply chain); (2) the type of value chain (i.e. pulp and paper, biomass, lumber, all types, other), and (3) type and sub-type of digital technologies (i.e. Process data collection tools, planning systems, interoperability and integration). This classification schema is the result of thorough collaboration of a multidisciplinary team of experts involved in the EU FP7 project FOCUS (Focus Consortium 2018). The selected articles have been stored, documented and classified using the open source software Zotero (Roy Rosenzweig Center for History and New Media 2018). The fourth step relates to Content Analysis. The authors carefully analyzed each paper concerning their contribution to the body of knowledge in the field of FbSCs. The results are documented in the following sections.

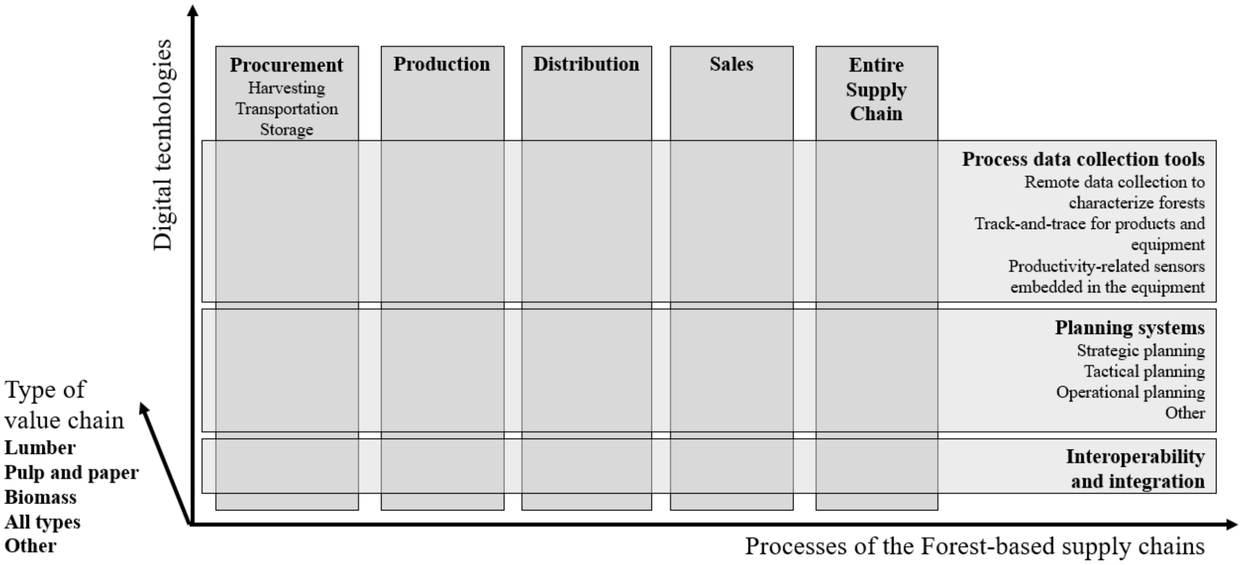

Figure 1: 3-dimensional classification schema used for classifying the publications considered in this literature review.

Next, guidelines were defined in the course of a 2-phase collaborative process similar to the one described in Marques *et al.* (2013). In this context, a guideline is a statement by which to determine a course of action. Guidelines have been successfully used to assist practitioners in various domains, including the development of technologies for the forest sector. In this research, guidelines have been used to express the experts' opinion about the main outcomes of the literature review and also to express their implicit knowledge in the development and use of technologies for forest-based supply. This may help to guide future work. The process of guidelines identification has been conducted by 12 experts involved in the FP7 research project, FOCUS, including 4 technology providers, 3 forest practitioners and 5 researchers from Portugal, Austria, Belgium, Finland, Germany and Switzerland. During the first phase, the experts met in a workshop to discuss the results of the literature review and conduct a brainstorm exercise for identifying relevant practices, also based on their personal experiences. In a second phase, two researchers took the lead in consoling the information into guidelines. Then, each expert assessed the proposed guidelines and expressed their suggestions in a second (remote) workshop. Consensus was finally reached in respect to the relevant guidelines and its adequate writing.

3. Literature overview

This chapter presents the literature review conducted for this paper, and describes the relevant literature. The literature is divided into thematic complexes and described in the sections of this chapter. The thematic sections contain digitizing technologies for process data collection, advanced planning systems for FbSCs and technologies to support collaboration in SCs.

3.1. Classification results

This review brings together 132 publications which are published between 1995 and 2017. Figure 2 presents the absolute distribution of the publications according to their publication type and publication year. In total, 102 journal publications, 12 conference proceedings, 10 book chapters and 8 reports have been reviewed. This equals to a relative distribution of 77% journal papers, 9% conference proceedings, 8% book chapters, 6% reports. Looking at the publication frequency per year, starting from 1995 until 2017, it is notable that there is a constant publication rate during the period from 2007 until 2012 where each year more than 10 papers have been published. Of course, the year 2017 is not representative for the whole year, as the literature search was done in May 2017.

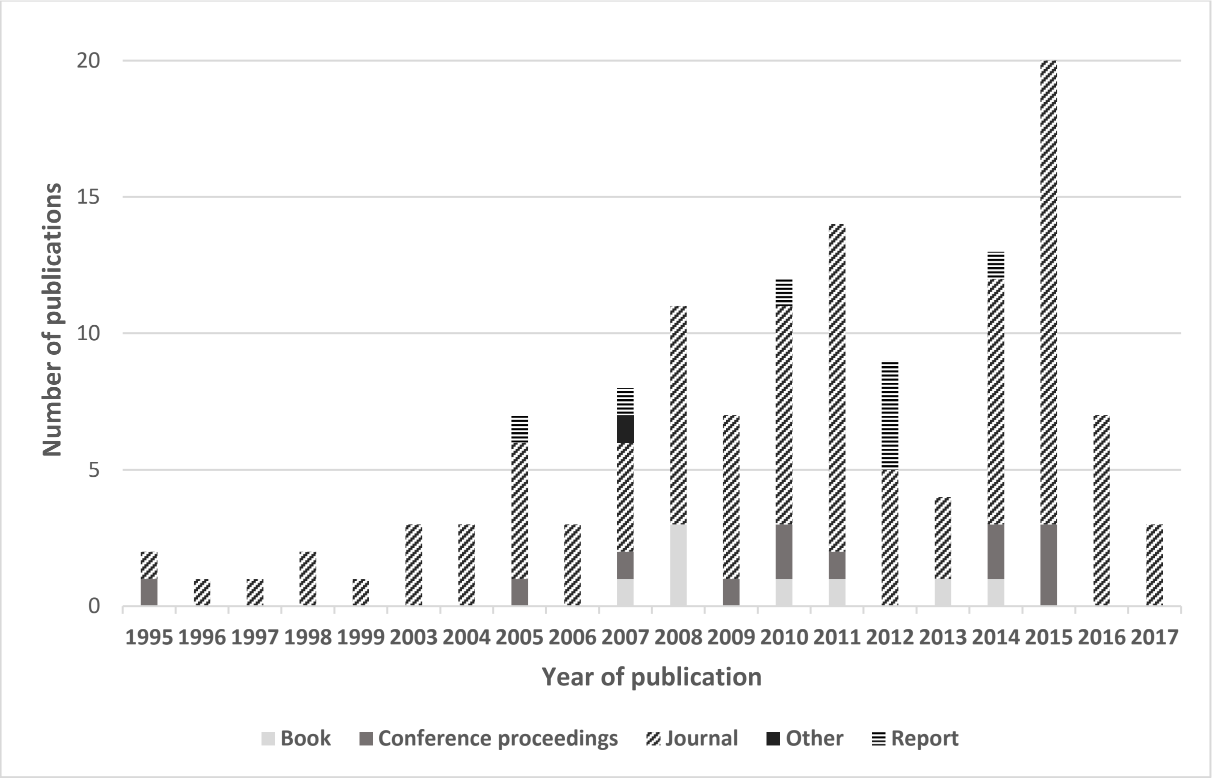

Figure 2. Distribution of publications according to the publication year and publication type (1995-2017).

Each publication has been classified according to their digital technology, the FbSC process and the type of the value chain addressed. Table 1 shows a detailed distribution of the publications according to these classification criteria. First of all, it is clear that the dominant fields are the lumber and biomass supply chains – having a share of 64% (lumber) and 25% (biomass) of all selected publications. Furthermore, an overwhelming majority of the publications covers planning systems focusing on procurement – 92 of 132 papers. In general 113 papers are dealing with procurement, which equals to 86% of all publications. Only 23% of the relevant publications are focused on interoperability and integration. Most of these publications look at interoperability and integration from the perspective of lumber value chains. In addition, for biomass value chains most papers focus on planning systems in procurement.

Table 1. Distribution of publications according to their FbSC type, process, and digital technology.

	All	**Biomass**	**Lumber**	**other**	**Pulp & Paper**	**Total**
Distribution				2	2	**4**
Interoperability and integration				2	1	**3**
Planning systems					1	**1**
Procurement	3	26	82	1	1	**113**
Interoperability and integration	1	1	19			**21**
Planning systems	2	24	55	1	1	**83**
Process data collection tools		1	8			**9**
Production		2			1	**3**
Interoperability and integration					1	**1**
Planning systems		2				**2**
Sales			1			**1**
Planning systems			1			**1**
Entire supply chain	1	5	2	2	1	**11**
Interoperability and integration		1	2	1	1	**5**
Planning systems	1	4				**5**
Process data collection tools				1		**1**
Grand Total	**4**	**33**	**85**	**5**	**5**	**132**

3.2.Process data collection tools

To ensure a seamless communication between stakeholders in the FbSC, (near) real-time data should be collected and shared across the FbSC. Therefore, this section focuses on sensor technologies to enable the collection of (near) real-time data. However, the smartphone will play a role in the future for data collection within the forest as is shown by Rosset *et al.* (2014).

3.2.1. Remote data collection to characterize forests

Data collection for forest inventory using smartphones is gaining momentum in the community. At least two systems for smartphones are available: Trestima and MOTI. Trestima (Trestima Inc. 2018; Siipilehto *et al.* 2016) is a forest inventory tool developed for smartphones. The forest inventory data are determined and calculated based on photographs taken with the smartphone. Data are sent to the cloud and analyzed there, which helps to save precious battery power. MOTI (Berner Fachhochschule 2018) is similar to Trestima, but is targeted towards experienced professionals (Rosset *et al.* 2014). The application does not rely on an Internet connection as observations are stored in the smartphone. Both systems, MOTI and Trestima, are capable of support foresters in collecting forestry inventory data. As a consequence, these data could serve as starting point for managing the FbSC appropriately, based on recent forest inventory data.

The use of remote sensing techniques for forestry planning and inventory gained momentum with the development of high resolution sensor systems (satellite and aerial). Hence, in the mid-1990ies Holmgren and Thuresson (1998) concluded that image data contained little relevant information, and that other data collection methods were more efficient. Only some years later several papers elaborate on methodologies and techniques to extract information on forests from remotely sensed data (e.g. Gougeon and Leckie 2003; Desclée *et al.* 2006; Verbesselt *et al.* 2010; Carleer and Wolff 2004). Especially, the combination of LIDAR and satellite/aerial image data is regarded as promising technology to collect forest inventory data (Hirschmugl *et al.* 2007; Reutebuch *et al.* 2005; Dalponte *et al.* 2008; Wulder 1998). With the help of satellite and aerial images, forest disturbances can be detected and monitored (e.g. Jin and Sader 2005; Neigh *et al.* 2008).

Unmanned aerial vehicles (UAVs) were initially developed for military use, but have been increasingly deployed in civilian applications – such as mapping, monitoring, and natural resources (Newcome 2004). Paneque-Gálvez *et al.* (2014) mention, that UAVs in forestry are primarily used to monitor forest fires (Ambrosia *et al.* 2003; Casbeer *et al.* 2006; Merino *et al.* 2012), but also to map tree crowns, forest stands and volume estimation (Lin *et al.* 2011; Hung *et al.* 2012; Dunford *et al.* 2009; Aber *et al.* 1999). Zhang *et al.* (2016) show that lightweight UAVs offer a certain potential for long-term ecological monitoring of small areas (local scale). Similar to the latter paper, Puliti *et al.* (2015) show that UAVs have the following advantages for monitoring small forested areas: a) high spatial and temporal resolution b) UAVs provide timely information on a local scale.

3.2.2. Track-and-trace forest products and equipment

RFID and wireless sensing technologies are amongst the most used for Track-and-trace forest products and equipment. RFID sensors can further collect relevant measurement data along the chain. Accurate, real-time data can be used e.g. to improve yield and logistic processes and to reduce waste and environmental impacts. Compared to other means of automatic identification such as optical methods, RFID technology has clear advantages in terms of reliability, robustness and read range. Especially dirt, dust and mechanical damage are challenges for optical methods that can be eliminated by using special RFID transponders. For identification purposes passive RFID technology is typically the most cost-efficient solution as the transponders are low-cost and maintenance-free (Häkli *et al*. 2013). The potential of RFID in timber supply chains has been highlighted in Korten and Kaul (2008) as well as in Murphy *et al.* (2012). As there are a multitude of products generated out of wood, it is hard to determine the lifespan of a “product” – and the need to track it along the supply chain. As a first attempt literature focuses on the tracing of the wood in the procurement stage of the FbSC. Nevertheless, tracing of the timber could be extended to other stages of the FbSC as well and amended with other sensors (e.g. humidity or temperature). Besides RFID, the use of terrestrial LIDAR systems has proven to be successful in predicting the wood quality of standing trees (Stängle *et al.* 2014).

The two dominant and commercially available technologies of passive RFID are Near Field Communication (NFC) and Ultra-High Frequency (UHF) RFID. NFC, a short-range technology operating at the frequency of 13.56 MHz, has gained popularity in consumer applications, as the NFC reader has become a standard feature of today’s cellular phones (NFC Forum 2018). UHF RFID that enables read ranges of up to 10 meters is a standard technology in logistics and industry defined by the ISO standard 18 000 – 6C, commonly known as EPC Gen2 (GS1 EPCglobal Inc. 2018). Wood with varying moisture content is a challenging environment and mounting platform for a UHF transponder, both electrically and mechanically. Therefore, the standard transponders designed for logistics applications are not usable for forest applications as such. Special UHF RFID transponders for marking round wood have been developed (Häkli *et al*. 2013). In order to extend the functionality of a RFID system, it is possible to add sensing components, such as temperature or humidity sensors or passive transponders. A few sensors are also commercially available (e.g. Mitchell 2005). Active transponder is a radio transmitter that works on its own battery and sends the identification and the measurement data either directly to a base station or via a network formed by other sensors (RFCode Inc. 2018). The standards for active radio based wireless sensors include Bluetooth LE, ZigBee and Dash-7. Föhr *et al.* (2014) used smart phones with NFC features as well as gate readers equipped with wireless internet connection to transfer data from RFID-tacked biomass containers.

In respect to track-and-trace wood trucks, a number of approaches are mentioned in scientific literature (e.g. Scholz 2010; Scholz 2011; Castonguay and Gingras 2014; Holzleitner *et al.* 2011). Generally, monitoring trucks in (near) real-time involves determining the truck's position and status (e.g. engine status or load condition) and sending them to a server, where the data are stored for visualization and analysis purposes (Menard *et al.* 2007; Devlin *et al.* 2008; Scholz *et al*. 2008; Scholz 2010; Scholz 2011; Castonguay and Gingras 2014). The analysis and visualization can be achieved with desktop or web-based Geographical Information Systems (GIS). Web-based GISs have the advantage of being accessible via the Internet, utilizing standardized services and offering the possibility to instantly visualize the current position and other auxiliary sensor data.

A certain number of similar solutions use the location-based service metaphor to transmit data from the vehicles to a central server (D'Roza and Bilchev 2003; Adams *et al*. 2004; Brockfeld *et al*. 2007; Brimicombe and Li 2009). Location-based services are services that utilize the self-positioning capabilities of mobile devices – which can be mounted on trucks, and submit or receive information relevant for its position. A generic system architecture for that purpose is presented by Scholz *et al*. (2008), Scholz (2010), Scholz (2011) and Castonguay and Gingras (2014). The architecture for such Location-based services can be either proprietary or follow open standards.

The sensors that gather data of the vehicles are sensors with self-positioning capabilities, i.e.

making use of Global Navigation Satellite Systems (GNSS). For Europe, the in-development Galileo system is of interest, but currently U.S. operated Global Positioning System (GPS) and the Russian GLONASS are the favored GNSSs. For gathering other vehicle relevant data, the Controller Area Network (CAN) Bus of vehicles offers a number of data relevant for the FbSC, such as current load of the truck, activity of the truck (loading, driving, etc.), or breakdown. Coupling CAN Bus data and GNSS with the location-based service metaphor seems like a possible strategy to gather location-aware data from timber trucks (Rao and Rao 2013).

3.2.3. Productivity-related sensors embedded in the equipment

The monitoring of the productivity of forest operations can contribute to manage and optimize the FbSC, in order to optimize subsequent operations like transport, storage or production. Besides the methods mentioned in the prior sections, it is possible to exploit sensors present on forest machinery to generate productivity related data. The objective is to obtain (near) real-time productivity data from forestry machines (e.g. harvester, forwarder, skidder and skyline yarder systems) and log transportation (trucks), to collect data of the ongoing harvesting, forwarding and transportation processes.

Ziesak *et al.* (2015) and Mittlboeck *et al.* (2015) describe an approach to monitor forest machinery data containing of CAN bus via the software iFOS and a system called TimeControl (Wahlers Forsttechnik GmbH 2018). TimeControl together with iFOS allows the recording of input from the operators and the fusion of this data stream with sensors embedded in the machine. The operator is able to report on e.g. the following operations: transport, work, repair, break, service, etc. The system iFOS is able to document on the machinery data like: engine revolutions, forces on rear blade, hydraulic oil temperature, driving speed, position, etc.

Hence, this system is able to document any disturbances (e.g. delays, machinery breakdowns) and execution updates (e.g. volume flows and machinery productivity - produced m^3 timber /hour). Based on the data, by embedded sensors, it is possible to detect deviations of executed versus target goals which were specified in the plan.

3.3.Planning Systems

Since all kinds of planning problems arise along the wood supply chain, and cover different time horizons, supply chain management and optimization have proven to be of increasing importance in the forest industry (Carlsson *et al.* 2005). Planning the activities in FbSC requires decisions at the strategic, tactical and operational level, which differ in their temporal and spatial scales as well as in their information requirements and aggregation levels. A variety of papers elaborate on approaches to model and optimize the planning of FbSC on a strategical, tactical and/or operational level, including the approaches to improve the efficiency of the FbSC. Different examples indicate that optimization of supply chains is crucial and brings added value in comparison to traditional decision making (Ouhimmou *et al.* 2009; Shabani *et al.* 2016; Ghaffariyan *et al.* 2013). Several review papers already exist bringing together literature covering the use of Operations Research (OR) methods applied to the FbSC (e.g. D'Amours *et al*. (2008) and Rönnqvist (2003)) and more widely the biomass-based supply chain (e.g. Bravo *et al.* (2012); De Meyer *et al.* (2014); Wee *et al.* (2012)). Therefore, this chapter does not claim to represent and exhaustive list of literature, but focuses the criteria defined in Section 2.

3.3.1. Strategic planning

Planning on a strategic level is about optimizing the long-term decisions related to the design of the forest-based supply network and the allocation of forest operations. This has to be done with respect to income generated by harvesting and other cost intensive operations such as planting, tending or (to a less extent) thinning for a specified spatial region over a given time horizon (e.g. Jones *et al.* 2008) and/or in relation to market prices for feedstock and end product (Kong *et al.* 2015). The geographical extent subject to strategic planning is at least a forest estate, a collection of forest stands or sub-compartments. In contrast, it is possible to approach long-term planning from the single-tree upwards, which disregards planning area constraints existing in planning (Martín-Fernández and García-Abril 2005). The time horizon of strategic planning may reach from several years to decades depending on the rotation length. A thorough review of Decision Support Systems (DSS) for forest management is presented in Packalen *et al.* (2013). This review includes both research prototypes and commercial solutions such as the Iptim software for Integrated Planning for

Timberland Management (Simosol 2018).

In general, there are two main approaches to strategic planning: simulation-based approaches (Muys *et al.* 2010) and optimization (Rönnqvist 2003). In scenario-based planning, a management regime is proposed and the outcome is simulated – which is in turn evaluated by the planners. This approach is iterative, as planners may simulate several different scenarios at a time or one after the other and compare the results (Lappi *et al.* 2014). Eker (2011) uses simulation to assess different procurement systems for unutilized logging residues. Simulation is also introduced, whether or not in combination with optimization, to move towards hierarchical planning with the goal to provide greater flexibility to operational level managers and a mechanism to anticipate its impact on the strategic and tactical level plans (Gautam *et al.* 2015; Paradis *et al.* 2013; Kong *et al.* 2014) Optimization approaches mandatorily need the formulation of an objective for the plan and the constraints under which the objective is satisfied. The defined problem is subsequently solved with a mathematical optimization method. In general, there are various optimization methods available: variations of Linear Programming (LP), Integer Programming (IP), Mixed Integer Programming (MIP) and metaheuristics (e.g. Tabu Search, Simulated Annealing, Genetic Algorithms) for single objective formulations (De Meyer *et al.* 2014). Although each model has its specific use, generally these optimization models are then applied to define the optimal number, type and/or location of a new terminal and/or biorefinery in relation to biomass supply, product demand and the operations in the supply chain (Leduc *et al.* 2012; Parker *et al.* 2010; De Meyer *et al.* 2015; Natarajan *et al.* 2012; Mirkouei *et al.* 2015; Palander *et al.* 2013; Ranta *et al.* 2014). Therefore, these optimization models often include spatial information regarding feedstock resources, existing and potential refinery locations and a transportation network to determine the optimal locations, technology types and sizes of manufacturing facilities to satisfy their objective (Parker *et al.* 2010; De Meyer *et al.* 2015). To improve decisions considering time issues, De Meyer *et al.* (2016) add a growth model to simulate biomass growth and regeneration after harvest to the equation. Dansereau *et al.* (2010) apply mixed-integer linear programming to compare the behavior in manufacturing-centered supply chain with the behavior in a margins-centric supply chain.

3.3.2. Tactical and operational planning

Tactical and operational planning are restricted to shorter planning horizons and smaller spatial extents compared to what is applicable with the strategic planning. The tactical decision level addresses medium term (usually monthly) decisions, related to the wood-flow, covering a planning horizon between 6 months and 5 years (D'Amours *et al.* 2008), with an extension to 10 years in some cases. The overall wood-flow starts with standing trees in forests and continues with operations such as harvesting, bucking, sorting, transportation to terminals, sawmills, pulp and paper mills, heating plants, etc. for conversion into all kinds of products (Carlsson *et al.* 2005). A typical example of an optimization model addressing tactical planning is presented by Gunnarsson *et al.* 2004. Operational planning encompasses short term decisions related to activities in the field. Hence, planning horizons of operational planning range from a few seconds to 6 months (Rönnqvist 2003). The literature on tactical and operational forest planning reports the use of a wide range of mathematical models, which include LP, IP, MIP, Non-Linear Programming, Dynamic Programming and Constraint Programming (Rönnqvist 2003).

Harvest scheduling describes the decisions needed to be taken regarding which stands to harvest and in which temporal order within the planning horizon. Medium to short term tactical harvest scheduling problems consider smaller management areas, and have shorter planning horizons, which allow a linkage with operational considerations, like bucking (Chauhan *et al.* 2009; Chauhan *et al*. 2011; Epstein *et al*. 1999; Gerasimov et al. 2014). Beaudoin *et al*. (2008) as well as Bredström *et al*. (2010) presented an annual planning problem with integrated harvest scheduling/sequencing. Bredström *et al*. (2010) amended the optimization with harvest machine assignment. Both use a two phase solution method where one sub-problem – e.g. machine assignment - is solved and serves as input for the other sub-problem - e.g. harvest scheduling. Harvest planning on operational level comprises decisions related to the extraction of logs from the felling sites to the road side and bucking/sorting operations. Biomass recovery issues and skidding problems on steep slope terrain can be solved with optimization approaches by designing an optimal off-road transport network (Ezzati *et al.* 2015; Montgomery *et al.* 2016). Bucking operations basically contain the cutting of harvested trees into different log types, with respect to the demand of the market, in order to receive the maximum value. To optimize bucking operations, an algorithm is needed to perform the optimization on the levels of stem, stand and forest (Chauhan *et al*., 2011). Methods for optimizing bucking operations are found e.g. in Marshall *et al*. (2006), Chauhan *et al*. (2011), Epstein *et al*. (1999), Dems *et al.* (2017) and Laroze and Greber (1997). Epstein *et al*. (1999) propose a multi-period procurement model that takes harvesting, bucking and transportation into account. Chauhan *et al*. (2011) extend the latter methodology of Epstein *et al.* (1999) by a hierarchical model where the matching of supply and demand, as well as bucking are solved independently and iteratively.

Road network planning is often integrated with harvest scheduling and deals with road construction, upgrading and clearing of snow in order to access forest stands. Murray & Church (1995) presented an integrated IP model that addresses medium-long term harvest scheduling and road building decisions considering adjacency constraints. They used Interchange, Simulated Annealing and Tabu Search as solution methodologies. Andalaft *et al*. (2003), Guignard *et al*. (1998) and Weintraub *et al*. (1996) presented MIP harvest planning models to determine where roads can be built/upgraded according to different quality standards. Maximum slope (Gruber and Scholz 2005) and turn radius of trucks and earthwork when the road crosses hillsides (Epstein *et al*. 2006) are among the other technical considerations, which are - although rarely - taken into account. Henningsson *et al*. (2007) describe two incapacitated fixed charge network MIP models, including multiple time periods and different road classes. These models are used in the optimization module of a DSS called RoadOpt (Karlsson *et al*. 2006).

Transportation planning addresses the transport of timber from the roadside to the destination, which can be either a pulp and paper mill, a saw mill, a heating system, a terminal, etc. (Andersson *et al*. 2008; Akhtari *et al.* 2014; Alam *et al.* 2012; Alayet *et al.* 2013; Beaudoin *et al.* 2007; Carlsson *et al.* 2005). Tactical transportation planning relies on an aggregated supply and demand that is necessary for establishing timber flows between origin and destination locations. Of significant importance is the possibility to consider backhaul routes (Carlsson and Rönnqvist 2007; Hirsch and Gronalt 2008). In addition, wood bartering between companies can be also included (Palander and Väätäinen 2005; Forsberg *et al*. 2005). Transportation planning at operational and tactical level mainly addresses truck scheduling and dispatching. In order to model the problems at hand, the Vehicle Routing

Problem (VRP) approach and the Pickup and Delivery Problem (PDP) variants (Audy *et al*. 2012a) are used. The first approaches towards truck scheduling have been published by Weintraub *et al*. (1996) that resulted in the project ASCIAM. In general, solution methods for transportation planning include MIPs (Palmgren *et al*. 2004; Palmgren *et al*. 2003; Rey *et al*. 2009). The solution is calculated with a two-phase column generation method. Tabu Search is proposed by Gronalt and Hirsch (2007) based on the Unified Tabu Search Algorithm (UTSA) for a general VRP in order to generate truck schedules. Flisberg *et al*. (2009; 2012) extend the UTSA, which is applied to a consolidated PDP in order to transform the PDP into a VRP. El Hachemi *et al*. (2009; 2011a) propose models addressing decisions that take supply and demand assignment into account when calculating truck schedules. Hence, the methodology first generates the wood flow from supply to demand, followed by the generation of the daily routes. In order to minimize non-productive activities in the supply chain (truck and loader waiting time, empty trucks), El Hachemi *et al*. (2011b) propose a two-phase solution methodology that comprises constraint programming and an IP model. Scholz (2015) uses an Adaptive Large Neighborhood Search methodology to optimize truck schedules and timber flow from source to destination points. Because there is the need to solve dispatching models quickly (close to real-time), there is a tradeoff between solution speed and quality. Rönnqvist and Ryan (1995) report on a hybrid solution method in which two different greedy heuristics search for the best routes for each truck. Carlsson *et al*. (1998) use an IP model in which entire routes (i.e. set of different trips) are represented as variables with the idea to allocate trips to existing truck routes. Gerasimov *et al.* (2014) present a tool set for Russian logging companies combining different optimization tools to support truck routing, fleet utilization levels, and choice of transport method.

3.3.3. Addressing uncertainty in FbSC planning

Since predicting the availability of raw materials is often impossible, uncertainty has been incorporated in harvesting planning models to move towards a robust harvesting planning model (Bajgiran *et al.* 2017). Some models, looking at the complete supply chain, introduce uncertainty to their supply chain planning optimization question. Uncertainty plays a key role in different stages, such as uncertainty in biomass availability and biomass quality (Shabani *et al.* 2014; 2016a; 2016b; Sharifzadeh *et al.* 2015), timber supplies (Vergara

González *et al.* 2016) and uncertainty related to biomass-to-biofuel conversion efficiencies (Xie and Huang 2015). Marques *et al.* (2014) combine their (operational) optimization approach with discrete-event simulation models to tackle uncertainty in planning harvesting and forest operations. These discrete-event simulation models are able to assess the performance and to identify bottlenecks associated with the execution of the optimized, deterministic plans, when unforeseen events occur (Marques *et al.* 2014; Myers *et al.* 2003). Furthermore, the quality of the feedstock or the intermediate product is decisive for its final destination (Ghaffariyan *et al.* 2013). Therefore, several models keep track of changes in feedstock quality throughout the supply chain (De Meyer *et al.* 2015; De Meyer *et al.* 2016; Dems *et al.* 2015; Sosa *et al.* 2016; Van Dyken *et al. 2010*; Alayet *et al.* 2013; Andersson *et al.* 2016)

Most optimization models strive to minimize costs in the supply chain costs or to maximize the profit in the supply chain (De Meyer *et al.* 2014). However, also environmental and social oriented objectives are decisive to make the supply chain sustainable as a whole. For multi-objective problems, methods such as Multi-Criteria Decision Analysis (Kangas *et al*. 2008), goal programming (Kangas *et al*. 2008) and multi-criteria approval (Laukkanen *et al.* 2004) can be applied. Examples of multi-objective optimization in strategic, tactical and operational planning can be found in Broz *et al.*(2017), Dong *et al.* (2010), Kühmaier and Stampfer (2012), Vaskovic *et al.* (2015) and Palander (2011a; 2011b).

Other approaches have been applied to wood-based supply chains, besides optimization and simulation approaches. For example, Chang *et al.* (2014) performed a disaggregated trade-flow analyses to investigate the global competitiveness of lumber.

3.4.Interoperability & Integration and Collaboration

The following section elaborates on technologies and initiatives that enable the sharing of data and/or information across institutional borders. To date several interoperability initiatives and standards exist – especially on the syntactic level – whereas the integration in each stakeholder's systems and the collaboration of stakeholders is still regarded as work in progress.

3.4.1. Interoperability

Interoperability represents technologies and methodologies which ensure seamless data and information sharing over institutional and organizational “borders”. For example, Rossman *et al.* (2008) have developed the “Virtual forest” as an intelligent planning and decision support tool for forest growth and wood mobilization. In order to efficiently gather and visualize the data by bringing together databases, aerial surveys and satellite technology with virtual reality, robotics and machine learning.

Interoperability needs to be solved on a technical level (i.e. syntactic interoperability). If syntactical interoperability is ensured, literature suggests that two or more computers should be equipped with systems to automatically interpret the information exchanged in a meaningful and accurate manner. This concept is regarded as semantic interoperability, which is e.g. utilized in the Semantic Web.

From the IT-perspective, a supply chain can be represented by spatio-temporal information chunks present in applications or in databases connected via web-based Service-Oriented Architectures (SOAs) (Sahin and Gumusay 2008). SOA itself is not a technology but rather a strategic concept (Detecon Consulting 2006). The goal of a service-oriented architecture approach is the optimization of IT flexibility, IT productivity and business processes as well as achieving better reusability of data and processes (Liebhart 2007), which makes it an ideal concept to be considered in modern location-enabled information infrastructures. If the functionality is made available as a service over a network, it is referred to as a web service. Papazoglou (2008, p. 5) defines a web service as a “self-describing, self-contained software module available via a network, such as the Internet, which completes tasks, solves problems or conducts transactions on behalf of a user or application”. In order to fully benefit from the service concept, the standardization of interfaces between the different components of the forest supply chain plays an important role for planning and control of the overall system.

A prerequisite for allowing applications and systems to communicate with each other in an agile and flexible way is the interoperability between the systems and interfaces used. The Open Geospatial Consortium (OGC) and ISO have created web service interface standards for publishing, accessing and visualizing spatio-temporal information (de la Beaujardiere 2006). The standards emerging from the OGC Sensor Web Enablement Initiative (SWE) are designed to collect sensor measurements in a standardized way and augment the sensor data with the spatio-temporal dimension (Bröring *et al*. 2011). Thus, any machine control data or timber log data, mostly in the format of the Standard for Forest machine Data and Communication (StanForD) (Arraiolos *et al.* 2011; Fritz *et al*. 2010), can be coupled with a spatial and temporal reference. StanForD constitutes a de-facto standard that covers all types of data communications present in forest machines. In addition, standards of SWE guarantee standardized transmission, storage and dissemination of the sensor data. SWE enabled services will be designed to support the discovery of sensor assets (harvesters, trucks, etc.) and capabilities, access to those resources and data retrieval, subscription to alerts, and tasking of sensors to control observations (Bröring *et al*. 2011).

As a first step towards standardization in the wood supply chain, Von Schnetzler *et al.* (2009) propose a modification of the generally used Supply Chain Operations Reference (SCOR) model to describe and standardize the wood supply chain. This model enables a generalized mapping of forest reality and ensures a common understanding, for describing and analysing processes, interfaces, etc. (Von Schnetzler *et al.* 2009). Santa-Eulalia *et al.* (2010; 2011) present FORAC Architecture for Modeling Agent-based Simulation for Supply chain planning (FAMASS) as a framework to provide a uniform representation of distributed advanced Planning and scheduling systems using agent technology to support simulation analysts. Within this context, Frayret *et al.* (2007) also present a generic software architecture to combine agent-based technology and operations research-based tools in order to integrate the ability of agent technology in distributed decision problems, and use Operations Research (OR) to develop and exploit specific normative decision models.

3.4.2. Collaboration

Addressing the interoperability requirements is mandatory but not in itself sufficient to assure effective collaboration between the agents of the FbSC. Previous research already established the importance of collaboration to increase the efficiency of multi-echelon supply chain SC (e.g. Barratt 2004; Holweg *et al*. 2005; Mesfun and Toffolo 2015). Collaboration approaches are identified as the key to unveil the potential cost optimization and profitability (Audy *et al*. 2012a; Beaudoin *et al*. 2010; Frisk *et al*. 2010; Lehoux *et al*. 2011). Yet, implemented examples of collaborative systems are still hardly found. Some examples of inter-firm collaboration where studied in forest logistics and transportation. Carriers or shipping companies collaborate by pooling their needs, requests and/or resources to obtain significant cost reductions (Agarwal and Ergun 2010; Audy and D'Amours 2008; Audy *et al.* 2011; Carlsson and Rönnqvist 2007; Frisk *et al.* 2010). Current hurdles in implementing collaboration approaches in the FbSC are to be found in company policies that hinder the cooperation between different stakeholders. Mostly these restrictive company policies are fueled by confidentially of data and cost allocation problems between the partners (Marques *et al.* 2016). In addition, a lack of technical solutions and standards to share data and information may prevent stakeholders to cooperate in the FbSC – as existing solutions would require a certain investment in technical capabilities of the stakeholders. If a FbSC is dominated by SME's these investments in technical capabilities could be a hurdle for implementing collaborative approaches – such as a Semantic Web approach for sharing data in the FbSC (Weinberger and Scholz 2018).

To implement collaboration approaches, a number of techniques exist. First, there are approaches from OR, in which mathematical formulations, exact and heuristic solution methods have been used to optimize and integrate the perspective of different agents (e.g. saw mill and haulers) (D'Amours *et al*. 2008, Akhtari and Sowlati 2016; Gautam *et al.* 2014; Kurniawan *et al.* 2011; Machani *et al.* 2014; Mansoornejad *et al.* 2010). Second, economic models exist that address the distribution of costs and benefits among stakeholders such as incentives or cost/savings allocation mechanisms (Audy *et al*. 2007; Forsberg *et al*. 2005). Some researchers focus on collaborative strategies, such as Vendor Management Inventory (VMI) or collaborative forecasting, where Collaborative Planning, Forecasting and Replenishment (CFPR) is the more recent methodology. Both approaches are based on information exchange and joint decisions. Examples in the forestry sector are described in Lehoux *et al*. (2007; 2009; 2011).

Existing frameworks (Audy *et al*. 2012b; Arraiolos *et al.* 2011; Azouzi and D'Amours 2011; Little *et al.* 2012; Zhang *et al.* 2016: Jerbi *et al.* 2012) identify crucial issues, originating from interactions among involved agents in FbSCs (e.g. the information exchange or the cost/savings distribution issue). However, they fail to provide tools to identify opportunities within the supply chain for which implementation of such collaborative strategies would be beneficial. Furthermore, when talking about collaboration a lot of questions arise related to confidentiality of data and agreements on cost allocation (Marques *et al.* 2016).

4. Guidelines for the future development of technologies in forest-based supply chains

Based on the literature review and researchers past experiences, guidelines have been defined to guide future research and development towards a seamless information flow for integrated management of FbSCs, facilitating data exchange and collaboration.

4.1 Strengthen the planning with a tight integration of strategic and tactical levels as well as to provide easy-to-use optimization tools for professionals

A tight integration of strategic and tactical planning is not that common in practice. This poses a clear challenge to effectively utilize strategic planning for optimal supply chain management.

Much research has been conducted in OR about forest planning, but few IT-tools are available for and utilized by professionals. This is especially true in Central Europe where conditions are challenging to implement simulation of forest growth and management operations at the detail level required for optimization. Main challenges are related to heterogeneous site conditions, close-to-nature silviculture, multiple-purposes forestry and the ownership structure.

4.2 Extend the technological capabilities of forest-based supply chains with sensors

Fostering sustainability and efficiency in FbSCs requires monitoring harvesting operations and giving real-time feedback to all included actors in this process. The target must be to decrease the reaction time to the various requests such as machine problems, declining productivity, delay in the harvest or new demands from sawmills. The clear process orientation (as opposite to machine orientation) provides extra value for the typical, complex multi-partner value chains in forest harvesting.

Generally, there is a need for an integrated, (near) real-time, process oriented solution combining sensor measurements, position and spatial data. Thus, relevant data for the supply chain – e.g., of the trucks and the harvesting machinery – can be visualized in (near) real-time utilizing the map metaphor, the web-based GISs. In addition, the integration of various sensor measurements with positional data enables e.g., the detection of deviation from an optimized haulage plan, which in turn can notify a logistics manager or an optimization system. Finally, this enhances the current situation, as current supply chain (SC) optimization solutions have a rather static nature – i.e. they generate optimized plans for a given situation. By utilizing (near) real-time monitoring capabilities, the system can react instantaneously and alter the plans for e.g. trucks accordingly in real-time.

RFID already proved to be useful to track wood products along the value chain. The possibilities to extend its technological capabilities with sensor measurement, like moisture, has not yet been assessed for practical usage. However, this represents an important issue considering the quality of wood-based product, especially biomass, and its deterioration along the value-chain.

4.3 Implement a new and an innovative approach to integrate planning and control

All kinds of events may require an immediate or less urgent changing of the existing, optimized plan (Broman *et al.* 2009; Rosset *et al.* 2015). For example, after the storm Gudrun, there was a direct shortage of both harvest and transportation capacities for the forest company Sveaskog, requiring the over-night adaptation of the existing logistic planning (Broman *et al.* 2009).

The planning models, described earlier, are designed to define the optimal allocation of resources with respect to objectives, requirements and constraints of the stakeholders in the supply chains (Rosset *et al.* 2015). Control techniques detect deviations of the plan that may cause interventions that require altered plans for the stakeholders (Rosset *et al.* 2015). Among the control techniques, model predictive control (MPC) has proved to be an attractive alternative to apply in SC management (Sarimveis et al. 2008; Hai *et al*. 2011). The main advantages of MPC in SCs are its ability to deal with variability in supply and demand (Wang *et al*. 2007; Puigjaner and Laínez 2008) and the possibility to integrate constraints in the process (Wang *et al*. 2007). A preliminary analysis highlights the benefits of MPC in a biomass supply chain in Finland (Pinho *et al.* 2015).

Model predictive control (MPC) represents a new way to consider FbSCs in terms of dynamically interconnected tanks (e.g., wood material at different planning and processing stages), which levels are supervised and anticipated as well as adjusted in an (half-)automated and optimized way to comply with target stock levels and constraints. Depicted as such, MPC represents potentially a powerful technology for collaboration among SC actors. Sensor data will play a major role to supervise stock levels in an automated way, when stressing the metaphor of interconnected tanks.

However, the chances of success mainly depend on the willingness of SC stakeholders to share their data. From the technological point of view, the challenges are:

1) To define which part of planning and control can be delegated to MPC, especially which operations to adjust stock levels over time in an automated way.
2) The integration of MPC with planning tools on a strategic, tactical and operational level.
3) To tackle the functionalities related with supervision and anticipation within the MPC model itself.

4.4 Develop a platform for bottom-up integration of IT-solutions

Within the FlexWood project (Fritz *et al.* 2010; Koch and Unrau 2012; Little and Manzano 2012) a top-down approach has been applied to create a solution for the supply chain of wood sourcing to a sawmill (Koch and Unrau 2012). However, in order to be attractive for users and to support integration and collaboration in SCs, the platform should be:

1) applicable to any supply chain within the realm of the forest-based production sector, or any other sector sharing similar characteristics of dynamically changing resources with geographically distributed sourcing, e.g. agriculture;
2) based on a bottom-up approach of bringing together already existing solutions for different pieces of a supply chain to support optimal planning and control of the whole supply chain;

This implies that several integration techniques need to be supported as well as different data contents. Although certain common characteristics do exist, the data content used in planning is often case specific. Therefore, a rigid approach to "standardizing" the data specification for the integrating platform is a moot point. A flexible data structure, allowing format changes on a case-by-case basis, might fit better in such an integrating platform.

Although software solutions for other SCs exist that encompass the management and/or documentation of the whole SC, the objective here is to create a platform that is capable of integrating different solutions that cover different parts of the SC with the help of standardization. The application of solutions from other SCs may seem as valid option, but the adoption of solutions fitted to other SCs fails to cope with the complexity of the FbSC – either in the number of stakeholders, products and different tasks to accomplish. This is also mentioned in Rönnqvist *et al.* (2015) that describe 33 open problems to optimize the FbSC. To our knowledge, no IT solution integrates all data on the supply chain (forest management, harvesting, transportation, and wood processing). The challenge will be to head towards ubiquitous access to process management data. The feasibility to develop such an integrating platform has been proven in the EU/FP7-funded FOCUS-project - Advances in Forestry Control and Automation Systems in Europe.

4.5 Promote collaboration among the supply chain actors

Collaboration allows improving the profitability of FbSCs. It provides opportunities to improve SC efficiency without large investments by sharing needs and/or resources. It also requires additional planning and control integration of the entire SC. For doing so, it is necessary to develop a methodology that takes advantage of the existing collaboration partnerships but also that identifies new collaborative opportunities and supports their implementation.

5. Conclusions

Since the activities in the FbSC are performed by various entities, complex interdependencies between different entities result in inefficient supply chains due to opposing objectives and actions by the stakeholders. It is clear that collaboration between stakeholders will provide opportunities to improve FbSC efficiency, but they can hardly be realized without large investments by sharing needs and/or resources. However, solving these issues requires a seamless information flow to foster cooperation and collaboration in the supply chain.

From the literature, the authors identify that a variety of optimization models and tools exist concerning the planning in FbSCs. Most models focus on one or only a few forest planning problems. Therefore, it is necessary to strengthen the planning with an integration of models addressing the decisions on strategic, operational and tactical level as well as to provide easy-to-use optimization tools for professionals. However, an optimized planning will not support the collaboration and cooperation between the stakeholders in the supply chain. Although preliminary, indications point to the added value of model predictive control in combination with sensor technologies.

The literature review of this article revealed that there is no specific piece of software missing to optimize and track the FbSC, as there are numerous products on the market and scientific initiatives/projects around. The crucial issues are to integrate the heterogeneous systems present in the FbSC and to share data between the stakeholders involved. In order to coordinate different actors in the FbSC, systems utilizing model predictive control approaches could be implemented. These systems rely on a (near) real-time, and accurate digital representation of the reality (i.e. the FbSC), which can be achieved with the help of sensor measurements.

The proposed integrated system architecture allows the combination of approaches for planning and control of (forest-based) supply chains with sensor technology and geographic information systems. This platform serves as the basis for the collaboration between the stakeholders of the supply chain and for integrating and sharing data over the whole supply chain in both vertical and horizontal dimensions. This platform ensures the advantage of the existing collaboration partnerships but also that identifies new collaborative opportunities and supports their implementation. In addition the modular development of the architecture allows easy addition or removal of models and approaches without changing the core of the architecture, questioning the foundations of the system or requiring major, new developments.

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Appendix: List of papers for the literature review and their classification

Author	**Year**	**Title**	**Type**	**Digital technology**	**Processes of FbSCs**	**Value Chain Type**
Akhtari & Sowlati	2015	Hybrid simulation and optimization approaches to tackle supply chain complexities – A review with a focus on forest products supply chains	Journal	Interoperability and integration	Procurement	Lumber
Akhtari *et al.*	2014	Optimal flow of regional forest biomass to a district heating system	Journal	Planning systems	Procurement	Biomass
Alam *et al.*	2012	Modeling Woody Biomass Procurement for Bioenergy Production at the Atikokan Generating Station in Northwestern Ontario	Journal	Planning systems	Procurement	Biomass
Alyet *et al.*	2016	Centralized supply chain planning model for multiple forest companies	Journal	Planning systems	Procurement	Lumber
Andalaft *et al.*	2003	A problem of forest harvesting and road building solved through model strengthening and Lagrangean relaxation	Journal	Planning systems	Procurement	Lumber
Andersson *et al.*	2008	RuttOpt — A decision support system for routing of logging trucks	Journal	Planning systems	Procurement	Lumber
Andersson *et al.*	2016	A model approach to include wood properties in log sorting and transportation planning	Journal	Planning systems	Procurement	Lumber
Arraiolos *et al.*	2011	ICT deployment strategy in Aquitaine WSC: The ExploTIC breakthrough	Conference proceedings	Interoperability and integration	Procurement	Lumber
Audy & D'Amours	2008	Impact of benefit sharing among companies in the implantation of a collaborative transportation system - An application in the furniture industry	Book	Interoperability and integration	Distribution	other

Audy *et al.*	2011	Cost allocation in the establishment of a collaborative transportation agreement—an application in the furniture industry	Journal	Interoperability and integration	Distribution	other
Audy *et al.*	2007	Virtual transportation manager: A web-based system for transportation optimization in a network of business units	Conference proceedings	Interoperability and integration	Procurement	Lumber
Audy *et al.*	2012a	Planning methods and decision support systems in vehicle routing problems for timber transportation: A review	Report	Planning systems	Procurement	Lumber
Azouzi & D'Amours	2011	Information and Knowledge sharing in the collaborative Design of Planning Systems within the Forest Products Industry: Survey, Framework and Roadmap.	Journal	Interoperability and integration	Procurement	Lumber
Bajgrian *et al.*	2017	Forest harvesting planning under uncertainty: a cardinality-constrained approach	Journal	Planning systems	Procurement	Lumber
Beaudoin *et al.*	2008	Hierarchical forest management with anticipation: an application to tactical–operational planning integration	Journal	Planning systems	Procurement	Lumber
Beaudoin *et al.*	2010	Negotiation-based distributed wood procurement planning within a multi-firm environment	Journal	Planning systems	Procurement	Lumber
Beaudoin *et al.*	2007	Tactical supply chain planning in the forest products industry through optimization and scenario-based analysis	Journal	Planning systems	Procurement	Lumber
Bredström *et al*.	2010	Annual planning of harvesting resources in the forest industry	Journal	Planning systems	Procurement	Lumber
Broman *et al.*	2009	Supply Chain Planning of Harvest and Transportation Operations after the Storm Gudrun	Journal	Planning systems	Procurement	Lumber
Broz *et al.*	2017	Strategic planning in a forest supply chain: a multigoal and multiproduct approach	Journal	Planning systems	Procurement	Lumber
Cambero *et al.*	2015	Strategic optimization of forest residues to bioenergy and biofuel supply chain	Journal	Planning systems	Procurement	Biomass
Carlsson & Rönnqvist	2007	Backhauling in forest transportation: models, methods, and practical usage.	Journal	Planning systems	Procurement	Lumber

Carlsson & Rönnqvist	2005	Supply chain management in forestry-case studies at Södra Cell AB	Journal	Planning systems	Procurement	all
Carlsson *et al.*	1998	Operative planning and dispatching of forestry transportation	Journal	Planning systems	Procurement	Lumber
Castonguay & Gingras	2014	FPInnovations' FPSuiteTM Monitoring Tools: an integrated platform to monitor the entire forest supply chain	Book	Process data collection tools	Procurement	Lumber
Chang & Gaston	2014	The competitiveness of Canadian softwood lumber: a disaggregated trade-flow analysis	Journal	Planning systems	Sales	Lumber
Chauhan *et al.*	2009	Multi-commodity supply network planning in the forest supply chain	Journal	Planning systems	Procurement	Lumber
Chauhan *et al.*	2011	Supply network planning in the forest supply chain with bucking decisions anticipation	Journal	Planning systems	Procurement	Lumber
Czabke	2007	Lean thinking in the secondary wood products industry: challenges and benefits	Other	Interoperability and integration	Production	other
D'Amours *et al.*	2008	Using operational research for supply chain planning in the forest products industry	Journal	Planning systems	Procurement	all
Danserau *et al.*	2010	Sustainable Supply Chain Planning for the Forest Biorefinery	Journal	Planning systems	Procurement	Biomass
De Meyer *et al.*	2015	A generic mathematical model to optimise strategic and tactical decisions in biomass-based supply chains (OPTIMASS)	Journal	Planning systems	Procurement	Biomass
De Meyer *et al.*	2016	Considering biomass growth and regeneration in the optimisation of biomass supply chains	Journal	Planning systems	Procurement	Biomass
Dems *et al.*	2017	Annual timber procurement planning with bucking decisions	Journal	Planning systems	Procurement	Lumber
Dems *et al.*	2015	Effects of different cut-to-length harvesting structures on the economic value of a wood procurement planning problem	Journal	Planning systems	Procurement	Lumber

Devlin *et al.*	2008	Timber haulage routing in Ireland: An analysis using GIS and GPS	Journal	Process data collection tools	Procurement	Lumber
Dong & Wang	2010	Optimization of Timber Procurement and Logistics	Conference proceedings	Planning systems	Procurement	Lumber
Eker	2011	Assessment of procurement systems for unutilized logging residues for Brutian pine forest of Turkey	Journal	Planning systems	Procurement	Biomass
El Hachemi *et al.*	2009	A heuristic to solve the weekly log-truck scheduling problem.	Conference proceedings	Planning systems	Procurement	Lumber
El Hachemi *et al.*	2011a	A heuristic to solve the synchronized log-truck scheduling problem	Journal	Planning systems	Procurement	Lumber
El Hachemi *et al.*	2011b	A hybrid constraint programming approach to the log-truck scheduling problem	Journal	Planning systems	Procurement	Lumber
Epstein *et al.*	1999	A system for the design of short term harvesting strategy	Journal	Planning systems	Procurement	Lumber
Epstein *et al.*	2006	A combinatorial heuristic approach for solving real-size machinery location and road design problems in forestry planning	Journal	Planning systems	Procurement	Lumber
Ezzati *et al.*	2015	An optimization model to solve skidding problem in steep slope terrain	Journal	Planning systems	Procurement	Lumber
Flisberg *et al.*	2009	A hybrid method based on linear programming and tabu search for routing of logging trucks	Journal	Planning systems	Procurement	Lumber
Flisberg *et al.*	2012	FuelOpt: a decision support system for forest fuel logistics	Journal	Planning systems	Procurement	Biomass
Föhr *et al.*	2014	Cost-Benefit Analysis for Forest Biomass Supply Chains by Using RFID-Technology and Interchangeable Containers	Conference proceedings	Process data collection tools	Procurement	Biomass
Forsberg *et al.*	2005	FlowOpt – A decision support tool for strategic and tactical transportation planning in forestry	Journal	Planning systems	Procurement	Lumber

Frayet *et al.*	2007	Agent-based supply chain planning in the forest products industry	Journal	Planning systems	Procurement	Lumber
Frisk *et al.*	2010	Cost allocation in collaborative forest transportation.	Journal	Interoperability and integration	Procurement	Lumber
Fritz *et al.*	2010	FlexWood: Description of standards.	Report	Interoperability and integration	entire supply chain	Lumber
Gautam *et al.*	2015	Value-adding through silvicultural flexibility: an operational level simulation study	Journal	Interoperability and integration	Procurement	Lumber
Gautam *et al.*	2015	Modelling hierarchical planning process using a simulation-optimization system to anticipate the long-term impact of operational level silvicultural flexibility	Journal	Planning systems	Procurement	Lumber
Gerasimov & Sokolov	2014	Decision Making Toolset for Woody Biomass Supply Chain in Karelia	Journal	Planning systems	Procurement	Biomass
Ghaffariyan *et al.*	2013	Analysing the effect of five operational factors on forest residue supply chain costs: A case study in Western Australia	Journal	Planning systems	Procurement	Biomass
Gronalt & Hirsch	2007	Log-truck scheduling with a tabu search strategy	Book	Planning systems	Procurement	Lumber
Gruber & Scholz	2005	GIS based Planning of Forest Road Networks	Conference proceedings	Planning systems	Procurement	Lumber
Guignard *et al.*	1998	Model tightening for integrated timber harvest and transportation planning	Journal	Planning systems	Procurement	Lumber
Gunnarson *et al.*	2004	Supply chain modelling of forest fuel	Journal	Planning systems	Procurement	Biomass
Hakli *et al.*	2013	Challenges and possibilities of RFID in the forest industry	Book	Process data collection tools	entire supply chain	other
Henningsson *et al.*	2007	Optimization models for forest road upgrade planning	Journal	Planning systems	Procurement	other

Hirsch & Gronalt	2008	Optimization techniques to reduce empty truck loads in round timber transport	Journal	Planning systems	Procurement	Lumber
Holweg *et al.*	2005	Supply Chain Collaboration: Making Sense of the Strategy Continuum	Journal	Interoperability and integration	entire supply chain	other
Holzleitner *et al.*	2011	Analyzing time and fuel consumption in road transport of round wood with an onboard fleet manager	Journal	Process data collection tools	Procurement	Lumber
Jerbi *et al.*	2015	Optimization/simulation-based Framework for the Evaluation of Supply Chain Management Policies in the Forest Product Industry	Conference proceedings	Interoperability and integration	Procurement	Lumber
Jones & Ohlmann	2008	Long-range timber supply planning for a vertically integrated paper mill	Journal	Planning systems	Procurement	Pulp & Paper
Kangas *et al.*	2008	Decision support for forest management	Book	Planning systems	Procurement	Lumber
Karlsson *et al.*	2006	RoadOpt: A decision support system for road upgrading in forestry.	Journal	Planning systems	Procurement	Lumber
Koch & Unrau	2012	Final report FlexWood project.	Report	Interoperability and integration	entire supply chain	Lumber
Kong & Rönnqvist	2014	Coordination between strategic forest management and tactical logistic and production planning in the forestry supply chain	Journal	Planning systems	Procurement	Lumber
Kong *et al.*	2015	Using mixed integer programming models to synchronously determine production levels and market prices in an integrated market for roundwood and forest biomass	Journal	Planning systems	Procurement	Biomass
Korten & Kaul	2008	Application of RFID (Radio Frequency Identification) in the timber supply chain	Journal	Process data collection tools	Procurement	Lumber
Kühmeier & Stampfer	2012	Development of a Multi-Criteria Decision Support Tool for Energy Wood Supply Management	Journal	Planning systems	Procurement	Biomass

Kurniawan *et al.*	2011	Integration of Production and Supply Chain Strategic Planning for Renewable Resources under Sustainability Considerations: Teakwood Case Study	Journal	Interoperability and integration	Procurement	Lumber
Lappi & Lempinen	2014	A linear programming algorithm and software for forest-level planning problems including factories	Journal	Planning systems	Procurement	Lumber
Laroze & Greber	1997	Using tabu search to generate stand level, rule-based bucking patterns	Journal	Planning systems	Procurement	Lumber
Laukkanen *et al.*	2004	Applying voting theory in participatory decision support for sustainable timber harvesting	Journal	Planning systems	Procurement	Lumber
Leduc *et al.*	2012	CHP or biofuel production in Europe?	Report	Planning systems	Production	Biomass
Lehoux *et al*.	2007	Collaboration and decision models for a two-echelon supply chain: A case study in the pulp and paper industry	Report	Planning systems	Distribution	Pulp & Paper
Lehoux *et al.*	2011	Collaboration for a two-echelon supply chain in the pulp and paper industry: the use of incentives to increase profit	Journal	Interoperability and integration	Distribution	Pulp & Paper
Little & Manzano	2012	FlexWood: Design of the overall architecture	Report	Interoperability and integration	Procurement	Lumber
Machani *et al.*	2014	A mathematically-based framework for evaluating the technical and economic potential of integrating bioenergy production within pulp and paper mills.	Journal	Interoperability and integration	Production	Pulp & Paper
Mansoornejad *et al.*	2010	Integrating product portfolio design and supply chain design for the forest biorefinery	Journal	Interoperability and integration	entire supply chain	Biomass
Marques *et al.*	2015	A comprehensive framework for developing inter-firm collaboration – A study in the forest-based supply chain	Journal	Interoperability and integration	Procurement	Lumber
Marques *et al.*	2014	Combining optimization and simulation tools for short-term planning of forest operations	Journal	Planning systems	Procurement	Lumber
Marshall *et al.*	2006	Three mathematical models for bucking-to-order	Journal	Planning systems	Procurement	Lumber

Martin-Fernandez	2005	Optimisation of spatial allocation of forestry activities within a forest stand	Journal	Planning systems	Procurement	Lumber
Mesfun & Toffolo	2015	Integrating the processes of a Kraft pulp and paper mill and its supply chain	Journal	Interoperability and integration	entire supply chain	Pulp & Paper
Mirkouei & Haapala	2015	A network Model to Optimize Upstream and Midstream Biomass –to-Bioenergy Supply Chain Costs	Conference proceedings	Planning systems	entire supply chain	Biomass
Mitchell	2005	Methods of moisture content measurement in the lumber and furniture industries	Report	Process data collection tools	Procurement	Lumber
Montgomery *et al.*	2016	Modeling work plan logistics for centralized biomass recovery operations in mountainous terrain	Journal	Planning systems	Procurement	Biomass
Murphy *et al.*	2012	Current and Potential Tagging and Tracking Systems for Logs Harvested from Pacific Northwest Forests	Journal	Process data collection tools	Procurement	Lumber
Murray & Church	1995	Heuristic solution approaches to operational forest planning problems.	Journal	Planning systems	Procurement	Lumber
Muys *et al.*	2010	Simulation tools for decision support to adaptive forest management in Europe	Journal	Planning systems	Procurement	Lumber
Myers & Richards	2003	Supporting wood supply chain decisions with simulation for a mill in northwestern BC	Journal	Planning systems	Procurement	Lumber
Natarajan *et al.*	2012	Optimal Locations for Methanol and CHP Production in Eastern Finland	Journal	Planning systems	Production	Biomass
Ouhimmou *et al.*	2009	Optimization Helps Shermag Gain Competitive Edge	Journal	Planning systems	Procurement	Lumber
Palander	2011b	Modelling renewable supply chain for electricity generation with forest, fossil, and wood-waste fuels	Journal	Planning systems	Procurement	Biomass
Palander	2011a	Technical and economic analysis of electricity generation from forest, fossil, and wood-waste fuels in a Finnish heating plant	Journal	Planning systems	Procurement	Biomass

Palander & Voutilainen	2013	Modelling fuel terminals for supplying a combined heat and power (CHP) plant with forest biomass in Finland	Journal	Planning systems	Procurement	Biomass
Palander & Väätäinen	2005	Impacts of interenterprise collaboration and backhauling on wood procurement in Finland	Journal	Interoperability and integration	Procurement	Lumber
Palmgren *et al.*	2003	A solution approach for log truck scheduling based on composite pricing and branch and bound	Journal	Planning systems	Procurement	Lumber
Palmgren *et al.*	2004	A near-exact method for solving the log-truck scheduling problem.	Journal	Planning systems	Procurement	Lumber
Paradis *et al.*	2013	On the risk of systematic drift under incoherent hierarchical forest management planning	Journal	Planning systems	Procurement	Lumber
Parker *et al.*	2010	Development of a biorefinery optimized biofuel supply curve for the Western United States	Journal	Planning systems	Procurement	Biomass
Ranta *et al.*	2014	Supply Logistics Modelling for Large-Scale Biomass Users	Conference proceedings	Planning systems	Procurement	Biomass
Rey *et al.*	2009	A column generation model for truck routing in the Chilean forest industry.	Journal	Planning systems	Procurement	Lumber
Rönnqvist & Ryan	1995	Solving truck despatch problems in real time.	Conference proceedings	Planning systems	Procurement	Lumber
Rönnqvist *et al.*	2015	Operations Research challenges in forestry: 33 open problems	Journal	Planning systems	entire supply chain	all
Rosset *et al.*	2015	Planning and control of forest-based supply chains utilizing an integrated model-based approach with focus on forest ecosystem management.	Conference proceedings	Interoperability and integration	Procurement	all
Rosset *et al.*	2014	MOTI - L'inventaire forestier facilité par le smartphone.	Report	Process data collection tools	Procurement	Lumber
Rossman *et al.*	2008	The Virtual Forest - Space- and robotics technology for the efficient and environmentally compatible growth-planning and mobilization of wood resources.	Book	Interoperability and integration	Procurement	Lumber

Santa-Eulalia *et al.*	2011	Agent-based experimental investigations of the robustness of tactical planning and control policies in a softwood lumber supply chain	Journal	Planning systems	Procurement	Lumber
Santa-Eulalia *et al.*	2010	Modeling Agent-Based Simulations for Supply Chain Planning: the FAMASS Methodological Framework	Conference proceedings	Planning systems	Procurement	Lumber
Scholz	2015	Spatial Adaptive Large Neighborhood Search for Wood Supply Chain Optimization.	Journal	Planning systems	Procurement	Lumber
Scholz	2010	Real-time spatial optimization.	Book	Interoperability and integration	Procurement	Lumber
Scholz	2011	System architecture for spatial decision support in wood supply chain management.	Book	Interoperability and integration	Procurement	Lumber
Scholz *et al.*	2008	Optimizing the wood supply chain–concept and methods	Journal	Planning systems	Procurement	Lumber
Shabani & Sowlatii	2016a	Evaluating the impact of uncertainty and variability on the value chain optimization of a forest biomass power plant using Monte Carlo Simulatio	Journal	Planning systems	entire supply chain	Biomass
Shabani *et al.*	2014	Tactical supply chain planning for a forest biomass power plant under supply uncertainty	Journal	Planning systems	entire supply chain	Biomass
Shabani & Sowlati	2016b	A hybrid multi-stage stochastic programming-robust optimization model for maximizing the supply chain of a forest-based biomass power plant considering uncertainties	Journal	Planning systems	entire supply chain	Biomass
Sharifzadeh *et al.*	2015	Supply chain network design and operation: Systematic decision-making for centralized, distributed, and mobile biofuel production using mixed integer linear programming (MILP) under uncertainty	Journal	Planning systems	Procurement	Biomass

Sosa *et al.*	2015	Controlling moisture content and truck configurations to model and optimize biomass supply chain logistics in Ireland	Journal	Planning systems	Procurement	Biomass
Stängle *et al.*	2014	Clear wood content in standing trees predicted from branch scar measurements with terrestrial LiDAR and verified with X-ray computed tomography	Journal	Process data collection tools	Procurement	Lumber
van Dyken *et al.*	2010	Linear mixed-integer models for biomass supply chains with transport, storage and processing	Journal	Planning systems	Procurement	Biomass
Vaskovic *et al.*	2015	Multi-Criteria Optimization Concept for the Selection of Optimal Solid Fuels Supply Chain from Wooden Biomass	Journal	Planning systems	Procurement	Biomass
Vergara *et al.*	2015	Impact of timber volume and grade estimation error on the British Columbia Coastal supply chain	Journal	Planning systems	Procurement	Lumber
Von Schnetzler *et al.*	2009	The Supply Chain Operations Reference (SCOR)-Model to describe the value-added chain in forestry	Journal	Interoperability and integration	Procurement	Lumber
Weintraub *et al.*	1996	A truck scheduling system improves efficiency in the forest industries	Journal	Planning systems	Procurement	Lumber
Xie & Huang	2015	Sustainable Biofuel Supply Chain Planning and Management Under Uncertainty	Journal	Planning systems	Procurement	Biomass
Zhang *et al.*	2016	Decision support system integrating GIS with simulation and optimisation for a biofuel supply chain	Journal	Planning systems	Procurement	Biomass

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