An analysis of potential improvements within Lithuanian sawlog supply

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Abstract

The wood supply from the forest to the industry is often characterized by high variability caused by the divergent structure of forest products, seasonality and uneven geographical distribution of forest resources and forest products industries. Based on previous knowledge on wood supply this thesis aimed to identify existing wood supply patterns and strategies in the Lithuanian state forest sector, to evaluate supply chain performance for sawmills and to examine potential improvements for roundwood transportation as well as handling operations at the sawmill. The research presented in this thesis was based on data gathered in the timeframe of 2000-2008.

The studies demonstrated how state forest enterprises in wood supply and sawmilling activities focused on so called main products, as compared to by-products (I, II). This was reflected by the lead times which for high value assortments were 2.5 times shorter compared to low value assortments (I). This was also reflected in the degree of dynamics between upstream and downstream positions at the sawmills, which for by-products were 40 % lower than for main products (II). Although the study showed some signs of coordination between wood supply and market sales, the wood supply from state forest enterprises were still primarily driven by silvicultural requirements and not by market signals (I, II).

Roundwood transportation planning was carried out independently by each state forest enterprise. The results (III) demonstrated that, given the existing geographical distribution of forest resources and customers, improved transport planning can potentially reduce roundwood ttransport costs. It was found that up to 60 % of volume for studied period could be included in a backhaul route thus resulting in an average potential reduction of transport costs by 14 % (III).

Discrete-event simulation model was applied for analysing roundwood handling operations at a sawmill (IV). The model proved to be an effective tool for simulating different roundwood handling operations and could be used as a supportive management tool. It enabled the identification of key factors – roundwood sourcing and delivery scheduling - that could improve capacity utilization both for the sawmill and roundwood hauling.

Keywords: supply chain, strategy, lead-time, transport planning, backhaul, sourcing, scheduling, simulation.

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Dedication

To my loved ones. I am grateful for their continuous support.

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Puodžiūnas, M. and Fjeld, D. (2002). Evaluation of supply chain strategies in Lithuanian forest enterprises: a case study. *Baltic Forestry* 8(2): 64-70.

II Puodžiūnas, M., Fjeld, D. and Wästerlund, I. (2003). Evaluation of supply chain performance metrics for Lithuanian state sawmills. *Baltic Forestry* 9(2): 20-28.

III Puodžiūnas, M., Rönnqvist, M. and Fjeld, D. (2004). The potential for improvement of tactical planning of roundwood transport in Lithuanian state forest enterprises. *Baltic Forestry* 10(1): 79-88.

IV Puodžiūnas, M. and Fjeld, D. 2008. Roundwood handling at a Lithuanian sawmill – discrete-event simulation of sourcing and delivery scheduling. *Baltic Forestry* 14(2): 163-175.

The contribution of the authors to the papers included in this thesis was as follows:

I **"Evaluation of supply chain strategies in Lithuanian forest enterprises: a case study"**. M. Puodžiūnas & D. Fjeld. M. Puodžiūnas & D. Fjeld cooperated in the development of study methods and production of manuscript. All data collection and analysis was done by M. Puodžiūnas.

II **"Evaluation of supply chain performance metrics for Lithuanian state sawmills"**. M. Puodžiūnas, D. Fjeld, & I. Wästerlund. M. Puodžiūnas & D. Fjeld cooperated in the development of study methods, analysis and final revision of manuscript. All data collection was done by M. Puodžiūnas. I. Wästerlund contributed to revision of the manuscript.

III **"The potential for improvement of tactical planning of roundwood transport in Lithuanian state forest enterprises"**. M. Puodžiūnas, M. Rönnqvist & D. Fjeld. All data collection and analysis performed by M. Puodžiūnas. Methods & programming developed by M. Rönnqvist. M. Puodžiūnas, M. Rönnqvist & D. Fjeld cooperated in the production of manuscript.

IV **"Roundwood handling at a Lithuanian sawmill – discrete-event simulation of sourcing and delivery scheduling"**. M. Puodžiūnas & D. Fjeld. All data collection and analysis performed by M. Puodžiūnas. M. Puodžiūnas & D. Fjeld cooperated in the development of methods and production of manuscript. Computer programming performed by D. Fjeld.

Abbreviations

BS	Business Strategy
CSI	Customer Service Index
ICT	Inventory Cover Time
InvP	Sawn Wood Inventory
InvR	Roundwood Inventory
KPI	Key Performance Indicator
LP	Linear Programming
OR	Operations Research
SC	Supply Chain
SCC	Supply Chain Council
SCM	Supply Chain Management
SCOR	Supply Chain Operations Reference
SCS	Supply Chain Strategy
SMS	Supply Management Strategy
SS	Supply Strategy

1 Introduction

The roundwood and forest products markets in Lithuania have been greatly affected by the political transition of the past decades. After many years of the forest sector being almost invisible to other European countries the collapse of Soviet Union enabled Lithuania to re-enter European markets. A fundamental change in forest operations accompanying this transition was the gradual replacement of the whole-stem cutting method with the cut-to-length system. While this change enables a potentially higher degree of customer orientation in wood supply, a higher degree of coordination in the supply chain is required to realize this potential.

Since regaining independence in 1991 Lithuanian sawmills have made a particularly rapid recovery and redirected exports from Eastern to Western markets. That was particularly important because of their role as a supplier to other wood-working industries. At present, a total annual capacity of sawn wood accounts 1.15 million m^3. The export of wood products, paper, furniture and prefabricated wooden constructions is responsible for 9 % of the national export incomes. The average annual cut has been approximately 7.2 million m^3, of which Lithuania has exported up to one-fifth, mainly in the form of pulpwood (Anon., 2013).

This dissertation focuses on potential improvements within the wood supply function for the sawmill sector. A wood supply perspective requires a widening of the traditional focus on forest operations to include all operations from forest to mill and their integration with mill production. This starts with a clarification of some basic terminology and concepts for the supply chain (SC) perspective. It is followed by mapping of supply operations and measuring potential transport improvements from forest to mill. That leads to the discussion on how the existing supply chain operates and what potential improvements within the supply chain could be implemented. Finally, some concluding remarks are provided to focus on improved coordination of wood supply and demand that is fundamental for reaching the desired supply chain strategy.

1.1 A framework of supply chain terminology

Mentzer et. al. (2001) define a supply chain as “a set of three or more companies directly linked by one or more of the upstream and downstream flows of products, services, finances, and information from a source to a customer”. In practice these chains are often structured as networks. The link between companies or functions within a supply network implies coordination. A goal of coordination involves a common strategy for all units involved in supply operations. Strategy is the leading element for the supply chain hierarchy of strategic, tactical and operational levels and the strategic level involves determination of objectives as well as the development of resources to accomplish these objectives. Nested within the strategic level is the tactical level where engagements are planned and executed to accomplish objectives assigned to formations or units. This then leads to the operational level where operations are planned, conducted and sustained to accomplish strategic objectives within the area of operations. This hierarchy implies that the focus on improved coordination within the supply chain will inevitably guide the development of forest operations management.

A number of different perspectives on strategy can be seen in the literature and an overview of strategy terms with relevance for wood supply is presented in Table 1. Evered (1983) defines strategy from a process-perspective and sees it “as a continuous process by which goals are determined, resources are allocated and pattern of cohesive actions is promoted by the organization in developing competitive advantages”. Andrews (1987) argues that the word strategy retains a close connection to a conscious purpose and in its simplest form can describe “a very specific plan of action directed at a specific result within a specific period of time”.

Table 1. *An overview of strategy terms with relevance for wood supply.*

Terms	Definition	Reference
Supply Chain (SC)	A set of three or more companies directly linked by one or more of the upstream and downstream flows of products, services, finances, information from a source to a customer	Mentzer et al. (2001)
Strategy	Process-based perspective Plan-based perspective	Evered (1983) Andrews (1987)
Business Strategy (BS)	Directed towards the long term, being intended to provide continuity and integrity to the whole company Guides the way a firm performs individual activities and organizes its entire value chain	Nollet et al. (2005) Porter (1990)
Supply Strategy (SS)	Medium term plan where broader definitions of strategy should be converted into concrete and specific actions Supply strategy is composed of a series of plans, consolidated in a master plan for coherence and integrity, thus ensuring and demonstrating its contribution to corporate and business strategic objectives' Starts by segmenting decisions and decisions according to three levels (strategic/tactical/operational)	Nollet et al. (2005)
Supply Management Strategy (SMS)	Describes specific actions or particular ways of accomplishing decisions made in the SS	Nollet et al. (2005)
Supply Chain Management (SCM)	Systematic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole	Mentzer et al. (2001)
Supply Chain Strategy (SCS)	Defines how the supply chain should operate in order to compete How the supply chain processes shall be structured and coordinated to support the company in achieving its business strategies	UPS (2005) Audy et al. (2011)

Strategic planning normally is applied within individual business units and refers to business strategy (BS). Business strategy is directed towards the long term, being intended to provide continuity and integrity to the whole company

(Nollet et al. 2005). Key decisions involve choices on products and markets and even other soft objectives. Porter (1990) acknowledged that in a constantly changing business environment, it may be difficult to come up with an appropriate (business) strategy but even then strategy “guides the way a firm performs individual activities and organizes its entire value chain” towards three generic strategies of cost leadership, differentiation and focus. Functional strategies are medium term plans where broader definitions of strategy should be converted into specific actions. Supply strategy is one such functional strategy and is explicitly defined as “being composed of a series of plans, consolidated in a master plan for coherence and integrity, thus ensuring and demonstrating its contribution to corporate and business strategic objectives” (Nollet et al. 2005). Supply strategy content starts with segmenting decisions into the hierarchy of strategic, tactical and operational levels. The specific actions or ways of accomplishing decisions within the supply strategy are referred to as supply management strategies (SMS).

Mentzer et al. (2001) defines supply chain management (SCM) given by as “systematic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole”. Different types of strategic coordination may be termed supply chain strategy (SCS) which UPS (2005) defines simply as “how the supply chain should operate in order to compete”. The definition of SCS is further developed by Audy et al. (2011) as “how the supply chain processes shall be structured and coordinated to support the company in achieving its business strategies”. Together, the terms introduced above form a framework giving structure to the numerous elements guiding the development of forest operations management in wood supply.

1.2 Supply chain coordination concepts

An enormous number of studies are available on coordination of operations within supply chains in the manufacturing sector. A few have been identified which relate to the framework of terms introduced earlier. Frayret et al. (2004) analysed the coordination and control issues in manufacturing systems. According to the way the manufacturing control responsibilities are distributed across the organization, it has been shown that different coordination mechanisms can be implemented to manage the interdependencies among manufacturing activities. The authors (Frayret et al. 2004) proposed a new classification scheme of coordination and control developed on agent-based technology which appeared to be suitable to implement various types of control architecture. Cousins (2005) in a study of supplier-manufacturer relationships examined how companies aligned supply (management) strategy with business strategy. This study showed how cost focus typically lead to operational collaboration which involves sharing of operations planning information, developing and sharing forecasts for supply and demand and joint capacity management systems. Alternatively, differentiation focus typically lead to strategic collaboration which involves aligning customer requirements, technology sharing and joint product development. Frohlich and Westbrook (2001) widened the scope of collaboration to include suppliers, manufacturers and customer. They examined how a varying direction (supplier vs. customer) and depth of integration (access to planning systems, sharing production plans, knowledge of inventory levels, joint communication network) influenced manufacturer performance improvements. In this case, the direction and degree of collaboration was termed supply chain strategy.

Fisher (1997) developed a dichotomy of innovative and functional supply chain strategies. Lehtonen (1999) adapted Fisher’s dichotomy to the Nordic pulp and paper sector to examine and characterize two sector-specific supply chain strategies between paper mills and their customers: flexible and efficient. In Lehtonen’s dichotomy the efficient supply chain strategy is characterized by high utilization of production facilities, even-flow of materials, standard product range and lower customer service levels. The efficient supply chain strategy was assumed to prevail in much of the Nordic forest sector, resulting in slow response to market fluctuations. In contrast, the flexible supply chain strategy was characterized by an uneven-flow of materials and a wider product range where high customer service levels play a major role in companies’ performance. Flexibility in this context is often referred to as agility (Christopher, 2000) and can even be considered in a supply chain context.

1.3 Coordination challenges in wood supply

Challenges in supply network coordination are imposed by sector-specific conditions. While most manufacturing industries must cope with demand variability, an additional challenge for the forest sector is seasonal supply variability caused by varying transport conditions in both logging and transport. The divergent product identity and increasing number of assortments and downstream customers makes this supply network particularly challenging to coordinate. Methods for quantifying variability have been developed by Fransoo & Wouters (2000) and used in wood supply simulation by Haartveit & Fjeld (2003). In addition, Audy et al. (2012a) propose a framework for estimating overall variability in both supply and demand based on 5 environmental characteristics (roundwood heterogeneity, accessibility to harvesting rights, harvesting and transport conditions, contract commitment horizon and frequency of change in demand). A few studies have also investigated the occurrence of demand distortion effects (Forrester, 1961) in the forest products sector (Hameri 1996; Hameri and Lehtonen 2001; Moyaux, et al. 2007) but these studies did not extend as far upstream as wood supply.

Referring to supply chain strategy in wood supply, numerous studies have examined supply chain processes from perspectives of process configuration. Some very general process configurations for Swedish and Finnish wood supply are given by Bäckström & Åström (2003) and Uusitalo (2005), respectively. Assortment-specific process mapping has also been done by Andrén & Fjeld (2004), Helstad (2006) and Hapaniemi (2001) for pulpwood, sawlogs and biofuel, respectively. Schnetzler et al. (2009) utilized the Supply Chain Operations Reference (SCOR) model of the Supply Chain Council (SCC 2008) to map a general model for case studies in Central Europe. Audy et al. (2012a) adapted the SCOR model for comparative case studies in North America, South America and Europe and also mapped average lead times of these wood supply chains. Haartveit et al. (2004) mapped processes, lead- and inventory cover times for both the supply and distribution chain for a number of Canadian sawmills. In the Nordic countries a number of key performance indicators (KPI) are used for following-up the service levels of wood supply to receiving mills. These vary from a simple measurement of delivery precision (delivered volume in relation to ordered volume per assortment and period) to more sophisticated customer service indexes (CSI) measured as an aggregate of multiple weighted KPIs. Although many of these are well-known within the sector (Andrén, 2004), actual results are unavailable for general research purposes.

As indicated above, many dimensions and methods exist for mapping the functioning of the wood supply chain. The fundamental difference between these studies is the focus on mapping structures versus quantifying performance. Ideally, different supply chain strategies should be reflected in their respective performance metrics. No studies have documented key performance indicators for Lithuanian wood supply. Such values could be used to help quantify performance for suppliers aiming for efficient versus flexible supply chain strategies. However, the actual degree of variation in supply and demand also needs to be quantified in order to indicate the need for coordination between wood supply and mill production.

1.4 Examining coordination in wood supply

Improved coordination within the supply chain is a challenging task which can provide a competitive advantage for a company. Carlsson and Rönnqvist (2005) demonstrated that improved wood flow coordination with pulp production and distribution to customers can lead to significant cost reductions. This study segmented planning decisions into strategic, tactical and operational levels for wood procurement, pulp mill production, distribution and sales functions, yielding a complete supply chain planning matrix which has since been used to form a framework for later studies.

Given that transport is the connecting link between forest and mill and that it typically constitutes up to 40 % of the operational costs in wood supply (D'Amours et al. 2008) a focus on transport operations is motivated. Well-coordinated transport activities are a necessary element for companies aiming to achieve goals of both efficiency (e.g. high capacity utilization) and flexibility (e.g. high customer service level). Everyday discussions in the Lithuanian forest sector indicate that transportation is not sufficiently coordinated between organizations. The mix of suppliers and transport systems in Lithuania is similar to that of the Nordic countries, making Nordic transport practices potentially relevant for developing Lithuanian practices. An overview of relevant Nordic transport studies and their respective research methods is therefore presented below (Table 2).

Table 2. *An overview of some Nordic research on roundwood transport planning models segmented according to strategic, tactical and operational levels.*

Levels	Planning Decision	Reference
Strategic	General materials acquisition planning models with different sources and transport modes	Lukka (1994)
	Transport system	Frisk et al. (2006) Forsberg et al. (2005)
	Roads and infrastructure	Richards and Gunn (2000) Olsson (2004) Henningsson et al. (2007)
Tactical	Wood flow planning	Bergdahl et al. (2003) Frisk et al. (2006) Forsberg et al. (2005) Broman et al. (2006)
	Wood flow planning with consideration to backhauling	Carlsson and Rönnqvist (1998; 2005) Carlsson et al. (2006) Eriksson & Rönnqvist (2003)
Operational	Routing	Palmgren et al. (2003, 2004) Andersson et al.(2008) Flisberg et al. (2007)
	Scheduling	Korpilahti (1987) Väätäinen et al. (2005) Marques et al. (2012)

The transport decision models noted in Table 2 are solved by a selection of operations research (OR) methods. Commonly, there are two classes of models – mathematical and simulation - used to solve these. A mathematical model is a formal structure that creates a framework within which a problem can be analyzed. Mathematical programming uses non-linear and linear models. Linear programming (LP) is one of the most widely used tools for solving OR problems. It is primarily concerned with the determination of the best allocation of scarce resources. Simulation models are an alternative to mathematical models in analyzing complex systems. Simulation models statistically describe system behaviour by replicating system performance for a specified number of times. They are divided into two categories – continuous and discrete-event simulation. While the state of a continuous model changes continuously over time, the state in a discrete-event model changes at discrete points in time which correspond to specific events, f. e. the arrival of trucks at a mill. A major strength of discrete-event simulation is its ability to model random events and to predict the effects of the complex interactions between these events (Anon., 2004).

Earlier transport studies have described a wide selection of available models and suitable OR methods. The improved coordination of wood flow and mill production with respect to transport planning starts from developing supply sources and transport systems (strategic level). Within this framework wood flow is re-planned periodically to better coordinate procurement areas with mill production (tactical level). For the Lithuanian context, Puodžiūnas (1998) carried out studies of wood flow planning that indicated that state forest enterprise solved these decisions independently and that there existed potential savings for improved wood flow planning. This type of collaborative planning can be solved between independent enterprises by wood barter (Audy et al., 2010). At the tactical level, flow planning can even take into consideration potential backhaul flows (Carlsson and Rönnqvist, 1998; Eriksson and Rönnqvist, 2003). Possibilities to exploit backhaul potentials have been studied by Carlsson et al. (2006) and Auselius (2010). A collaboration framework for this has been described by Audy et al. (2010).

Within the tactical plan established for wood flows, transport must be executed at the operational level with vehicle routing. Routing is a complex task subject to the high number of alternatives and constraints (Palmgren et al. 2003; Palmgren et al. 2004; Andersson et al. 2008; Flisberg et al. 2007). Roundwood transport represents a special case, where the number of restrictions is especially large. These restrictions include, for example, factors such as the geographic movement of supply nodes (active landings) and the specificity of certain landings for certain truck types. The influence of climate on infrastructure bearing capacity and the effects of roundwood freshness on mill processes and product quality are also critical restrictions (Karanta et al., 2000). Scheduling of deliveries is of particular importance for larger mills with a high number of daily deliveries. In this context, scheduling has been shown to be an effective solution to avoid truck queuing problems (Korpilahti 1987; Väätäinen et al. 2005; Marques et al. 2012) and reduce roundwood handling costs.

The overview of Nordic studies on transport planning show a selection of topics for improving truck transport operations in the Lithuanian context. Considering the tactical level, given that methods are already developed for both identifying backhaul flows and quantifying the potential cost savings, this is a type of study suitable for further investigation in Lithuania. Later research on realizing backhaul potential can also be useful for supporting implementation aspects. Considering potential topics at the operational level, the potential complexity of planning vehicle routing is high and roundwood transport represents a special case where the number of restrictions is especially large. This topic is therefore judged as unsuitable for a single research paper. However, given the later establishment of larger mills with more frequent deliveries, delivery scheduling is considered a relevant topic for both suppliers and mills.

1.5 Objectives

This thesis focuses on issues within sawmill wood supply under Lithuanian conditions. The papers can be placed into two classes: mapping supply chain operations and examining potential improvements in transport from forest to mill. The four papers are specified in Table 3.

Table 3. The *issues investigated in the respective Papers (I-IV).*

Broad orientation	Issues investigated per paper	
Mapping SC operations from forest to mill	I. Existing supply chain strategies in wood supply and key metrics	II. Variability of supply and demand from forest to mill
Examining potential improvements of roundwood transport from forest to mill	III. Coordination of transport planning between suppliers/haulers	IV. Coordination of wood deliveries between suppliers/ haulers and sawmills

Based on the issues described above, the main objective of the thesis was to map supply chain operations for Lithuanian sawmills and to test methods for identifying and estimating potential improvements in transport from forest to mill.

The main objective was divided into the following 4 sub-objectives for the respective papers:

1. To evaluate criteria for characterizing supply chain strategies in state forest enterprises with key metrics.
2. To evaluate metrics for quantifying supply chain variation in the sawmilling sector.
3. To estimate the potential improvement effect of coordination of backhauling between state forest enterprises and their haulers.
4. To estimate the potential improvement effect of delivery scheduling between suppliers/haulers and the larger sawmills.

Papers I-III are limited to the scope of state forest enterprises and sawmills while paper IV extends the scope to larger non-state-owned sawmills. The research presented in this thesis was done during the time frame of 2000-2008 and therefore reflect the assumptions and conditions relevant during this period of transition.

2 Materials & Methods

The studies incorporated various elements of operations management from forest to sawmill. Each study mapped or estimated different aspects of supply operations and used a variety of methods.

2.1 Paper I: Supply chain strategies

The aim for Paper I was to evaluate criteria for characterizing supply chain strategies in state forest enterprises. Two key metrics were used: lead time and delivery precision. Two state forest enterprises were selected and the management was interviewed in order to identify their intended supply chain strategy (SCS). The criteria for identification of the SCS were based on Lehtonens (1999) efficient and flexible dichotomy and their associated characteristics.

Monthly delivery precision was measured for each of both enterprises' customers for a one year period. The data was gathered from sales agreements and monthly sales reports. The efficient enterprise had 57 customers and the flexible one had 53. Almost all customers were from domestic market. Two and four customers were from foreign markets for efficient and flexible enterprises, respectively. Delivery precision was calculated as the ratio between delivered volume and agreed volume per customer.

Lead times were estimated for 30 stands from each enterprise including 15 stands with high demand (e.g. high value birch) and 15 stands with low demand (e.g. spruce pulpwood). Within the species and assortment stands were selected randomly. The harvesting type in selected stands was final cutting. Lead times were calculated as the time from initiation of harvesting to completion of delivery.

2.2 Paper II: Supply chain variability metrics

The aim of Paper II was to evaluate metrics for quantifying supply chain variability in the state sawmilling sector based on monthly flows and inventories. It has to be noted that by the time these thesis were published the state sawmilling sector in Lithuania experienced drastic changes. The political decision was taken to restructure this sector resulting in privatization of some of the sawmills and in closure of others.

The study originally selected 6 state forest enterprises sawmills. Their economic results are shown in Table 4. All state forest sawmills were already classified according to high (H), medium (M) and low (L) economic potential (Anon., 2002). They were also grouped according to their product focus. Sawmills 1 to 4 focused on production of higher-quality (main) assortments. Sawmills 5 and 6 were focused on the lower quality (by-product) assortments. For tracing the monthly flows, after processing two classes of aggregated assortments are defined: main products (edged and un-edged sawn wood of coniferous and deciduous species) and by-products (pallet wood of all species).

Table 4. *Some key characteristics for sawmills selected for Paper II. The estimated economic potential is indicated in parentheses (H=high, M=medium, L=low).*

Sawmill number	Focus	Roundwood consumption in 1000 m^3 (2000/2001)	Revenue in 1000 € (2000 / 2001)	Assets in 1000 €
1 (H)	main products	27.2 / 27.1	1809 / 1586	774
2 (H)	main products	10.9 / 11.1	678 / 639	1406
3 (M)	main products	19.5 / 25.2	888 / 778	585
4 (M)	main products	12.5 / 17.2	543 / 572	572
5 (L)	by-products	6.1 / 7.1	259 / 269	120
6 (L)	by-products	3.5 / 3.6	220 / 165	129

Monthly product flows and inventories were collected for each sawmill for one calendar year of operations. Complete data was not available for mill 1 and it was excluded from subsequent analysis. The data included the volume of received round wood (R), processed sawn wood (P), and sold sawn wood (S) as well as the month-end's volume of inventories for round (InvR), sawn wood (InvP).

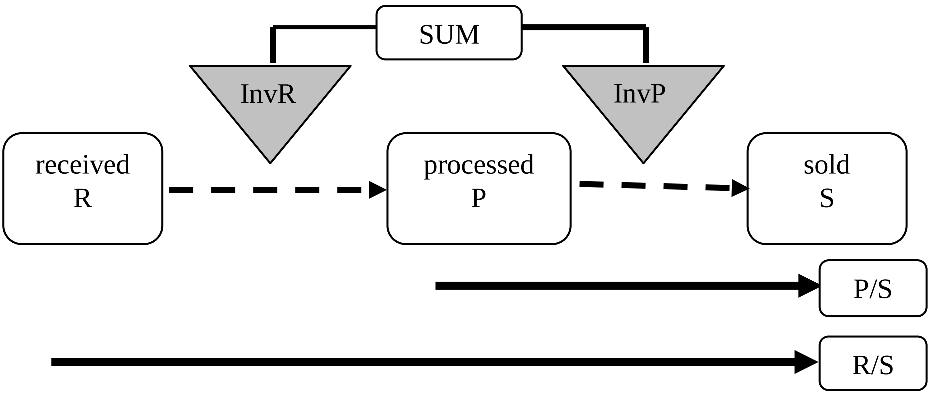

Figure 1. The monthly flows recorded for each of the studied sawmills in Paper II. R, P and S represent received roundwood, processed sawn wood, and sold sawn wood, respectively. The sum inventory includes both roundwood and sawn wood.

Based on this data a number of metrics were estimated for main and by-products, respectively. These included the coefficient of variation for monthly volumes (CV=standard deviation/average), average inventory cover time (ICT in terms of the number of days of production they represent), the degree of dynamics between upstream and downstream positions (ρ=cross correlation coefficient between monthly time series for the respective flows) and supply variability quotient (ω=ratio between coefficients of variation for upstream vs. downstream flows). Degree of dynamics (ρ) and supply variability quotients (ω) were calculated for both received roundwood to sawn wood sales (R/S) and processed sawn wood to sawn wood sales (P/S) as shown in Figure 1.

2.3 Paper III: Potential roundwood transport improvements

The aim of Paper III was to estimate the potential improvement effect of coordination of backhauling between state forest enterprises and their haulers. The potential improvement with backhauling was estimated for a one month case study (January, 2002) and compared the transportation costs for historical roundwood flows to the cost for the same flows utilizing backhauling. The case study covered middle-southern part of Lithuania and 13 state forest enterprises were involved. The variables required for the analysis are listed in Table 5.

Table 5. Input variables for the case study of backhauling in Paper III.

Input class	Variable specification
Volume restrictions	Volume per assortment supplied per landing (supply node) Volume per assortment demanded per mill (demand node)
Spatial assumptions	Landing position Mill position
Transport assumptions	Transport distance matrix (landing to mill) Transport cost function and transport saving for backhauling
Operational assumptions	Maximum route length Load size, driving speed, terminal time

The historical flows from landing to mill were available for each day of the studied period. These were aggregated to 7 different combinations of planning horizons:

- 1 week: 4 sets of one-week periods (week 1, 2, 3, 4)
- 2 weeks: 2 sets of two-week periods (week 1-2, 3-4)
- 4 weeks: 1 four-week periods (week 1-4).

The potential cost savings for backhauling was calculated with a tactical transport planning model which minimizes transport costs under given supply and demand restrictions. The model generates potential backhauls and enters these into a linear-programming model which then chooses the combination of direct and backhaul flows giving the lowest sum costs while fulfilling the supply and demand restrictions. The original model formulation was developed by Carlsson and Rönnqvist (1998) and a custom software version was created by Rönnqvist for this study. The software enables both to identify profitable backhauls and to calculate their respective potential cost savings without influencing historical wood destination decisions.

Parameters were set to levels typical for Lithuanian conditions. A number of key assumptions were also possible to adjust in the model such as truck load size, average driving speeds and the maximum time limit for a feasible backhaul. This made it possible to model cost savings for alternative scenarios. These alternative are shown in Table 6.

Table 6. *Standard and alternative assumptions for calculating the economic potential for backhauling in Paper III.*

	Standard assumptions	Alternative assumptions
Average load size	25 m^3	35 m^3
Working time per day	480 min	960 min
Average driving speed	50 km/h	70 km/h

2.4 Paper IV: Potential roundwood handling improvements

The goal of Paper IV was to estimate the potential improvement effect of delivery scheduling between suppliers/haulers and larger sawmills. The sawmill modeled was based on a real case with an annual consumption of 250,000 m^3 (with operation 7 days per week and 3 shifts per day). Roundwood storage capacities were limited to 20,000 m^3 and 35,000 m^3 before and after sorting, respectively. The mill had a supply structure consisting of both domestic sources arriving by truck (approx. 60 %) and import sources arriving by rail (approx. 40 %). Each source had specific log sizes and rejection proportions which determine sorter production (m^3/h). The historical distribution of arrivals (in 6 hour periods) and sorter production (m^3/h) were based on data collected from 667 loads.

A discrete-event model of the roundwood handling was built in the ARENA simulation package described in Kelton et al. (1998). The activities modeled include unloading of trucks, movement to sorting and sorting. Queuing is modeled for trucks waiting for unloading and loads waiting for sorting. Priorities for allocating loader capacity are based on status for truck and sorter queues (see Figure 2).

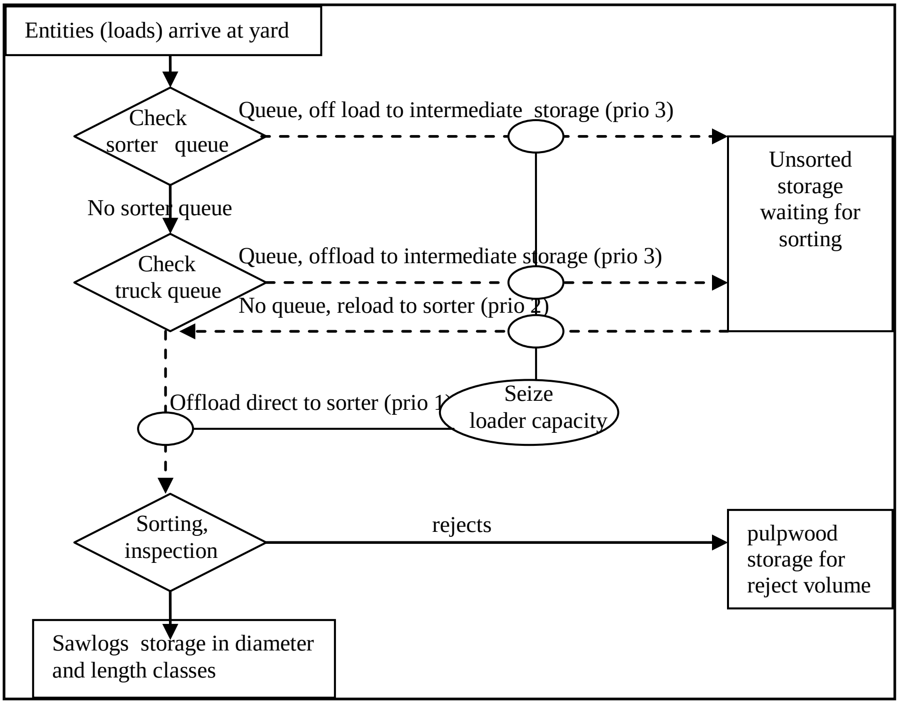

Figure 2. A flowchart overview of the arrival, unloading and sorting of loads in the discrete-event model used in Paper IV.

Different sourcing and scheduling alternatives were simulated under both present (21,000 m^3/month) and expected future delivery volumes (30,000 m^3/month). Volumes were also modeled using single and double loader capacity. The dynamics of the animated system were observed visually to check system behavior. Loading and unloading times were adjusted as well as the limit for the maximum number of loads allowed in the sorter queue. The available capacity utilization (%) for the sorter module was then adjusted until a one-to-one ratio was gained between modeled and actual production.

The study involved running different sourcing and scheduling scenarios with present delivery volumes in order to compare their potential effects on sorter production and intermediate storage before sorting for both present and future volumes (Table 7). The alternative to the present supply structure involves replacement of 2 import sources with a corresponding increase of domestic sources. The alternative to the present delivery scheduling was an even distribution of truck load arrival for each of the six-hour arrival periods.

Table 7. *The sourcing and truck delivery scheduling alternatives modeled in Paper IV for present and future wood supply volumes.*

Monthly delivery volume (1000 m^3)	Sourcing alternative	Truck scheduling alternative (% arrivals per 6 h period)	
		1. present (2/24/56/17)	2. improved (25/25/25/25)
21´ (one loader)	A. Present	21A1	21A2
	B. Reduced import increased domestic	21B1	21B2
30´ (two loaders)	A. Present	30A1	30A2
	B. Reduced import increased domestic	30B1	30B2

3 Results

3.1 Paper I: Supply chain strategies

Some key figures for how the supply chains operated for the two enterprises are shown in Table 8. Typical supply agreements for the efficient enterprise were based on an annual prognosis with variations indicated per quarter. Typical supply agreements for the flexible enterprise were also based on an annual prognosis but without an indication on how the volumes could vary. Supply agreements for both enterprises, however, were confirmed on a monthly basis.

Table 8. *Key figures and annual supply fulfillment for the efficient and flexible enterprises studied in Paper I.*

SCS	Total annual volume	No. assort.	Focus assort.	Typical supply agreement			Annual supply fulfillment	
				Forecast	Indicated variation	Order adjustment	All	10 largest
Efficient	71,000m^3	5	All	Annual	Quarterly	Monthly	-17.8 %	-14.8 %
Flexible	47,000m^3	6	veneer	Annual	None	Monthly	-21.9 %	-33.8 %

Annual fulfillment of supply agreements was low and during studied period fell short by 17.8 % and 21.9 % for the efficient and flexible enterprises, respectively. The corresponding results for the 10 largest customers were 14.8 % and 33.8 %. Four of 10 (40 %) customers of the efficient enterprise purchased within 20 % of the volumes indicated in the original yearly prognosis. The corresponding number for the flexible enterprise was 2 of 10 (20 %). Data on the confirmed monthly orders were not available.

The average lead times were on average 45 days for the efficient and 42 days for the flexible enterprise. The shortest average lead times were found for veneer (22 days), which was followed by sawlogs (39 days), pulpwood (49 days) and palletwood (58 days).

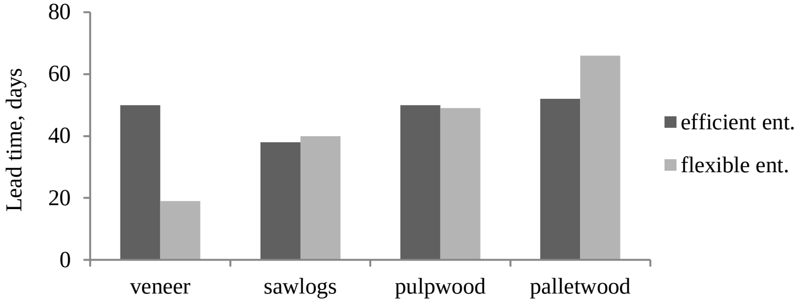

Figure 3. Lead times for different assortments for the efficient and flexible enterprises studied in Paper I.

The comparison of the lead times for similar assortments for the two studied enterprises is shown in Figure 3. Lead times varied less for the efficient enterprise (38-52 days) than for the flexible enterprise (19-67 days). The shortest lead time in the efficient enterprise was for birch sawlogs but it was almost twice the lead time for birch veneer in the flexible enterprise. The longest lead times were found for black alder palletwood in the flexible enterprise and aspen palletwood in the efficient enterprise.

3.2 Paper II: Supply chain variability metrics

Metrics were estimated for main and by-products flows processed by 5 mills with complete data (one year). Average values for mills focusing on main products (2-4) and by-products (5-6) are shown in Table 9.

Table 9. *Key numbers for the sawmill classes studied in Paper II.*

Mills	Annual volume (m^3)	Focus (% of volume)	Variation in monthly flows		Supply variability quotient (ω)	Degree of dynamics (ρ)
			CV_r	CV_s		
2-4	11,000-25,000	63 % main products	0.35	0.17	2.01	0.60
5-6	3,500-7,100	67 % by-products	0.40	0.40	1.10	0.53

The coefficients of variation for monthly sawn wood sales (CV_S) varied considerably between sawmills. The mills focusing on main products had lower sales variation (0.17) than mills focusing on by-products (0.40). The quotients of supply variability (ω) were highest for mills focusing on main products and lower for mills focusing on by-products.

Generally, buffer volumes were higher for the main products than by-products (Figure 4). On average buffer level in the supply chain for main products accounted 46 days compared to 22 days level for by-products. For the mills focusing on main products, most of the inventory was accumulated as sawn wood (31 day). For by-products, processed sawn wood roughly constituted half of the total inventory.

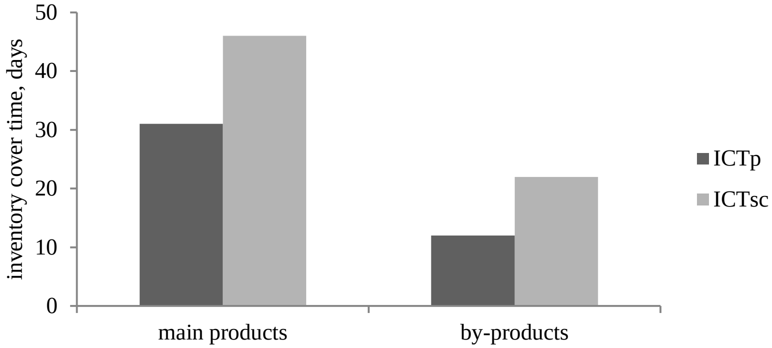

Figure 4. The average inventory cover times (days) for processed sawn wood (ICT_P) as well as for the accumulated cover time for the whole supply chain (ICT_{SC}) for the main products and by-products.

In order to indicate the degree of dynamics (ρ) between upstream and downstream flows, cross correlation coefficients were estimated from the monthly time series. The average correlation between variation in received roundwood and sawn wood sales was slightly higher for mills focusing on main products (ρ=0.60) than mills focusing on by-products (ρ=0.53).

3.3 Paper III: Potential roundwood transport improvements

The case study using the backhaul flow optimization model indicated that the existing distribution of supply and demand nodes in the Lithuanian state forest sector gives a potential to reduce transport costs. The size of the potential savings varied with the assumptions of the analysis.

The proportion of the total volume which could be transported in a backhaul flow varied with the length of the period for which flows were analyzed and the minimum load size. For a minimum 20 m^3 load size, the proportion dropped from 30 % for 4 weeks, 25 % for 2 weeks and 20 % for 1 week. The reduction of backhauls is logical as part of the flows combined in a backhaul in the 4 weeks planning period are now separated in distinct planning period and consequently, cannot be combined in a backhaul. The average savings for the whole flow plan varied from a minimum of 0.9 LTL/m^3 (6 %) to a maximum of 1.8 LTL/m^3 (12 %)[1].

Table 10. *Range of potential savings of transport costs enabled by backhauling in Paper III.*

	Minimum	Maximum
Proportion of flow in backhaul (%)	13	30
Savings per backhaul (LTL/m^3)	2.1	3.1
Average savings (LTL/m^3)	0.9	1.8

Increasing the minimum load size reduced the proportion of volumes possible to backhaul. This case is caused by the fact that due to higher minimum volume in one load some of the roadside stocks are eliminated as being too small for a backhaul. For a 4 week optimization increasing the minimum flow size to 25 and 35 m^3 further reduced the proportion possible to backhaul by 14 and 41 %, respectively. The effects of changing assumptions on potential savings were modeled for combinations of minimum load size, operating hours and driving speeds (Figure 5). The assumption having the greatest effect on potential savings was operating hours. The increase from 480 min (single shift) to 960 min (double shift) resulted in a 13 % increase in the volume possible to backhaul and a 41 % increase in average savings per m^3.

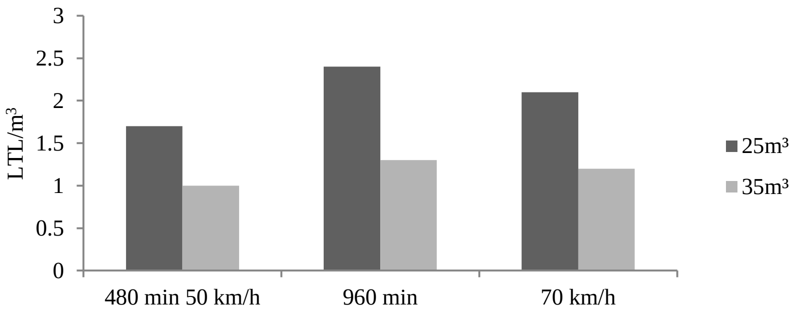

Figure 5. The effect of changing transport assumptions (daily operating time in minutes and driving speed in km/h for different load sizes) on potential average savings due to backhauling in Paper III.

[1] Exchage rate: 1EUR = 3.4528 LTL

3.4 Paper IV: Potential roundwood handling improvements

After calibration of the model with the present sourcing and arrival schedules the full set of four alternatives of sourcing and scheduling alternatives were simulated with present and future volumes. The three outputs of interest were truck queuing, intermediate storage before sorting (loads) and sorter production (m^3/day). The present delivery volumes (21,000 m^3/month) were modeled primarily with one loader. The future delivery volumes (30,000 m^3/month) were modeled with primarily 2 loaders.

With current supply volumes, improved scheduling reduced average truck queue times from 80 to 45 minutes with current sourcing and from 91 to 24 minutes for alternative sourcing (Table 11). Doubling loader capacity was the only solution giving acceptable queue times. For future supply volumes double loader capacity gave acceptable queue times for all alternatives.

With current supply volumes, improved scheduling reduced the queue of unsorted loads from 19 to 12 loads with current sourcing and from 11 to 6 loads for alternative sourcing. All alternatives for future supply volumes resulted in intermediate storage of over 25 unsorted loads. Improved scheduling reduced the queue of unsorted loads from 164 to 141 for current sourcing and from 72 to 31 for alternative sourcing.

Table 11. *Queues and capacity utilization for sourcing and scheduling alternatives while modeling present (21,000 m^3/month with 1 loader) and future volumes (30,000 m^3/month with 2 loaders) in Paper IV.*

Delivery volumes	21,000 m^3/month					30,000 m^3/month				
	21A1		21A2	21B1	21B2	30A1		30A2	30B1	30B2
No. loaders	1	2	1	1	1	1	2	2	2	2
Avg. truck queue time (min.)	80	3	45	91	24	133	6	3	10	2
Intermediate storage (loads)	19	17	12	11	6	240	164	141	72	31

Sorter productivity for all sourcing and scheduling alternatives are shown in Figure 6. The results demonstrated that scheduling had no positive effect on sorter production with present supply volumes but did offer a slight improvement with future volumes. Alternative sourcing, offered a positive effect for both present and future volumes and was the only acceptable alternative for future supply volumes (901 and 949 m^3/day for alternatives 30B1 and 30B2).

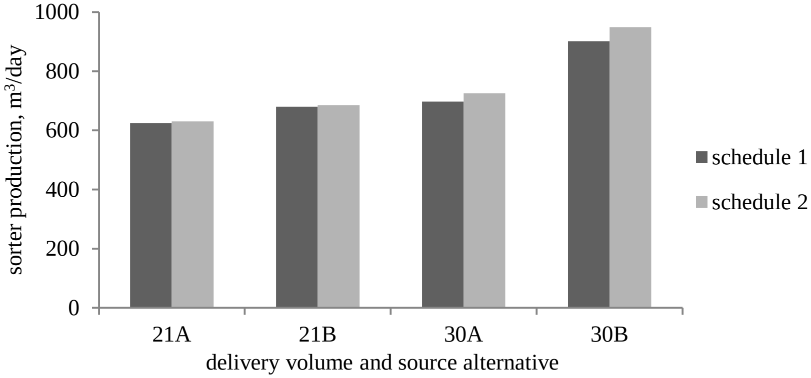

Figure 6. Daily sorter production (m^3/day of approved sawlogs) for sourcing and scheduling alternatives while modeling present (21,000 m^3/month with 1 loader) and future supply volumes (30,000 m^3/month with 2 loaders) in Paper IV.

4 Discussion and conclusions

Many research perspectives have been used to examine the economic performance for individual operations within silviculture, harvesting and transportation, however few studies have been aimed at the wider selection of goals and performance demanded of the whole supply chain.

4.1 Papers I & II – mapping supply operations from forest to mill

Supply chain strategy as defined by UPS (2005), *how the supply chain should operate in order to compete*, is a simple but useful concept when examining the goals and performance of wood supply. According to the framework of supply chain terminology introduced in Table 1, SCS is the end result of many specific supply management strategies (particular ways of doing things) which are nested within the supply strategy (series of plans based on a segmentation of decisions on strategic, tactical and operational levels). In relation to this framework, forest operations management represent many of the specific supply management strategies supporting an overall supply strategy. Simple metrics should be able to evaluate the degree to which forest operations management support the goals expressed in the supply chain strategy.

The main results of Paper I consist of a selection of simple metrics. The results for annual supply fulfillment were surprisingly low in both cases (17.8 and 21.9 % for the efficient and flexible enterprises). A comparison of lead times showed that the biggest difference was observed in relation to product's value. The enterprise with efficient approach showed a low variation between assortments (from 38 to 52 days) while the enterprise with a flexible approach clearly prioritized high value products (19 days), leaving low value assortments longer in the forest (67 days).

The study sample for Paper I consisted of two typical state forest enterprises situated in the same region and with similar distance to key customers. The sample cases represent about five percent of the total number of such enterprises. Seen from the current day perspective a larger study sample (at least two enterprises per SCS) would be necessary to generalize typical metrics per enterprise type. The metrics chosen (delivery precision and lead times) were meant to be indicators of reliability and flexibility. There were however, some limitations regarding the way they were measured in this study. The analysis of monthly delivery precision, for example, was limited by the data collection methods. The monthly distribution of volumes within annual supply agreements are typically adjusted and confirmed as time progresses. In this study information on monthly adjustments and confirmed orders were not available and delivery precision has therefore been calculated in relation to the initial monthly prognosis. In the case of the flexible enterprise, the lack of any indication of quarterly variations makes the monthly prognosis particularly imprecise. In addition, follow-ups of delivery precision are normally applied per assortment, whereas Paper I applies these on the total volume per customer.

The use of the term lead time in Paper I is also simplified. Lead time in this study includes only the time for the wood to pass through harvesting and transport to the mill. Lead time is typically defined as the time from ordering until the time when the goods are delivered. In theory it refers to the decoupling point concept described by Wikner and Rudberg (2005) as ‘’the point in the flow of goods where forecast-driven production and customer order - driven production are separated’’. In wood supply, where the main variable is the rate of wood flow and not a single order of a specific volume, the term lead time can then be redefined as the time from when the customer orders an adjustment in flow and to the time when the customer experiences the effect of the adjustment. Seen in this light, the study´s definition of lead time does not capture the time required for customer’s information to penetrate the supplier´s organization and influence harvesting or transport activities. In addition, the lead time defined in this study includes time for both harvesting and transport. A direct communication from the receiving mill to the forest operations managers could enable an quicker flow adjustment by re-directing transport directly from road-side stocks, resulting in a shorter lead time than indicated in this study.

Paper II examined the coordination of wood supply to sawmill processing and sales. By quantifying monthly variations it enabled a baseline for the actual level of variation which can be expected by sawmills in both up- and downstream flows. The supply variability quotient (ω) for mills focusing on main products demonstrated twice the monthly variation in roundwood supply when compared to sawnwood sales. The 46 day inventory cover time (roundwood and sawn wood together) for these mills provides some insight as to how the supply variability is handled, however most (68 %) of the total inventory was accumulated as sawnwood products. The cross-correlation coefficient (ρ=0.60) quantified the degree of dynamics between received roundwood and sawnwood sales and is an indication of a correspondence between sawn wood sales driving the need for replenishment from wood supply.

The study sample for Paper II is considered to be representative as it examined 5 state owned sawmills out of 20. It would have been desirable to have data on inventory levels at roadside as well. This was not available for this study but would enable a broader scope of echelons and would fill the gap in understanding the adjustment of flows from harvesting versus transport. The choice of metrics in Paper II gives a basis for insight into wood supply system dynamics. In order to compare flows between products before and after processing some measure of relative variation is necessary. The definition of the supply variability quotient based on Fransoo & Wouters (2000) has functioned well for this purpose. The degree of correspondence between variations in up- and downstream flows as indicated by the cross-correlation coefficients appears to have demonstrated some differences between different situations. The lack of similar measures from other studies, however, makes interpretation vague. Future development of better measures and methods should improve interpretation possibilities.

A number of studies have quantified related metrics for other wood supply situations (Table 12). Audy et al. (2012b) quantified lead times for 6 case studies in North America, South America and Europe. Lead times from forest to mill varied between 57 and 67 days where 54 days were associated with harvesting and 5 days with transport. Carlsson and Rönnqvist (2005) documented a reduction of lead times for pulpwood in Sweden from 79 to 50 days. Haartveit et al. (2004) documented variation in lead times from forest to sawmill in Canada between 210 and 36 days where the longest lead times were associated with coastal sawmills supplied via maritime transport while the shortest lead times were associated with interior mills supplied via road transport.

Table 12. *Comparison of lead times (days) and inventory levels (inventory cover times in days) from Paper II with other case studies.*

Case study	**Lead times (days)**		**Inventory levels (days)**			
	Harvesting	Transport	Supply	Mill/ Roundwood	Mill/ Sawn wood	Reference
CAN	210		100	60	35	Haartveit et al. (2004)
CAN	36		14	71	15	
LIT	45		n/a	14	31	Puodžiūnas & Fjeld (2003)
LIT	42		n/a	10	12	
PL	51	4.5				Audy et al. (2012b)
SWE	52.5	4.5				
CAN	52.5	4.5				
FRA	62	4.5				

Haartveit et al. (2004) also documented inventory levels (in terms of inventory cover times) along the supply chain from the forest to mill. Roundwood inventories at the mills varied from 60-71 days which was considerably more than the 10-14 days in Paper II. On the other hand, sawn wood inventories at the mill varied from 15-35 days which was similar to the results (12-31 days) in Paper II.

Inventories may be classified according to both location and purpose but their main function is to allow the different parts to operate at full capacity without disturbance from upstream or downstream flows. Short lead times typically enable lower inventory levels. Following this logic an interesting statistic which can be calculated from Table 12 is the ratio between the mill roundwood stocks and the lead time for harvesting and transport. In the Canadian cases this ratio varies from 1.9 to 0.3 and in the Lithuanian cases from 0.31 to 0.24. This can be compared to figures for Swedish and Finnish mills where typical values for mill roundwood stocks are 1-2 weeks and lead times 4 weeks, yielding a corresponding ratio of 0.25-0.5. At least in theory, a low ratio should indicate a reliable wood supply. The results from Paper II regarding monthly delivery precision indicate higher reliability for the efficient enterprise than the flexible enterprise. The results for annual supply fulfillment, however, indicated a weak commitment between suppliers and customers. However, the low order fulfillment rate might just be a result of the supply contract formats and their lack of any control mechanism or incentive system for fulfillment. While the actual deliveries for the studied enterprises were not closely linked to initial prognosis, the analysis of lead times demonstrated that the flexible enterprise had higher product-specific responsiveness. The focus on certain assortments demonstrates the enterprise’s willingness to utilize their raw material resources in possibly optimal ways whereas short lead times for key assortments indicates the ability to achieve this goal.

A number of authors have examined flexibility for manufacturing industries (e.g. Mandelbaum 1978). However, the agility framework developed specifically for wood supply by Audy et al. (2012b), is a step towards identifying ‘’how the supply chain processes shall be structured and coordinated in order to achieve business objectives’’. Ideally, future studies should both map specific configurations of supply chain processes and their supporting metrics and customer service indexes. In the discussion of flexibility Lundmark’s (1977) differentiation between operational, tactical and strategic flexibility may also be of use. Depending on if disturbances in the supply system are random, seasonal or permanent, different types of flexibility are required. Given the relatively low number of assortments in wood supply and focus on flow rates per assortment a simple measure of volume flexibility according to Lundmark’s segmentation could give a good base for metrics relevant to the operational and tactical issues in wood supply. Ideally, tactical and operational flexibility metrics could also be related to different typologies for tactical and operational agility. This, again, requires further development of typologies specifically for wood supply and its diverging product identities.

4.2 Papers III & IV - improving coordination of transport from forest to mill

Paper III showed that the geographical distribution of forest resources and mills presented a potential for reducing roundwood transport costs by truck. Up to 30 % of volumes for the studied period could be theoretically included in a backhaul flow with a potential 6-11 % reduction of transport costs. Reducing the planning period or increasing the minimum flow required for a backhaul reduced the number of relevant supply/demand nodes resulting in a lower proportion of possible backhauls. The study covered 13 state forest enterprises and a total delivered volume for the studied period of 15,000 m^3. This constitutes 5 % of the total monthly volumes delivered by state forest enterprises and is considered to be a representative sample.

The optimization model used identified and analyzed potential backhaul flows based on historical wood flows. The original tactical model described in Carlsson and Rönnqvist (1998) can also be used to determine each mill’s optimal catchment area, within the supply and demand restrictions, without backhauling. The model then generates potential backhauls which are added to the master flow optimization problem. Paper III, however, was based on the historical non-optimized flows and the effect of backhauling alone was examined. Studies on wood transport planning issues in Sweden by Carlsson and Rönnqvist (1998) showed potential savings from 0.4 to 3.0 % for flow optimization alone (without backhauling) and from 5 to 7 % for flow optimization with backhauling (Table 13). To compare, Puodžiūnas (1998) indicated that the potential costs savings for better flow planning alone (without backhauling) can reach up to 3.0 % for Lithuanian conditions. While the savings potential for better wood flow planning is similar to the Swedish cases, the potential savings for backhauling flows is different. Carlsson and Rönnqvist's estimate of potential for an optimal wood flow including backhauling was 5-7 % where the additional effect of backhauling alone varies from 3-5 %. This is approximately half of the potential calculated for backhauling alone in the Lithuanian case.

Table 13. *Comparison of potential transport costs savings for optimized wood flow taking in consideration backhauls from Paper III with other case studies.*

Case study	Wood flow (%)	Backhauls (%)	References
LIT	3	6-11	Puodžiūnas (1998; 2004)
SWE	0.4 – 2.9	5.1-6.8[2]	Carlsson and Rönnqvist (1998)

The geographical distribution of forest resources and mills in Lithuania has some unusual features which may help explain the high savings potential calculated for backhauling. There is only one harbor in the western part of the country and the main share of pulpwood has been exported through it. In fact, approximately one-third of the total annual harvest has been delivered to a relatively small area, resulting in a large one-way flow to balance against the many sawlog flows to the more geographically dispersed sawmills.

The realization of backhaul potential at an operational level requires opposing wood flows between cooperating transport organizations. Practical routines for this type of collaboration were mapped by Carlsson et al. (2006) and a formalized collaboration framework is shown in Audy et al. (2010). Auselius (2010) in an empirical study showed that the single most important factor for the realization of backhaul potential was the size of the available roadside stocks. This is one of many operational restrictions (or opportunities) that are not taken into consideration at the tactical level and the results of Paper III overestimate potential savings as they do not include all operational restrictions arising in real life situations.

[2] Optimized wood flow + backhauling

Much work remains concerning how to develop and implement a common transport planning system. A good example of such an implementation could be the Åkarweb planning system evaluated by Frisk (2003) and Eriksson & Rönnqvist (2003). A similar configuration adopting aspects noted by Carlsson et al. (2006), Auselius (2010) and Audy et al. (2010) would be worth investigating. Implementing such a solution through a coordinating unit of the state forest enterprises transportation system could enable both improved wood flows and transportation efficiency. Investigating the possibilities to establish such a coordinating unit would be a suitable topic for further studies. The transition towards bigger mills in the future will result in larger supply areas with increased transport work and a greater pressure to reduce costs. Currently EU requirements on vehicles weight, continuously increasing fuel prices, salaries and shortage of labor further motivate a focus on improved transport planning.

Paper IV aimed to estimate the potential effect of improved delivery scheduling between suppliers/haulers and the larger sawmills. The sourcing scenarios demonstrated a potential to increase productivity in the bottleneck operation (sorting) to levels which are acceptable for the planned production volumes (Figure 6). An acute problem for the particular mill at the time of the study was truck queuing. The mapping of initial arrival schedules (2/24/56/17 % arrivals per 6 hr period) indicated that most of the wood arrived during the 3rd time interval (1200-1800). Such patterns are typical for a routine of morning pick-up and afternoon delivery. The modeled average truck queuing time for initial delivery conditions was 80 min (Table 11) and improved scheduling (25/25/25/25 % arrivals per 6 hr period) reduced this queuing time by 44 %.

In practice, application of scheduled arrivals will meet many limitations and obstacles. First of all, for Lithuanian conditions there is usually only one driver operating a truck and thus work and rest regime regulations will put limitations on capacity utilization of the truck and complicate an optimized scheduling of deliveries. The second issue is that the opening hours of state forest enterprises are usually limited to one shift per day. Different operational restrictions (seasonal capacity restrictions, breakdowns and etc.) during transport operations also represent challenges to meeting tighter delivery schedules. Finally, it should be noted that paper IV represents a departure from the state forest enterprise context of papers I, II and III. The case study is based on the biggest private sawmill in the country consuming 15% of the national coniferous sawlog supply. The monthly roundwood consumption for this mill is therefore larger than the annual roundwood consumption for the state sawmills studies in Paper II.

Delivery scheduling of wood arrivals is classified as an operational problem and it is usually solved within the restrictions already set for sourcing and flow planning. The use of discrete-event simulation in this case also provided the possibility to simulate arrivals from different sources via different transport methods. The chosen method was an easily applied method to handle queuing of both trucks and loads in order to understand their interaction and combined effect on the indicated bottleneck at the mill. During the validation of the model it was noted that the simulated sorter production was higher than recorded production at the time. The animation which is standard in most object-oriented discrete-event gave the opportunity to discover errors in logic and system behavior but this stage of the work gave no explanations for the deviation. The month chosen for data collection excluded the lowest and highest periods of the year in terms of roundwood supply. The data collection period could have been extended (e.g. one quarter) and this would have given more representative figures. The deviation between modeled and actual production, should be linked to the modeling of sorting production as a function of source-specific load characteristics since the effect of scheduling was minimal (Figure 6). During the modeling an average log size per load instead of actual log size distributions per load was used and this is the most probable cause for the deviation.

The average truck queuing time (80 min) for the initial sourcing and scheduling scenarios constituted 17 % of total truck working time per day. This initial level corresponds well to the problems experienced in practice which initiated the study. A similar study by Väätäinen et al. (2005) for biofuel deliveries demonstrated a reduction of average queue times from approximately 20 minutes down to 5-10 minutes. This is represents a reduction of over 50 % which corresponds well to the results of Paper IV. The 44 % reduction in Paper IV, however, is based on a perfectly even inflow of wood per 6 hour period and this is optimistic given that most trucks are driven a maximum of two shifts. This limitation was also noted by Väätäinen et al. (2005). The total truck queuing time for roundwood transport under Lithuanian conditions, however, is expected to be even higher than in the experimental simulation because additional queue times which occur during loading operations in the forest have not been included in the model.

The possibility of improving delivery schedules is also dependent on the transport systems being used. Truck deliveries from sources within short distances are often subject to fewer constraints and can be more flexible in their scheduling. Supplementary rail deliveries from remote sources, however, are subject to numerous constraints and have limited possibilities for adjustment. In Paper IV, the effects of import sourcing are associated with rail deliveries. Helstad's (2006) study on managing supply uncertainties in sawlog procurement showed that most purchasing sawmills are dependent on multiple suppliers and their supply structure typically includes a number of stable sources as well as supplemental import volumes. In general, it can be said that imports from sources with economies in transition have often been characterized by lower reliability. Under such conditions, the ability to re-schedule deliveries from closer sources is important for counteracting delivery disturbances from import sources.

Currently, mills are putting more focus on delivery scheduling and a number of solutions now exist in practice. Increasing the resolution of coordination between suppliers/haulers to a daily basis requires booking of time slots during a day. This type of development assumes a weekly plan to build upon. Another OR-based solution is shown by Weintraub (1996) which has been applied in the Chilean forest sector. The importance of developing such solutions can be expected to increase as the sector structure progresses to larger mills relying on a higher and more even capacity utilization. In conclusion it can be noted that the success of improved transport coordination in Papers III and IV is mainly dependent on SC actors willingness to co-operate. Audy's et al. (2010) framework for logistics collaboration could provide a theoretical basis for further developing solutions when sharing resources, information, risks and benefits.

4.3 Concluding comments

The mapping in Papers I and II gave some primary results on how the SC performs in Lithuanian state forest enterprises. The metrics collected included lead times and delivery precision and the variability of supply versus demand. The results showed that wood supply flows varied twice as much as sawn wood sales. The initial supply variability was evened-out by high stocks levels at the mill which were mostly accumulated as a stock of sawn wood. The degree of dynamics which was quantified from monthly time series data indicated that sawnwood sales drives replenishment from wood supply. This conclusion, however, appears as a paradox given the fact that the cover time for roundwood stocks at the mills (15 days for main products) only covers one-third of the measured lead times (46 days for both harvesting and transport). This indicates that replenishment in practice is done from road-side stocks.

The analysis in Papers III and IV found potential improvements in transport coordination to Lithuanian sawmills. Wood flows can be efficiently planned using a number of already available tools for optimizing wood flow per delivery period. The tool used in this thesis, however, was limited to improving backhauling giving a theoretical cost savings potential from 6 to 11 %. Considering possible operational limitations in real-life perhaps half of this potential could be achieved in practice. The simulation of roundwood scheduling to a larger sawmill enabled the quantification of effects of both improved sourcing (i.e. choice of suppliers) and scheduling with increasing sorter productivity and reduced truck queuing. It should be noted, however, that tighter scheduling of mill deliveries further restrict transport planning and the possibility to realize backhaul potential. Solving these issues simultaneously yield a number of potential development efforts at strategic, tactical and operational levels.

Considering the results of Papers I-IV it can be stated that potential improvements between the forest and mills are considerable. Improved coordination of wood supply and demand is fundamental for reaching the desired supply chain strategy. This, linked with operational excellence, can increase competitiveness not only for the for the forest company but also for its partners and customers.

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