Aalto University
School of Science
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A Large-Scale Optimization Model for Tactical Wood Procurement Planning

Master's Thesis
Espoo, May 23, 2016

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ABSTRACT OF MASTER'S THESIS

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Large-scale wood sourcing requires complex planning processes that are often supported by optimization models. This thesis focuses on tactical wood sourcing at a large Finnish forest industry company. The company is building a new planning system in order to improve upon the current process that involves a less detailed model and requires large amounts of manual work to produce plans that can be implemented. The target of the new planning system is to improve decision making by providing a more accurate planning system and reducing manual efforts.

In this thesis, the wood procurement problem is formulated as a large linear programming model. The model is a multi-commodity flow problem with varying harvesting yields, multiple transportation modes, storage management, by-product generation and end-product substitution. This formulation is then solved with a commercial optimization solver resulting in a running time of some tens of minutes. Different results under varying input scenarios are presented and elaborated to demonstrate the model's ability to capture the essentials of the complex problem. The model's suitability for both continuous planning and what-if scenario work is also discussed.

Solving ill-structured real life problems using mathematical modeling techniques is difficult for two reasons in particular: i) the actual modeling work can be technically and process-wise a major challenge in a real business environment, and ii) the computational complexity borne of the business environment's features may involve severe challenges in solving such models and implementing useful decision support systems. This thesis presents a case where both difficulties were present and somewhat successfully overcome.

Keywords: Wood sourcing, supply chain management, decision support systems, tactical planning, linear programming

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Laajamittainen puunhankinta edellyttää monivaiheista suunnitteluprosessia, jota yleensä tuetaan optimointimalleilla. Tämä työ keskittyy erään suuren suomalaisen metsäteollisuuskonsernin puunhankintaan. Yhtiö kehittää parhaillaan uutta suunnittelujärjestelmää, jonka on tarkoitus parantaa nykyistä suunnitteluprosessia, jossa käytetään karkeampaa optimointimallia, ja joka vaatii suuren määrän käsityötä käytännöllisen hankintasuunnitelman tuottamiseksi. Hankkeen tarkoituksena on parantaa päätöksentekoa tuottamalla entistä tarkempi suunnittelujärjestelmä, joka samalla vähentää käsityön tarvetta.

Tässä työssä puunhankintaongelma on esitetty suurena lineaarisena optimointitehtävänä. Kehitetty malli on monen hyödykkeen virtausongelma, joka sisältää vaihtelevia hakkuiden lankeamia, useampia kuljetusmuotoja, varastonhallintaa, sivutuotteiden syntymistä ja kysynnän substituutteja. Tämä tehtävän ratkaisu kaupallisella ratkaisijalla kestää joitain kymmeniä minuutteja. Työssä käsitellään eri skenaarioiden tuottamia ratkaisuja ja esitellään mallin kykyä huomioida monimutkaisen ongelman avaintekijöitä. Työssä käsitellään myös mallin sopivuutta jatkuvaan suunnitteluun ja skenaariopohjaiseen analyysiin.

Erityisesti kaksi tekijää vaikeuttavat matemaattisen mallintamisen soveltamista käytännön ongelmiin: i) mallinnustyö voi olla teknisesti ja prosessin kannalta haasteellista liiketoiminnan käytännöissä, ja ii) toimintaympäristön ominaisuuksista aiheutuva laskennallinen monimutkaisuus voi tuottaa haasteita mallin ratkaisemisessa ja sen tulosten hyödyntämisessä. Tämä työ käsittelee tapausta, joissa kumpikin haaste ilmeni, ja joista kumpikin saatiin ainakin osittain ratkaistua.

Asiasanat:	Puunhankinta, toimitusketjun hallinta, päätöksenteon tukijärjestelmät, taktinen suunnittelu, lineaarinen optimointi
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Lastly, I would like to thank my family and friends for their continuing support and motivation. There is no doubt that my coming this far is in great deal thanks to you. I feel that I've learned equally as much outside of a class room than in one.

Helsinki, May 23, 2016

Eero Lehtonen

Abbreviations

AMPL	A Mathematical Programming Language
AP	Advanced Planning
ATP	Available-to-Promise
BA	Business Analytics
BU	Business Unit
CTP	Capable-to-Promise
DSS	Decision Support System
EIP	Executive Information System
ERP	Enterprise Resource Planning
FFIF	Finnish Forest Industries Federation
FFRI	Finnish Forest Research Institute
FSC	Forest Stewardship Council
GDSS	Group Decision Support System
PEFC	Programme for the Endorsement of Forest Certification
LP	Linear Programming
MILP	Mixed Integer Linear Programming
OLAP	On-Line Analytical Processing
OR	Operations Research
SCM	Supply Chain Management
VCM	Value Chain Management

Contents

Chapter 1

Introduction

The Finnish forest industry is undergoing a major transformation. According to the Finnish Forest Research Institute (FFRI 2013), paper production, historically a major part of the Finnish economy, is under pressure due to decreasing demand in Europe and North America. Asian paper production and consumption are seeing growth that supports pulp production in forested geographies. On the other hand, domestically more interest has been directed toward bio-economy, and the traditional forestry production portfolio is being expanded with new products such as biodiesel and advanced materials. As a part of the transformation, the Finnish industry is planning significant investments that are estimated to increase industrial wood consumption by approximately 10 million m^3 from the current figure of approximately 60 million m^3, putting pressure on wood sourcing activities (FFIF 2014). In the long term, FFRI also highlights efficiency as an increasingly important consideration, since growth opportunities are found in increasing value added per unit instead of increasing volume. Overall requirements in efficiency, sustainability and profitability put pressure on improving supply chain management in the industry.

Supply chain management in forestry and the paper and pulp industry has been studied extensively in the literature, and Operations Research (OR) among other disciplines has supported forestry organizations in planning activities (Bredström et al. 2004; Carlsson et al. 2009; Carlsson and Rönnqvist 2005; D'Amours, Rönnqvist, and Weintraub 2008). Recent efforts in OR have yielded methods that attempt to address not only the industry perspective but also the interests of other stakeholders, mainly concentrating on wildlife conservation and environmental concerns (Rönnqvist et al. 2015). OR has supported both the forest products industry as well as the public forestry organizations, with applications ranging from strategic long-term problems to operational short-term problems (D'Amours, Rönnqvist, and Weintraub 2008).

Of the numerous OR applications in forestry, this thesis focuses on wood sourcing by discussing the integration of all tactical planning decisions in a Finnish forest industry company's sourcing planning process - harvesting, bucking, transportation, storage and wood trades. This partially addresses a concern articulated by Rönnqvist et al. (2015), who suggest further integrating forest supply chain planning models across the value chain in order to accommodate demand-driven customer relationships.

In the literature, Fleischmann, Meyr, and Wagner (2005) introduce the Supply Chain Matrix and D'Amours, Rönnqvist, and Weintraub (2008) adapt it to the forest industry. Their framework serves as a basis for the approach in this thesis. Kong, Rönnqvist, and Frisk (2012) present a similar mid-term model considering the integration of the forest and bioenergy supply chains and simulate the behavior of the Swedish wood sourcing market. The model presented in this thesis bears similarities to the one the authors presented, while it also accounts for relevant characteristics of the Finnish environment and takes the standpoint of a single major party on the market. Little published research of tactical wood sourcing in the Finnish industry is found.

The case company UPM-Kymmene is one of the largest forest industry companies both in Finland and globally, with an annual turnover of approximately EUR 10 billion. UPM is strongly vertically integrated, with forestry related operations in pulp, timber, plywood, biofuels, paper, self-adhesives and forest energy. In 2015, UPM's wood sourcing totaled 17.7 million m^3, making it one of the country's largest wood consumers. (FFIF 2015; UPM-Kymmene Oyj 2016) The tactical planning problem described in this thesis is scoped according to the operations of UPM's wood sourcing unit and therefore differs from similar use-cases in other forestry companies.

1.1 Research Objectives

This thesis aims to improve the case company's wood sourcing process by developing an optimization model for its tactical planning process. The model is an essential part of a planning system that supports harvesting, trade, imports, storage and transportation decisions. The planning system is set to improve upon an existing model and associated manual processing required to translate its output to operational plans. These refinement and automation measures are expected to both reduce time spent on preprocessing data as well as improve decision making.

The model does not support strategic decisions such as site selection or road construction, or production, distribution and sales decisions further on in the supply chain. Thus, transportation options, available harvesting sites and internal demand are assumed to be given. The model provides essentially a cost-minimizing plan that satisfies wood demand from a set of mills. The model is targeted to fit domestic demand and, as such, it only accounts for sources and constraints relevant to the Finnish market and demand. In providing tactical decision support, the planning is done on a rolling monthly basis for the next 12 to 18 months. The time steps are connected via storage levels in addition to other constraints, and hence the plan needs to be computed simultaneously for the whole period instead of planning for each month separately.

The optimal plan needs to be robust: the end-user for the model needs to evaluate procurement plans with different assumptions and forecasts as inputs to the model, and the model yields feasible and appropriate solutions even though there might be mismatches between supply and demand. Thus, many constraints in the model are soft. For instance, unsatisfied demand or excess supply is penalized instead of having hard constraints for supply-demand balance. Furthermore, the model exhibits limited sensitivity to its inputs so that minor alterations to its inputs do not excessively alter the computed plan, reducing changes to operational planning upon minor changes in input data.

Finally, in order to provide meaningful decision support, the model accommodates ad-hoc analyses of the produced sourcing plans by being solvable in minutes. The model also behaves predictably, so that changes in constraint or variable cardinalities do not disproportionately affect the solution time.

Due to the problem's size, it is formulated as a linear programming (LP) model which excludes features that require integer variables, such as fixed costs related to selecting routes. The linearity requirement also excludes the possibility of using concave unit cost functions (i.e., costs subject to economies of scale), while still allowing for the more relevant convex unit cost functions representing for instance price elasticity of supply.

1.2 Thesis Structure

The rest of this work is structured as follows. Chapter 2 details the business problem in the context of wood sourcing in Finland as well in the case company. Chapter 3 discusses the relevant literature on decision support systems, advanced planning and their relevance to wood sourcing in particular. The LP model is described in Chapter 4 with additional detail on complexity reduction. Indicative results are presented and discussed in Chapter 5, and finally conclusions are presented in Chapter 6.

Chapter 2

Business Environment of the Case Company

The business environment for planning activities differs between countries and organizations, making it necessary to adapt planning activities accordingly. In this section the overall Finnish forest industry and wood procurement environment are described in terms of organization, ownership, regulation and trading. Subsequently the case company perspective is characterized in terms of its internal organization and supply chain structure.

2.1 Forest Industry and Wood Procurement in Finland

Rönnqvist et al. (2015) point out the importance of the forest industry in countries such as Canada, Chile, Finland, New Zealand and Sweden. For instance, Epstein et al. (1999) credit the Chilean forest industry as one of the drivers of the country's economic development during its transition to democracy. In Finland, the forest industry has also traditionally played an important role in the economy: Figure 2.1 shows the forest industry consistently accounting for approximately 20% of all national exports throughout 2004-2014. According to the FFRI (2014), approximately 75 million cubic meters of wood was harvested in 2013 and the forest industry consumed approximately 65 million cubic meters of wood, generating EUR 25.7 billion of turnover. The nationwide value-add from the forest industry was estimated at EUR 6.2 billion, or 3.6% of the total GDP.

Figure 2.1: Value of forest industry exports and their share of total Finnish exports (Source: FFIF)

While the forest industry as a whole continues to have a sizable impact on the economy, the industry itself has undergone a large transformation from paper driven to pulp driven. Furthermore the industry is believed to shift further away from paper manufacturing and toward advanced wood products such as biofuels and biocomposites (FFRI 2013). To demonstrate the shift from paper to pulp, Figure 2.2 shows the quarterly production of various forest industry sectors between 2006-2015, where the production as a whole decreased significantly from 2008 to 2009 and slightly recovered afterwards. There are however significant differences between the sectors' production development, with pulp production recovering to approximately 92% of Q1 2006 levels for Q4 2015, whereas paper and carton production in Q4 2015 amounted to only around 73% of the corresponding Q1 2006 figure.

Assessing the industry globally, Rönnqvist et al. (2015) note differences among countries with significant forest industry in practice, organization and ownership of companies as well as government regulations and vertical integration of the supply chain. In Finland, the industry is dominated by three large, integrated corporations - Stora Enso, UPM-Kymmene and Metsä Group, all borne of a number of M&A transactions. The first two are publicly traded, with the government acting as a minority shareholder in the former, while Metsä Group is owned by a cooperation of private forest owners. To demonstrate the three corporations' dominance, Figure 2.3 shows the use of industrial wood in Finland in 2014, where the three companies account

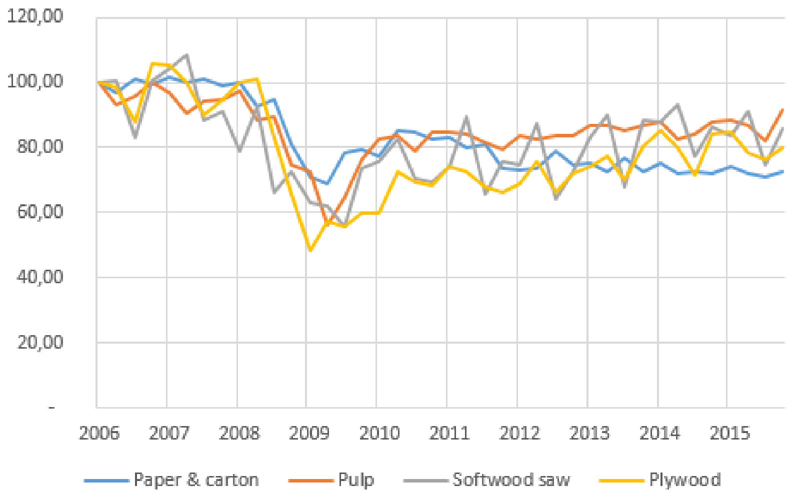


Figure 2.2: Quarterly production of various forest industry sectors between 2006-2015, percentage of Q1 2006 production levels (Source: FFIF)

for over three quarters of all domestic wood use. Furthermore, the FFIF list Stora Enso and UPM-Kymmene as the fifth and seventh largest forest industry companies worldwide, further demonstrating the consolidation of the Finnish industry (see Figure 2.4).

In terms of regulation, Finnish forests are subject mainly to the Forest Act of 2014 and the Nature Conservation Act of 1996. The aim of the Forest Act is to promote the economic, social and environmental aspects of forestry, with the latest changes to the law focusing on the competitiveness of the forest industry and the freedom of choice of forest owners by reducing regulation (Ministry of Agriculture and Forestry 2013). The Nature Conservation Act in turn aims to maintain biological diversity, conserve the beauty and scenic value of nature and promote the sustainable use of natural resources and environment, among others (Ministry of the Environment 1996).

In addition to legislation, forest owners may additionally opt to certify their forests, which introduces additional regulation and in turn allows for classifying wood harvested from the forest as certified wood. The need for certification is driven by demand for certified end products. Hence the certification of wood needs to be tracked throughout the supply chain. Of the two major global certifications, the FSC[1] certification is endorsed by environ-

[1]Forest Stewardship Council

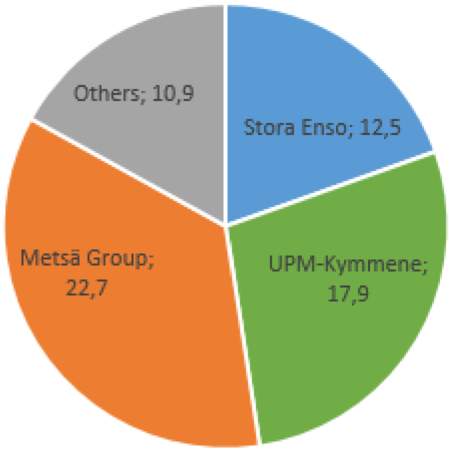


Figure 2.3: Industrial wood use in Finland in 2014, millions of cubic meters (Source: FFIF, companies' annual reports)

mental organizations while the PEFC[2] certification is not. Both certifications operate globally, but their exact regulations are set on a per-country basis.

Another notable characteristic of the Finnish forest industry affecting procurement planning is the geographical distribution of demand. Figure 2.5 shows the distribution of production plants throughout the country. Notably there is clear concentration of production capacity in certain regions, such as around Lappeenranta, Imatra and Kymenlaakso, where a significant amount of the industry is situated. In part, the economies of the industry encourage this: harvesting operations produce varying assortments of wood[3] and setting up plants that can process all the harvested wood locally avoids their relatively expensive transportation to remote plants. Historically a favorable setting of lakes and rivers has also played a role in locating forest industry plants, since they facilitate timber rafting and provide energy to the plants in the form of hydropower. The availability of roundwood also plays a part in locating plants. Due to colder climate, the growth rate of wood decreases toward the northern parts of the country and consequently the number of plants also decreases. In part, the concentration can hence be explained by availability of roundwood.

[2] Programme for the Endorsement of Forest Certification Schemes

[3] In this thesis, the phenomenon where a production activity simultaneously yields several kinds of output is referred to as co-production.

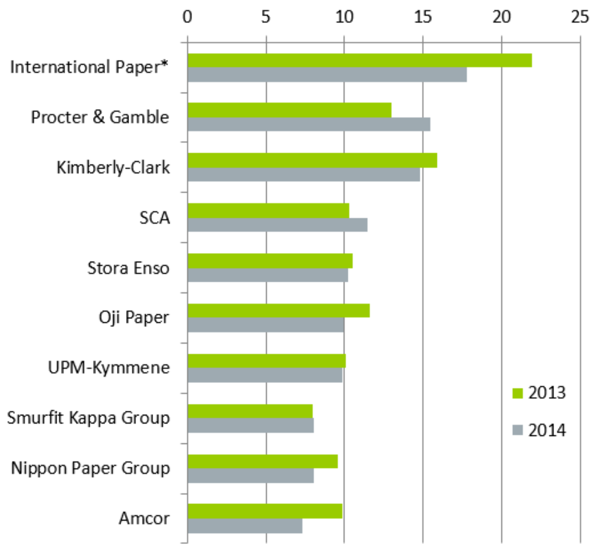


Figure 2.4: Largest forest industry companies globally in turnover, billion EUR

Globally, ownership of forests varies from country to country, with all forests in countries such as Russia and Turkey being owned by the state, while ownership of forests in most countries is split between public and private (Eurostat 2011). The majority of forests in Finland are subject to three kinds of ownership:

Private forests Private forests were originally held by tenant farmers under tenancy agreements. The farmers were allowed to purchase the forests in the 1920s. Private forests are also referred to as family forests.

State-owned forests State-owned forests are overseen by Metsähallitus, an unincorporated state enterprise, and serve both economical as well as environmental and social uses.

Company-owned forests are forests owned by limited companies, including but not limited to the three large corporations.

In addition minor forest areas are owned by entities such as congregations or other small communities. Figure 2.6 shows the distribution of forests between these groups. Notably most of the forests are privately owned and the state owns a significant minority. What is more, privately owned forests contain

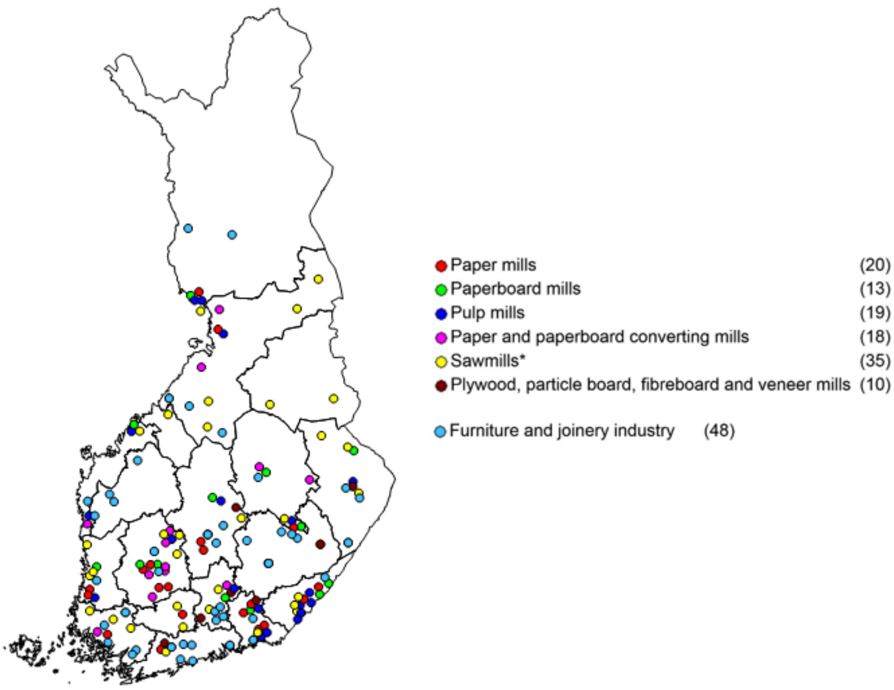


Figure 2.5: Forest industry production plants in Finland (Source: Finnish Forest Industries Federation)

more wood per area, mainly due to state-owned forests lying mostly in the northern part of the country. (FFA 2015; FFRI 2014)

Roundwood is also typically sourced via different methods. The Finnish forestry industry sources wood via a variety of different sources and trade types, namely

Stand Trades Stand trades are trades where a private forest owner sells roundwood from a site before it has been harvested. The buyer is then responsible for arranging for harvesting and transportation of the roundwood from the site. Often the buyer is obliged to harvest the site within two years of its purchase. The price in stand trades is quoted as the *stumpage price*, or the price of the wood excluding harvesting costs.

Roadside purchases roadside purchases are trades where a private forest owner sells harvested roundwood that has been transported to a temporary storage site often on the side of a road (often called roadside

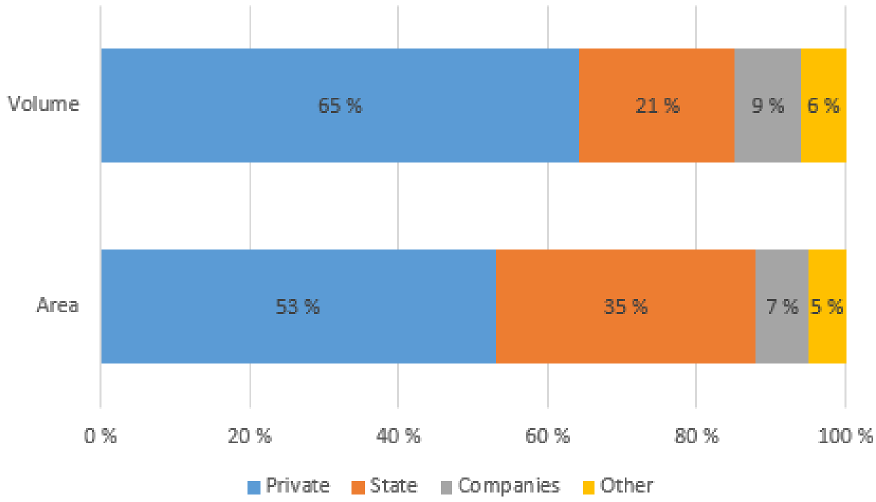


Figure 2.6: Forest ownership in Finland in 2013

storage). The buyer is responsible only for transporting the roundwood from the storage site. The price is in turn quoted as the *roadside purchase price* that includes harvesting costs.

Harvesting of company-owned forests Companies also harvest wood from forests under their ownership. Such harvesting does not incur external costs aside from possibly contracting harvesting services from an external provider.

Harvesting of state-owned forests Metsähallitus governs the harvesting of all state-owned forests. The harvested wood is then sold to mills.

Import A large share of demand is satisfied by imported wood. Most of the wood imported to Finland is sourced from Russia and in smaller amounts from the Baltic countries and Sweden.

Figure 2.7 shows industrial roundwood removals in Finland in 2013, where roughly two thirds of all removals are from stand trades and all private trades including both stand and roadside purchases form over three quarters of all removals. Furthermore, due to the nature of stand trades, their yield is subject to co-production of wood, which significantly affects how forest companies source wood. Few plants consume wood assortments in arbitrary parts and it is therefore necessary for procurers to balance trades to match local demand and avoid expensive transportation costs. It is an established practice to arrange such trades between companies that source wood from stand trades.

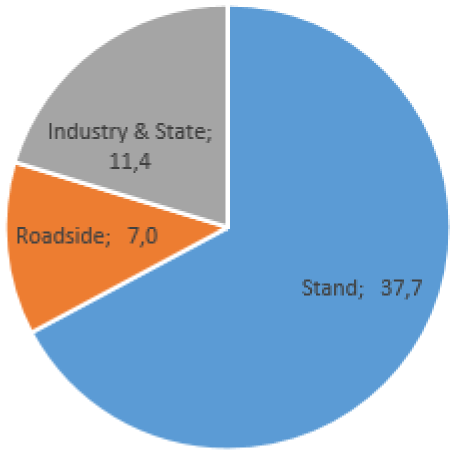


Figure 2.7: Industrial roundwood removals in Finland in 2013, million m^3

Additionally, some wood processing activities yield byproducts that could be used in other processing activities, such as wood chips produced by sawmills and plywood mills that can be used in pulp mills, and therefore also motivate wood trades between companies. On the other hand, roadside purchases and imports offer more flexibility in terms of purchasing specific assortments, thus also serving as means to balance the asymmetry between demand and standing trade supply.

In summary, the forest industry in Finland is characterized by its size, its shift from paper towards pulp and advanced wood products, the dominance of three large corporations, as well as varying modes of ownership and trade. The large-scale transformation of the industry has caused some reduction in production volume, but the industry still forms a significant part of the country's exports in terms of monetary value, and three large corporations continue to form the bulk of the business. The majority forests in Finland are divided between private, state and company ownership, and a purchases of private-owned roundwood are divided into stand trades, roadside purchases, further adding complexity to the operating environment.

2.2 Case Company

As indicated above, UPM-Kymmene is one the largest forest industry companies in both Finland and globally. In 2015 its sales totaled €10.1 billion. The corporation employs approximately 19 600 employees worldwide and is publicly traded on the NASDAQ Helsinki stock exchange. The corporation is divided into six main business areas in addition to some other operations. The main business areas (BAs) are structured as follows.

Biorefining Biorefining consists of the corporation's pulp, timber and biofuels businesses.

Energy Energy operates as an electricity producer in addition to trading on the physical and financial energy markets.

Raflatac Raflatac manufactures self-adhesive label materials.

Paper Asia Paper Asia serves growing markets with labeling materials, fine papers and flexible packaging.

Paper ENA Paper ENA produces magazine papers, newsprint and fine papers for several uses.

Plywood Plywood produces plywood and veneer products mainly for the manufacturing and construction industries.

In addition to the main business areas, the corporation operates a wood sourcing and forestry business unit as well as operations in biocomposites and biochemicals. The wood sourcing and forestry business unit (BU) sources wood for all corporation's business areas that consume wood or wood-based biomass. The BU also considers private forest owners selling wood to the corporation as customers and as such they are provided services related to forest management. In addition to private forest owners, the BU sources wood from state-owned and company-owned forests as well as B2B purchases and imports. Figure 2.8 shows the relative shares of types of sourcing to UPM mills globally in 2015, indicating how various sources are used to fulfill the corporation's roundwood demand. Globally the corporation sourced approximately 26 million m^3 of roundwood in 2015, of which approximately 18 million m^3 were sourced in Finland, forming the bulk of its operations. The planning

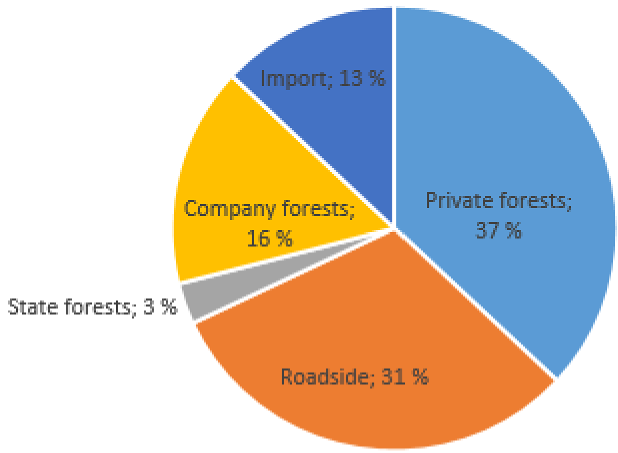


Figure 2.8: Sources of wood to UPM mills in 2015 (Source: UPM Annual Report 2015)

problem presented in this thesis focuses only on sourcing activities supplying the Finnish business.

Overall, the wood sourcing BU is therefore responsible for sourcing annually around 20 million m^3 of various wood assortments for several kinds of consumption. The demand is satisfied via various kinds of sources exhibiting different kinds of trade dynamics, and the demand as well as sources of wood are geographically dispersed. Transportation costs for wood constitute often up to 20% of the mill gate price[4] of cheaper wood assortments, making local consumption preferable to long-distance transportation.

[4]mill gate price is the total unit price incurred on wood from stumpage, harvesting, transportation and overhead items, or in other words all costs incurred in the sourcing BU until the shipment of wood is delivered through the the mill's gate.

Chapter 3

Review of Supply Chain Management in the Forest Industry

This chapter reviews the relevant literature in Supply Chain Management, Decision Support Systems, Advanced Planning and their relevance to case company's wood procurement planning in particular. There exists a comprehensive body of literature overall on Supply Chain Management and several authors have published research on applications in the forest industry and wood sourcing. The planning system presented in this thesis bears resemblance to planning systems discussed in the literature while in addition incorporating features needed to adapt the system to the Finnish business environment.

Supply chain management (SCM) in the forest industry and as a whole has benefited from the development of information systems, and especially planning activities have gained from increased computing capacity for solving larger and larger quantitative models (Carlsson et al. 2009). Decision Support Systems (DSS) are information systems designed to aid in semi-structured managerial problems from systems developed for structured problems, such as in inventory control (Gorry and Scott Morton 1971). In SCM, Advanced Planning Systems (APS) are such support systems that help managers in strategic, tactical and operational planning activities (Fleischmann, Meyr, and Wagner 2005).

3.1 Decision Support Systems

Gorry and Scott Morton (1971), integrating previous study by Anthony (1965) and Simon (1960), define Decision Support Systems as systems that assist businesses make decisions in a "semi-structured" setting, i.e., to make decisions where information is partially structured but to an extent exhibits novel and consequential properties. These decisions and information related to them are thus not completely automatable but rather only benefit partially from structured processing. The authors also argue that most managerial decisions are unstructured or semi-structured and furthermore anticipate further advances in information technology enabling computers to take over more and more of the unstructured domain, freeing up managers to concentrate on other problems.

The parallel development of information systems since the 1970s has contributed to utility of DSS, with Enterprise Resource Management (ERP) systems and the Internet facilitating collection and transmission of data for consumption and collaboration (Shim et al. 2002). For example, modern-day Business Intelligence (BI), having evolved from Data-driven DSS, has seen tremendous interest and growth as CIOs see analytics and business intelligence as a top priority and a source of competitive advantage (Gartner, Inc. 2012; Negash and Gray 2008). Several optimization packages have also developed cloud releases to allow the scaling of computing resources to solve ever larger problems (Gurobi Optimization, Inc. 2015; IBM 2015).

The concept of DSS encompasses a variety of different types of systems. To structure discussion, Power (2004) defines a framework that classifies DSS into five categories along their dominant components:

Data-driven DSS emphasize access to and manipulation of a large database of structured data, such as in management reporting systems, Executive Information Systems (EIS), BI and Online Analytical Processing (OLAP).

Model-driven DSS use accounting and financial models, representational models, and optimization models, emphasizing statistical and analytical tools over data intensity.

Knowledge-driven DSS provide decision support by leveraging "expertise" and "skill" that consist of knowledge of a particular domain and special purpose inference engines.

Document-driven DSS integrate a variety of storage and processing technologies to provide a document-based support. Notably the World Wide Web and search engines indexing its content can be understood as document driven DSS.

Communication-driven DSS utilize communication and collaboration technology to provide Group Decision Support Systems (GDSS) in the form of video-conferencing, online bulletin boards and email among others.

The classes are also described along secondary dimensions according to their targeted users, purpose, deployment and enabling technology. A DSS might target both intra-organizational users as well as inter-organizational groups such as customers and suppliers. The purposes of a DSS may range from function- and task-specific to general-purpose. Traditionally DSS are deployed as spreadsheets or via a client/server LAN, while the Web is highlighted as an emerging enabling technology for all DSS.

This thesis focuses on Model-driven DSS whose purpose is to help managers and staff in scheduling, financial planning and decision analysis. Power and Sharda (2007) give a detailed description of model-driven DSS and related research, further discerning sub-categories among model-driven DSS. Model-driven DSS is characterized by emphasis on quantitative models and use of parameters and data is focused on enabling ad hoc "what if?" sensitivity analysis by the user as opposed to their principal focus in Data-driven DSS. Among Model-driven DSS, the authors discern optimization and mathematical programming models as a separate class that has seen wide adoption in revenue management and supply chain management in particular. The authors also emphasize the need to study both technical and behavioral dimensions of Model-driven DSS in order to encourage their adoption of and acceptance.

More recently the concept of DSS has been studied from the perspective of Business Analytics (BA), emphasizing the capabilities provided by DSS. Model-driven DSS is associated with prescriptive and predictive analytics approaches that support use cases in strategic and operational planning as well as proactive decision making. (Hahn and Packowski 2015; Holsapple, Lee-Post, and Pakath 2014)

3.2 Advanced Planning in Supply Chain Management

While several definitions of Supply Chain Management exist in the literature, this thesis follows Stadtler (2005) in using the definition by Martin (1998) – "Supply Chain Management is the management of upstream and downstream relationships with suppliers and customers in order to deliver superior customer value at less cost to the supply chain as a whole." Stadtler (2005) further argues that the objective of increased competitiveness necessitates close co-operation and communication among the whole chain. Several divergent and convergent[1] flows introduce complexity into the chain and it is therefore common for individual organizations to only focus on an individual part of the chain. Therefore both intra- and inter-organizational communication is emphasized.

In order to illustrate the building blocks of SCM, Stadtler (2005) also introduces the House of SCM, as depicted in Figure 3.1. On the roof, Customer service and Competitiveness form the ultimate goal of SCM. The roof is supported by the two main pillars of Integration and Coordination. Choice of suitable partners, inter-organizational collaboration and leadership are required for successful integration of the supply chain, while use of information and communication technology, process orientation and Advanced Planning (AP) support the coordination of the supply chain.

Since managing the supply chain involves coordinating a large number of individual decisions, it is reasonable to incorporate decision support in SCM. In the literature this is often referred to as Advanced Planning (AP). According to Fleischmann, Meyr, and Wagner (2005), AP supports decision-making and coordination of the supply chain by identifying alternatives of future activities and selecting good ones according to some measure. The complexity of supply chains dictate that planning needs to be abstracted to models that can be analyzed and optimized. Ideally a single model would consider all relevant factors in the chain, but in order to limit complexity of the models and since activities and decisions along the supply chain vary in character and importance, planning is often carried out hierarchically, with

[1] In convergent flows, several input products are assembled to form a single output product, whereas in divergent flows, a single input product is split into several output products (Meyr, Wagner, and Rohde 2005)

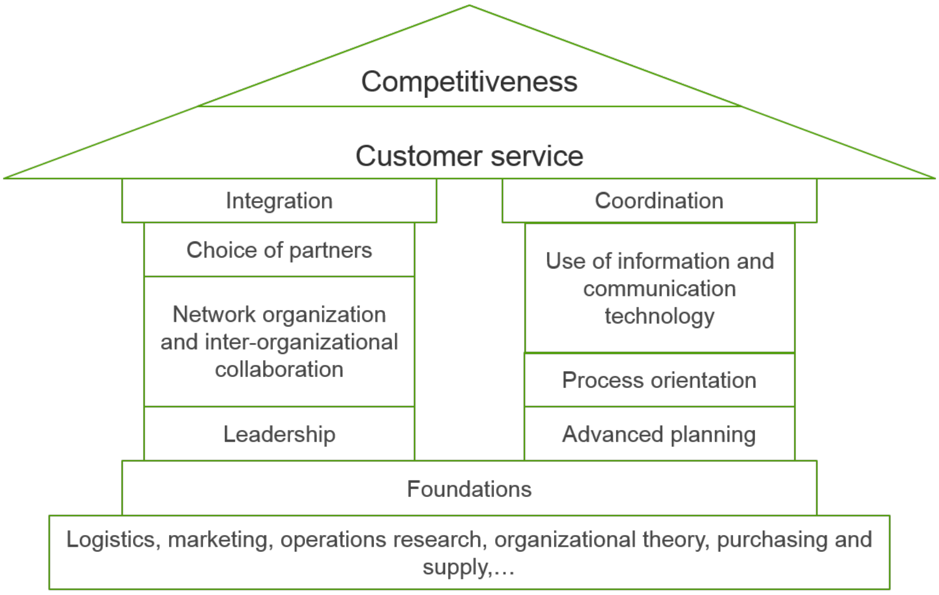


Figure 3.1: House of SCM (Stadtler 2005)

longer term planning setting the scope for shorter term planning. To reflect this, activities in SCM can be divided into a Supply Chain Planning Matrix along two dimensions: ”planning horizon” and ”supply chain process”, as depicted in Figure 3.2. The planning horizon spans from long-term or ”strategic” via mid-term or ”tactical” to short-term or ”operational”, and the supply chain process progresses from procurement via production and distribution to sales. The matrix also lists tasks that are present in typical supply chains.

As described by Stadtler (2005), Advanced Planning is supported by Advanced Planning Systems that are often implemented as separate software modules that are responsible of specific section of the Supply Chain Planning Matrix. Figure 3.3 shows a typical allocation of the matrix among different APS. Strategic Network Planning spans across the whole supply chain and is concerned with locating production sites, warehouses and customer areas as well as their capacities and transportation means between them over several years. Below strategic planning in the hierarchy lie the mid-term or tactical planning activities. Demand Planning provides both available and forecast demand to other modules in the matrix. Given the structure of the supply chain, Master Planning seeks to fulfill given demand in an effective manner across tactical procurement, production and distribution opportunities. A

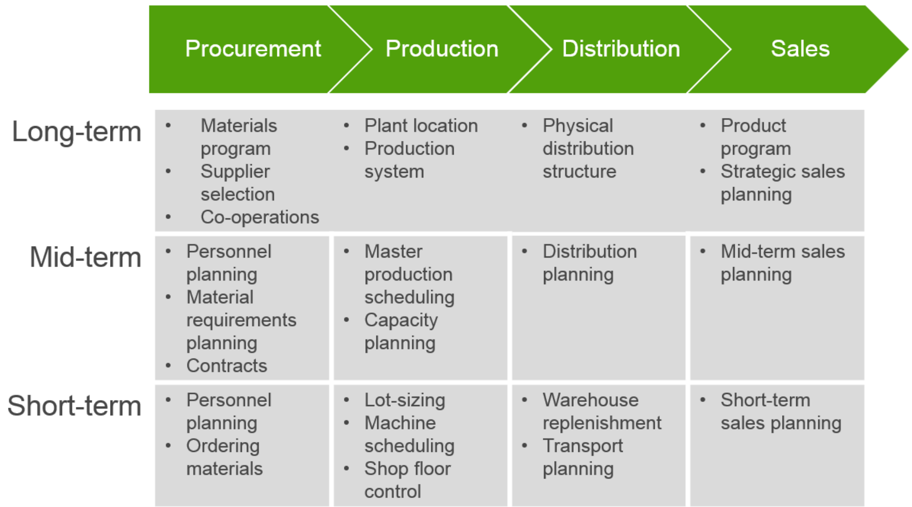


Figure 3.2: Supply Chain Planning Matrix (Fleischmann, Meyr, and Wagner 2005)

more detailed description of Master Planning is given below. On the operational layer of planning, Production Planning and Detailed Scheduling produce detailed plans within sites in accordance with the inter-site master plan. This planning in turn feeds into Purchasing and Material Requirements Planning that calculate short-term procurement quantities. Short-term Distribution and Transport Planning are executed according to given production quantities and outstanding orders and are therefore evaluated in more detail than in Master Planning. Finally Demand Fulfillment and Available-to-Promise (ATP) planning match inventory and expected supplies to committed customer orders, ATP quantities and Capable-to-Promise (CTP) quantities.

Rohde and Wagner (2005) define the purpose of Master Planning as synchronizing the flow of materials along the entire supply chain. This involves mid-term decisions on production, transport, supply capacities, seasonal stock and balancing of supply and demand with the objective of efficient utilization. Instead of devising decentralized local plans, the planning is suggested to take place centrally in order to consider all connected decisions and therefore avoid bottlenecks and suboptimal solutions. Pibernik and Sucky (2007) also advocate centralized planning while also noting how it is rare for all partners in the chain to find centralized planning acceptable. Rohde and

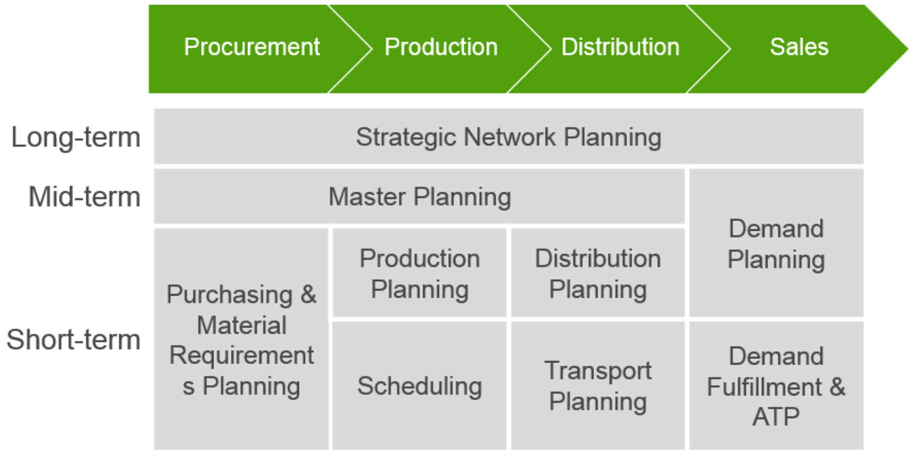


Figure 3.3: Hierarchy of Advanced Planning (Stadtler 2005)

Wagner (2005) further suggest aggregation of operational data as a means to reduce complexity and uncertainty in the planning process. Master Planning is next described in terms of its planning horizon, decisions involved, objectives, data and results.

As a mid-term decision-support, Rohde and Wagner (2005) note that Master Planning needs to consider at least one full seasonal cycle to balance all demand peaks. 12 months is mentioned as a typical horizon that takes into account seasonality throughout the year. Smaller bin size in discretization of the horizon is also described as improving accuracy at the cost of increased complexity. Larger bins are also advocated as allowing planning of quantities instead of individual transactions.

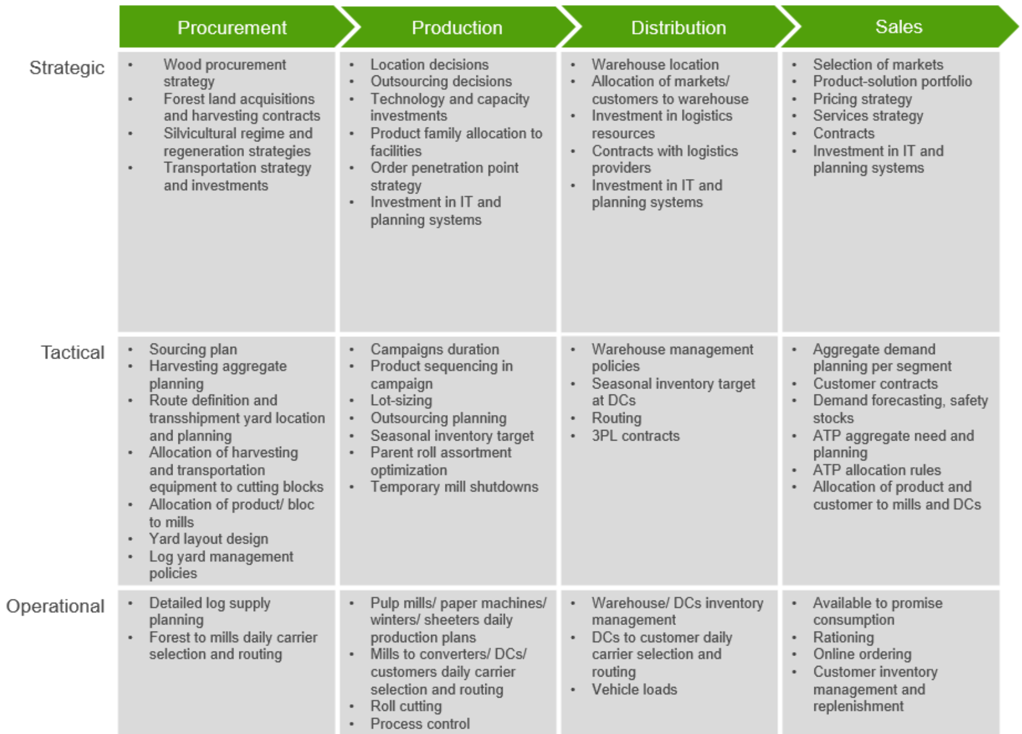
The decisions related to Master Planning are roughly categorized into production, transportation and inventories. Aggregation in the planning model allows for these decisions to be in the form of quantities. Due to the nature of the system, production and transportation quantities should also imply inventory quantities. All variables are however modeled in order to account for costs and constraints related to them. These decisions are meant to minimize total costs while respecting various constraints. Costs, capacities and other constraints are considered to be data that the Master Planning system receives as input. Output from the planning process are in turn the main outputs from the model. Rohde and Wagner (2005)

Rudberg and Thulin (2009) present a case study where a Master Planning APS has been implemented and improved operations efficiency through positive impact on inventory levels and throughput was subsequently observed. As advocated by Rohde and Wagner (2005) and Pibernik and Sucky (2007), the authors also conclude that centralization and efficient operation of the APS are prerequisites for a successful implementation.

3.3 Operations Research Applications in Wood Procurement

Carlsson et al. (2009) present a literature review into supply chain planning research in forestry and note that general-purpose APS, like presented above, are not entirely suitable to the forest industry since the planning problems often exhibit substantial unique characteristics. The authors adapt the Supply Chain Planning Matrix as presented above to the pulp and paper industry, with each section detailing the planning tasks pertaining specifically to the forestry supply chain (see Figure 3.4). D'Amours, Rönnqvist, and Weintraub (2008) emphasize the need to use hierarchical planning due to size of planning problems in the industry, also noting how the impact of improved forest management and forest operations on supply chain performance has been observed. The influence of seasonality and uncertainty are also indicated to bear significance. However, while Fleischmann, Meyr, and Wagner (2005) emphasize seasonality and uncertainty in demand, D'Amours, Rönnqvist, and Weintraub (2008) indicate their significance in the supply of the forestry supply chain: harvesting yields are stochastic by nature and especially the Nordic countries observe thaw that severely restricts harvesting opportunities during certain parts of the year.

Carlsson and Rönnqvist (2005) present several case studies of a large Swedish forest company, Södra Cell AB, including overall fiber-flow, pulp log sorting, production planning, terminal location and customer relation improvement. Cost-efficiency and transparency are mentioned as main arguments for adoption of decision support at the case company, while supply of data was identified as a challenge across all models presented. The need for tailored solutions over off-the-shelf APS was also indicated. Bredström et al. (2004) present mixed integer models used to determine daily supply chain decisions over a horizon of three months for the same company. By comparing manually generated plans and the optimized plans the authors found a profit opportunity in conducting shorter production planning to ac-



	Procurement	Production	Distribution	Sales
Strategic	• Wood procurement strategy • Forest land acquisitions and harvesting contracts • Silvicultural regime and regeneration strategies • Transportation strategy and investments	• Location decisions • Outsourcing decisions • Technology and capacity investments • Product family allocation to facilities • Order penetration point strategy • Investment in IT and planning systems	• Warehouse location • Allocation of markets/ customers to warehouse • Investment in logistics resources • Contracts with logistics providers • Investment in IT and planning systems	• Selection of markets • Product-solution portfolio • Pricing strategy • Services strategy • Contracts • Investment in IT and planning systems
Tactical	• Sourcing plan • Harvesting aggregate planning • Route definition and transshipment yard location and planning • Allocation of harvesting and transportation equipment to cutting blocks • Allocation of product/ bloc to mills • Yard layout design • Log yard management policies	• Campaigns duration • Product sequencing in campaign • Lot-sizing • Outsourcing planning • Seasonal inventory target • Parent roll assortment optimization • Temporary mill shutdowns	• Warehouse management policies • Seasonal inventory target at DCs • Routing • 3PL contracts	• Aggregate demand planning per segment • Customer contracts • Demand forecasting, safety stocks • ATP aggregate need and planning • ATP allocation rules • Allocation of product and customer to mills and DCs
Operational	• Detailed log supply planning • Forest to mills daily carrier selection and routing	• Pulp mills/ paper machines/ winters/ sheeters daily production plans • Mills to converters/ DCs/ customers daily carrier selection and routing • Roll cutting • Process control	• Warehouse/ DCs inventory management • DCs to customer daily carrier selection and routing • Vehicle loads	• Available to promise consumption • Rationing • Online ordering • Customer inventory management and replenishment

Figure 3.4: The Pulp and Paper Supply Chain Matrix (D'Amours, Rönnqvist, and Weintraub 2008)

commodate factors such as raw material inflow.

Kong, Rönnqvist, and Frisk (2012) describe a wood procurement problem as a multi-period multi-commodity network planning problem. The model includes multiple sources of supply in the form of multiple harvesting areas as well as multiple types of destinations in the form of saw mills, pulp mills and heating plants. The authors also incorporate price elasticity for raw material supply both as a quadratic constraint and as a discretized piecewise-linear constraint. Notably while integrating saw, pulp and energy markets is found to increase costs for sawmills and pulp mills, the total costs for the whole market are found to decrease. The authors have further extended the model by allowing selection of harvest areas in order to accommodate time-horizons that are longer than one year (Kong, Rönnqvist, and Frisk 2015).

Rummukainen, Kinnari, and Laakso (2009) discuss the wood transportation planning at Stora Enso, a large, related Finnish forest industry company. The planning is more operational as it is conducted over a short time period, with focus on individual truck loads and according to harvesting and mill production plans that have been produced using separate optimization models. The authors present optimization models for load optimization, load assignment and route optimization, of which the first two are found to produce implementable solutions within minutes, while the route optimization model requires hours to find high quality solutions a using the tabu search metaheuristic and the solutions are found to exhibit undesirably strong sensitivity to the model's inputs.

More recently Rönnqvist et al. (2015) present open research problems in the forest industry. The authors divide the problems into strategic, tactical and operational planning, fire management, conservation and the use of OR to address environmental concerns. Discussing Value Chain Management (VCM)[2] the authors consider demand-based planning to be in its infancy and call for developing an integrated planning framework for a demand driven value chain characterized by a sequence of divergent processes.

The tactical planning tasks discussed in this thesis bear resemblance to the tactical planning tasks presented in the Pulp and Paper Supply Chain Planning Matrix as described above. D'Amours, Rönnqvist, and Weintraub (2008) also point out how this supply task spans over the procurement, production and distribution stages of the supply chain. It is therefore consistent to consider the sourcing plan to constitute master planning as described by Rohde and Wagner (2005). The sourcing unit could be further viewed as an independent actor in the supply chain who interfaces with the rest of the business via internal sales. Tactical planning in the wood consuming businesses provides demand planning of the sourcing unit and the sourcing unit is in turn responsible for planning activities that seek to meet given demand.

3.4 Synthesis of the Sourcing Problem

To improve cost efficiency of the case company's wood sourcing, a planning system is needed. In line with the Supply Chain Planning Matrix discussed above, the supply chain of the whole corporation is first planned on a strategic or long-term level and with separate decision support tools. Next, tactical

[2] VCM addresses the coordination of a set of organizational units involved in bringing to market wood fiber -based products through management, engineering and planning decisions in order to enhance the performance of the units as well as the whole chain (Carlsson and Rönnqvist 2005).

planning in all phases of the supply chain is conducted in accordance with the long-term plan. Here demand from all wood consuming business areas are given as input to the tactical planning process of the wood sourcing BU, and the tactical procurement planning should yield corresponding plans for wood purchasing, own harvesting, trades, imports, storage and transportation of wood to meet the given demand while minimizing costs. Figure 3.5 displays the source, destination and stock categories as well as flows of wood between them. Since forestry and wood sourcing are subject to social and ecological considerations in addition to economical considerations, the planning process needs to also account for additional constraints, such as forest owner interests. The tactical plan is then further refined into a short-term operational plan for the next three months.

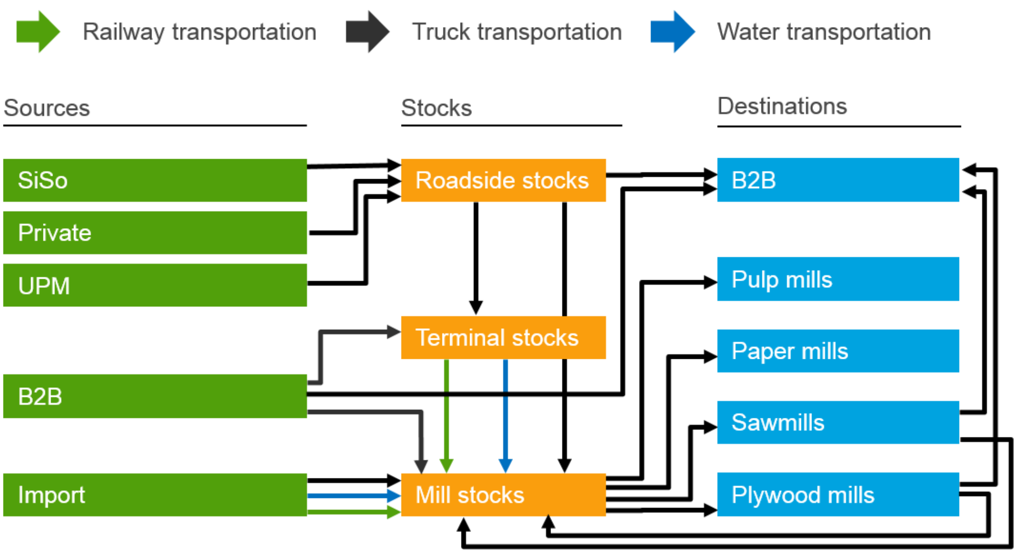


Figure 3.5: Wood flow across the sourcing network

Presently, tactical planning in the wood sourcing BU is supported by a Linear Programming (LP) model that generates a rolling single-period sourcing plan for the next 12 months. As its inputs, the model is given demand at each mill, wood supplies at each source and transportation opportunities between locations in addition to their respective costs and additional constraints, providing corresponding cost minimizing procurement, trade and transportation decisions as its outputs. A significant limitation to the model is that its output requires significant manual effort from the decision maker in order to turn it into a feasible monthly plan. Moreover, the model does not consider some relevant factors such as price elasticity of supply, which is believed to be a possible source of inaccuracy in the planning process.

Considering the limitations of the current planning system, the BU is developing an improved system that should both improve accuracy of its output as well as reduce the effort required to refine the output into a viable plan. The proposed system consists of an improved optimization model and an OLAP system facilitating analysis. Improved output quality and usability should further enable what-if analyses and ultimately yield better business decisions in the planning process.

Towards this end, the proposed optimization model considers relevant decisions in harvesting and other procurement options, wood trades between sourcing parties, transportation, storage and consumption. Wood flows in harvesting are modeled from standing reserve trades via harvesting decisions to splitting. Procurement of wood from roadside purchases, imports and by-production is also modeled. One-way and two-way trades between companies sourcing wood are also allowed. All sourced wood is subsequently tracked across a multi-mode transportation network consisting of wood sources, storage sites and internal and sales destinations. Demand is modeled using soft constraints in order to allow the model to prioritize consumption sites in case of material shortage. The optimal solution from the problem should reflect the minimum total cost at mill gate adjusted by various other penalty factors. The solution should also function as a viable tactical plan for the given time horizon, possibly with minor manual adjustments.

Chapter 4

Optimization Model

In this chapter the developed planning model is described. The first section lists the problem's sets on which the problem's parameters and variables are indexed. Then, parameters and decision variables of the model are listed and described. Using these definitions, the objective function and constraints are defined. Finally, measures to limit the problem size and otherwise improve its performance are discussed.

In brief, the optimization model is a multi-commodity flow problem with varying harvesting yields, multiple transportation modes, storage management, by-product generation and end-product substitution. The model can be roughly divided into sections

i) harvesting & roadside purchasing

ii) B2B purchasing & sales

iii) import

iv) transportation & storage

v) internal consumption & by-production.

They contribute independently to the objective function and are linked via transportation flow constraints. Table 4.1 shows a verbal description of the optimization model, with both objective function terms and constraints grouped in the aforementioned categories.

In order to analyze the model's behavior and to assess its development needs, a test dataset representative of an actual planning scenario was compiled. In total there are some hundreds of sources and some hundreds of sinks

Table 4.1: Verbal description of the optimization problem

	Minimize	Subject to
Harvesting & Roadside	• Harvesting costs • Reserve purchasing costs • Splitting penalties • Harvesting penalties • Roadside purchase costs	• Standing supply • Harvesting deadlines • Assortment co-production • Splitting • Weather conditions • Reserve balance • Roadside supply
B2B Purchasing & Sales	• Net trade balance = purchasing costs – sales revenue	• Purchasing supply • Sales demand • Trade partner balance
Importation	• Importation costs	• Importation supply
Transportation & Storage	• Transportation costs • Storage costs	• Transportation flows • Storage balance
Internal Demand & By-production	• Unsatisfied demand penalty	• Demand-consumption balance • Demand substitution • By-product generation

in the subject sourcing network. The number of sources is in part narrowed by grouping harvesting sites into larger clusters that are further organized in detail in operational planning. While the model has been developed as a pure LP model, the test dataset induces a problem with millions of decision variables and constraints for a full 12 month planning horizon over the whole Finnish geography, leading to computational complexity.

4.1 Notation

T	Time periods
$\hat{T}$	Time periods with an appended month to track stock levels after the optimization period
L	Locations
$LInt$	Integrate areas
LRT	Regional teams
$O \subset L$	Origins
$OHar \subset O$	Harvesting sources

$OPur \subset O$	Purchasing sources
$OImp \subset O$	Import sources
$S \subset L$	Stocks
$SRoad \subset S$	Roadside stocks
$STerm \subset S$	Terminal stocks
$SMill \subset S$	Mill stocks
$TMod$	Transportation types
$D \subset L$	Destinations
$DCon \subset D$	Consuming destinations
$DSal \subset D$	Sales destinations
W_p	Primary assortments
W	Assortments
$HType$	Harvesting types
$HSeas$	Harvesting seasons
$DItem$	Demand items
P	Partners
$P_t \subset P$	Trade partners

In addition the following mappings are used

$m_w : W \to W_p$	Surjective assortment mapping associating each wood assortment w to a primary assortment w_p
$m_w^{-1} : W_p \to \mathbb{P}(W)$	Corresponding inverse mapping associating primary assortment w_p with a subset of assortments, for which $w \in m_w^{-1}(w_p) \Leftrightarrow m_w(w) = w_p$ holds
$m_i : I \to \mathbb{P}(W)$	Demand item mapping associating each demand item i with a subset of wood assortments

$m_I : S \to LInt$	Surjective integrate area mapping associating a stock s with an integrate area $lInt$
$m_I^{-1} : LInt \to \mathbb{P}(l)$	Corresponding inverse mapping associating integrate area $lInt$ with a subset of stocks, for which $s \in m_I^{-1}(lInt) \Leftrightarrow m_I(s) = lInt$ holds
$m_R : L \to LRT$	Regional team mapping associating a location l with a regional team lRT,

where $\mathbb{P}(X)$ is the power set of set X.

4.2 Parameters

Parameter	Unit	Description
WACC	-	Weighed Average Cost of Capital corresponding to T
$s^{Har}_{l,hType,w_p}$	-	Share of primary assortment w_p produced from harvesting activities of type $hType$ in harvesting source l. Note that here it is natural to expect $\sum_{W_p} \left[s^{Har}_{l,hType,w_p} \right] = 1 \; \forall l \in O_H, hType \in HType$.
Spl_w	-	Indicator value to denote whether the assortment w is a result of splitting
p^{Spl}	€$/m^3$	Unit penalty for splitting wood
$s^{Spl,L}_{l,w}$	-	Lower limit for the share of split assortment w from all wood split from the same primary assortment
$s^{Spl,U}_{l,w}$	-	Upper limit for the share of split assortment w from all wood split from the same primary assortment
$v^{Har,U}_{l,hType,hSeas}$	m^3	Historical supply of available sites in harvesting source l that are available to harvest during season $hSeas$ and are subject to harvesting activity of type $hType$
$v^{Har,T}$	-	Relative harvesting supply tolerance

t^{Har}_{lRT}	hours/ month	Harvesting hours available per month for regional team lRT
$c^{Har,C}_{hType}$	m^3/ hour	Harvesting volume per hour for harvesting type $hType$
$v^{Res,L}_{l,hType,hSeas}$	m^3	Lower limit for the change of reserve levels in harvesting source l that is available to harvest during season $hSeas$ and is subject to harvesting activity of type $hType$
$v^{Res,U}_{l,hType,hSeas}$	m^3	Upper limit for the change of reserve levels in harvesting source l that is available to harvest during season $hSeas$ and is subject to harvesting activity of type $hType$
$s^{HSeas,L}_{l,t,hSeas}$	-	Lower limit for the share of harvesting sites associated with the season $hSeas$ at harvesting source l at time t compared to the total harvesting at the same source and time
$s^{HSeas,U}_{l,t,hSeas}$	-	Upper limit for the share of harvesting sites associated with the season $hSeas$ at harvesting source l at time t compared to the total harvesting at the same source and time
$s^{HSeas,T}$	-	Relative tolerance for harvesting season limits
$v^{Har,L,C}_{l,hType,hSeas,t}$	m^3	Lower limit for cumulative harvesting in harvesting source l that is available to harvest during season $hSeas$ and is subject to harvesting activity of type $hType$ up to time t
$p^{Har,C}$	€/m^3	Penalty for violating the cumulative harvesting limit
$v^{Rsid,U}_{l,w}$	m^3	Roadside supply for assortment w at harvesting source l
$c^{Rsid}_{l,w}$	€/m^3	Roadside cost for assortment w at harvesting source l
$v^{Pur,U}_{l,w,p,t}$	m^3	Purchasing supply for assortment w at purchasing source l of partner p at time t
$c^{Pur}_{l,w,p,t}$	€/m^3	Purchasing unit cost for assortment w at purchasing source l of partner p at time t

$v^{Sal,U}_{l,w,p,t}$	m^3	Sales demand of assortment w at sales destination l of partner P at time t
$r^{Sal}_{l,w,p,t}$	€$/m^3$	Unit revenue gained from assortment w at sales destination l of partner P at time t
$u^{P,L}$	-	Lower limit of partner utilization
$u^{P,U}$	-	Upper limit of partner utilization
$u^{P,T}$	-	Relative tolerance of partner utilization compared to purchasing and sales amounts
$v^{Imp,U}_{l,w,t}$	m^3	Import supply for assortment w at import source l at time t
$c^{Trns}_{o,d,tMod,w}$	€$/m^3$	Unit transportation cost of assortment w from location o to location d using transportation of type $tMod$
$Trns_{o,d,tMod}$	-	Indicator value to denote whether there exists a route from o to d using transportation mode $tMod$
c_w	€$/m^3$	Inventory unit value of assortment w
$v^{Str,T}_l$	m^3	Terminal storage capacity for terminal l
$v^{Str,L}_{l,w_p,t}$	m^3	Lower storage volume limit of primary assortment w_p at integrate area l at time t
$v^{Str,U}_{l,w_p,t}$	m^3	Upper storage volume limit of primary assortment w_p at integrate area l at time t
$v^{Str,Trgt}_{l,w_p,t}$	m^3	Target storage volume of primary assortment w_p at integrate area l at time t
p^{Str}	€$/m^3$	Unit penalty from deviating from a desired storage level for any primary assortment at any integrate location or time
$v^{Dem,U}_{l,i,t}$	m^3	Internal demand for demand item i at consuming destination l at time t
$s^{Dem,L}_{i,\hat{i},l}$	-	Lower limit for the share of demand item i compared to item $\hat{i}$ when delivered to consuming destination l

$s^{Dem,U}_{i,\hat{i},l}$	-	Upper limit for the share of demand item i compared to item $\hat{i}$ when delivered to consuming destination l
$p^{Con,\downarrow}_{l,i,t}$	€$/m^3$	Penalty for unsatisfied demand of item i at consuming destination l at time t
$s^{Dem,\downarrow,U}$	-	Upper limit for the share of unsatisfied demand in comparison to total demand for each consuming destination, demand item and time
$s^{Dem,\uparrow,U}$	-	Upper limit for the share of over-satisfied demand in comparison to total demand for each consuming destination, demand item and time
$s^{BPr}_{l,w,\hat{w}}$	-	Coefficient according to which consuming location l turns units of consumed wood of type w into units of by-product wood of type $\hat{w}$

In addition, define import cost curves

$$c^{Imp}_{l,w,t} = c^{Imp}_{l,w,t}(v^{Imp}_{l,w,t}) \quad \forall l \in OImp, w \in W, t \in T \tag{4.1}$$

and stand purchase cost curves

$$c^{StndPur}_{l,hType,hSeas,w_p} = c^{StndPur}_{l,hType,hSeas,w_p}(v^{StndPur}_{l,hType,hSeas,w_p}) \quad \forall l \in OHar, hType \in HType, hSeas \in HSeas, w_p \in W_p \tag{4.2}$$

where

$$v^{StndPur}_{l,hType,hSeas,w_p} = \sum_{t \in T} \sum_{\substack{w \in W \\ m_w(w)=w_p}} v^{Har,O}_{l,hType,hSeas,w,t} + s^{Har}_{l,hType,w_p} v^{ResDel}_{l,hType,hSeas} \quad \forall l \in OHar, hType \in HType, hSeas \in HSeas, w_p \in W_p. \tag{4.3}$$

Note it is required for $c^{Imp}_{l,w,t}$ and $c^{Har}_{l,hType,hSeas}$ to be (piecewise) linear and convex.

4.3 Decision Variables

Variable	Domain	Unit	Description
$v^{Har}_{l,hType,hSeas,t}$	$\mathbb{R}^+$	m^3	Harvesting amount at harvesting source l of harvesting type $hType$ and harvesting season $hSeas$ at time t
$v^{Har,O}_{l,hType,hSeas,w,t}$	$\mathbb{R}^+$	m^3	Harvesting output volume of assortment w at harvesting source l of harvesting type $hType$ and harvesting season $hSeas$ at time t
$v^{Har,C}_{l,hType,hSeas,t}$	$\mathbb{R}^+$	m^3	Violation of minimum cumulative harvesting amount at harvesting source l of harvesting type $hType$ and harvesting season $hSeas$ at time t
$v^{ResDel}_{l,hType,hSeas}$	$\mathbb{R}$	m^3	Reserve delta at harvesting source l of harvesting type $hType$ and harvesting season $hSeas$
$v^{StndPur}_{l,hType,hSeas,w_p}$	$\mathbb{R}^+$	m^3	Stand purchase harvesting source l of harvesting type $hType$ and harvesting season $hSeas$ and primary assortment w_p
$v^{Rsid}_{l,w,t}$	$\mathbb{R}^+$	m^3	Roadside purchasing amount for assortment w at harvesting source l at time t
$v^{Pur}_{l,w,p,t}$	$\mathbb{R}^+$	m^3	Amount of purchased wood of type w at purchasing source l of partner p at time t
$v^{Pur,O}_{l,w,p,t}$	$\mathbb{R}^+$	m^3	Amount of orphaned wood of type w at purchasing source l of partner p at time t
$v^{Sal}_{l,w,p,t}$	$\mathbb{R}^+$	m^3	Sales amount of assortment w at sales destination l of partner p at time t
$v^{Sal,\downarrow}_{l,w,p,t}$	$\mathbb{R}^+$	m^3	Unsatisfied sales demand of assortment w at sales destination l of partner p at time t
$v^{Sal,\uparrow}_{l,w,p,t}$	$\mathbb{R}^+$	m^3	Over-satisfied sales demand of assortment w at sales destination l of partner p at time t
u^P_p	$\mathbb{R}^+$	-	Partner utilization of partner p

$v^{Imp}_{l,w,t}$	$\mathbb{R}^+$	m^3	Amount of imported wood of type w from import source l at time t
$u^{Imp}_{l,w}$	$\mathbb{R}^+$	-	Import utilization of assortment w from import source l
$f_{o,d,tMod,w,t}$	$\mathbb{R}^+$	m^3	Flow of wood of type w from origin o to destination d using transportation of type $tMod$ at time t
$v^{Str}_{s,w,t}$	$\mathbb{R}^+$	m^3	Amount of stored wood of type w at storage location s at time t
$v^{Str,D}_{l,w_P,t}$	$\mathbb{R}$	m^3	Deviation from desired storage level of primary wood of type w_P at integrate area l at time t
$v^{Con}_{l,w,t}$	$\mathbb{R}^+$	m^3	Consumption of wood of type w at consuming destination l at time t
$v^{Con,\downarrow}_{l,i,t}$	$\mathbb{R}^+$	m^3	Unsatisfied internal demand of demand item i at consuming destination l at time t
$v^{Con,\uparrow}_{l,i,t}$	$\mathbb{R}^+$	m^3	Over-satisfied internal demand of demand item i at consuming destination l at time t
$v^{BPr}_{l,w,t}$	$\mathbb{R}^+$	m^3	By-production volume of wood of type w at consuming location l at time t

4.4 Objective Function

The objective function is composed of cost, revenue and penalty terms:

$$\begin{aligned} \min TC = CTrns\ (4.5) \quad &+ CHar\ (4.6) &&+ CStndPur\ (4.7) \\ + PSpl\ (4.8) \quad &+ PHarLow\ (4.9) &&+ CDel\ (4.10) \\ + CPur\ (4.11) \quad &- RSal\ (4.12) &&+ CImp\ (4.13) \\ + CStr\ (4.14) \quad &+ PStrDev\ (4.16) &&+ PDemUn\ (4.17) \end{aligned} \tag{4.4}$$

Transportation costs are summed as volume times unit cost over all routes, transportation modes, assortments and time periods:

$$CTrns = \sum_{o \in L} \sum_{d \in L} \sum_{tMod \in TMod} Trns_{o,d,tMod} \cdot \sum_{w \in W} \sum_{t \in T} f_{o,d,tMod,w,t} \cdot c^{Trns}_{o,d,tMod,w}. \tag{4.5}$$

Harvesting costs are summed as volume times unit cost over harvesting locations, harvesting types and time periods

$$CHar = \sum_{l \in OHar} \sum_{hType \in HType} \sum_{t \in T} \left[c^{H}_{l,hType} \cdot \sum_{w_p \in W_p} \sum_{hSeas \in HSeas} \sum_{w \in m_w^{-1}(w_p)} v^{Har,O}_{l,hType,hSeas,w,t} \right]. \tag{4.6}$$

Stand purchase costs are summed as total cost over harvesting locations, harvesting types and primary assortments

$$CStndPur = \sum_{l \in OHar} \sum_{hType \in HType} \sum_{hSeas \in HSeas} \sum_{w_p \in W_p} C^{StndPur}_{l,hType,hSeas,w_p} (v^{StndPur}_{l,hType,hSeas,w_p}). \tag{4.7}$$

Splitting penalties are summed as total volume of split wood over harvesting locations, harvesting types, harvesting seasons and time periods times the unit splitting penalty

$$PSpl = \sum_{l \in OHar} \sum_{hType \in HType} \sum_{hSeas \in HSeas} \sum_{\substack{w \in W: \\ Spl_w = 1}} \sum_{t \in T} v^{Har,O}_{l,hType,hSeas,w,t} \cdot p^{Spl}. \tag{4.8}$$

Lower cumulative harvesting bound violation penalties are summed as total violation volume over harvesting locations, harvesting types, harvesting seasons and time periods times the unit bound violation penalty

$$PHarLow = \sum_{l \in Ohar} \sum_{hType \in HType} \sum_{hSeas \in HSeas} \sum_{t \in T} v^{Har,C}_{l,hType,hSeas,t} \cdot p^{Har,C}. \tag{4.9}$$

roadside costs as purchasing volume times unit cost over harvesting locations, assortments and time periods

$$CDel = \sum_{l \in OHar} \sum_{w \in W} \sum_{t \in T} v^{Rsid}_{l,w,t} \cdot c^{Rsid}_{l,w}. \tag{4.10}$$

Purchasing costs are summed as total purchasing volume times unit purchasing cost over purchasing locations, assortments, purchasing partners and time periods

$$CPur = \sum_{l \in OPur} \sum_{w \in W} \sum_{p \in P} \sum_{t \in T} \left[v^{Pur}_{l,w,p,t} + v^{P}_{o_{P,O},w,p,t} \right] \cdot c^{Pur}_{l,w,p,t}. \tag{4.11}$$

Sales revenue are respectively summed as total sales volume times unit sales revenue over sales locations, assortments, purchasing partners and time periods

$$RSal = \sum_{l \in D_S} \sum_{w \in W} \sum_{p \in P} \sum_{t \in T} v^{Sal}_{l,w,p,t} \cdot r^{Sal}_{l,w,p,t}. \tag{4.12}$$

Import costs are summed as total import volume time unit cost over import locations, assortments and time periods

$$CImp = \sum_{l \in OImp} \sum_{w \in W} \sum_{t \in T} C^{I}_{l,w,t}(v^{Imp}_{l,w,t}). \tag{4.13}$$

Storage costs are calculated as their absolute capital costs, or total inventory value times cost of capital

$$CStr = \sum_{s \in S} \sum_{w \in W} \sum_{t \in T} v^{Str}_{s,w,t} \cdot [c_w + \mathbf{1}_{S_R}(s) \cdot 2\epsilon + \mathbf{1}_{S_T}(s) \cdot \epsilon] \cdot \text{WACC}, \tag{4.14}$$

where

$$\mathbf{1}_A(x) = \begin{cases} 1, & \text{for } x \in A \\ 0 & \text{otherwise} \end{cases} \tag{4.15}$$

is the indicator function and ϵ is a small incremental unit cost that is used to, ceteris paribus, encourage concentrating storage volume to stocks near end use locations.

Storage deviation penalties are calculated as the sum of absolute deviations over integrate areas, primary assortments and time periods times the unit deviation penalty

$$PStrDev = \sum_{l \in LInt} \sum_{w_p \in W_p} \sum_{t \in T} \left| v^{Str,D}_{l,w_P,t} \right| \cdot p^{Str}. \tag{4.16}$$

Unsatisfied demand penalties are calculated as the sum of unsatisfied volume times the respective unit penalty over consuming locations, demand items and time periods

$$PDemUn = \sum_{l \in DCon} \sum_{i \in DItem} \sum_{t \in T} \left[v_{l,i,t}^{Con,\downarrow} \cdot p_{l,i,t}^{Con,\downarrow} \right]. \tag{4.17}$$

4.5 Constraints

Constraints are also categorized according to the grouping shown in Table 4.1. Apart from the storage and flow balance constraints on the transportation network, all constraints are limited to their respective domain. All constraint definitions and brief descriptions are given in this subsection.

Figure 4.1 displays the handling of harvesting and stand purchases for a combination of location, harvesting type and season: the cumulative harvesting amount each month should exceed the accrued volume from expired stand trades, and stand purchases should compensate harvesting throughout the year so that reserves in the end of the planning period exceed the minimum final reserve level. This is reflected in the following constraints.

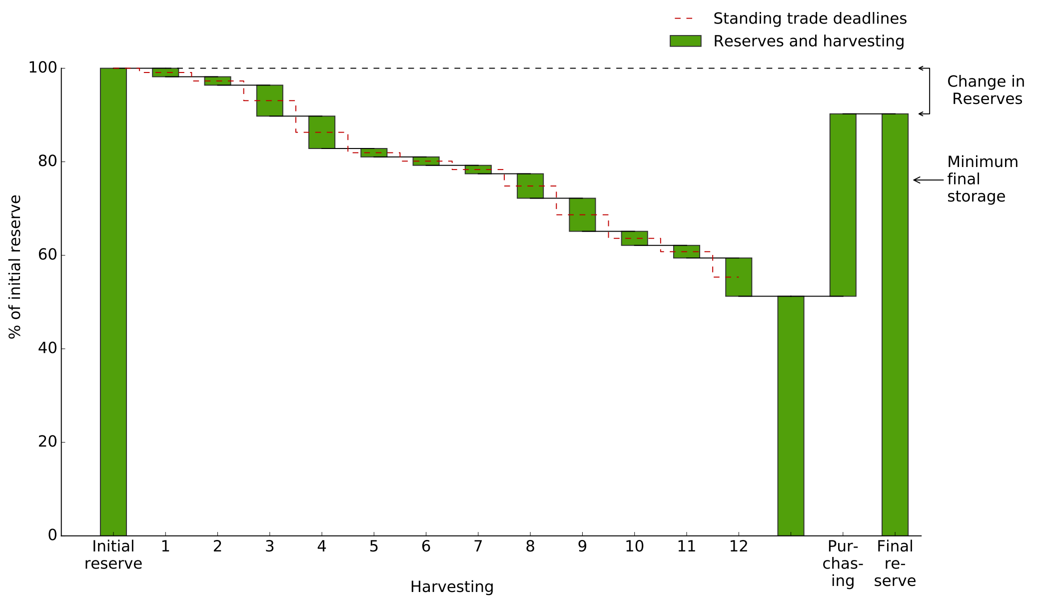


Figure 4.1: Indicative description of the harvesting and stand purchases mechanics

Harvesting amount and changes in standing reserve levels are compared to an adjusted upper limit for added reserves

$$\sum_{t\in T} v^{Har}_{l,hType,hSeas,t} + v^{ResDel}_{l,hType,hSeas} \leq v^{Har,U}_{l,hType,hSeas} \cdot (1 + v^{Har,T}) \qquad \forall l \in OHar, hType \in HType, hSeas \in HSeas. \quad (4.18)$$

Harvesting volume is required to exceed a given cumulative volume from expiring existing standing reserves

$$v^{Har,L,C}_{l,hType,hSeas,t} \leq \sum_{\tau\in T:\tau\leq t} v^{H}_{l,hType,hSeas,\tau} + v^{Har,C}_{l,hType,hSeas,t} \qquad \forall l \in OHar, hType \in HType, hSeas \in HSeas, t \in T. \quad (4.19)$$

Harvesting amount is subject to available harvesting hours in each regional team

$$\sum_{l\in m_R(lRT)} \sum_{hType\in HType} \sum_{hSeas\in HSeas} \frac{v^{Har}_{l,hType,hSeas,t}}{c^{Har,C}_{hType}} \leq t^{Har}_{lRT} \qquad \forall lRT \in LRT, t \in T. \quad (4.20)$$

The needed stand purchasing volume is related to the amount of wood harvested and the change in reserve levels

$$v^{StndPur}_{l,hType,hSeas,w_p} = \left[s^{Har}_{l,hType,w_p} \cdot v^{ResDel}_{l,hType,hSeas} + \sum_{w\in m_w^{-1}(w_p)} \sum_{t\in T} v^{Har,O}_{l,hType,hSeas,w,t} \right] \qquad \forall l \in OHar, hType \in HType, hSeas \in HSeas, w_p \in W_p. \quad (4.21)$$

The reserve level changes are also given absolute limits

$$v^{Res,L}_{l,hType,hSeas} \leq v^{ResDel}_{l,hType,hSeas} \leq v^{Res,U}_{l,hType,hSeas} \qquad \forall l \in OHar, hType \in HType, hSeas \in HSeas. \quad (4.22)$$

Harvesting is subject to co-production where harvesting activities yield primary assortments according to a given distribution

$$\sum_{w \in m_w^{-1}(w_p)} v^{Har,O}_{l,hType,hSeas,w,t} = s^{Har}_{l,hType,w_p} \cdot v^{Har}_{l,hType,hSeas,t}$$
$$\forall w_p \in W_P, l \in OHar, hType \in HType, hSeas \in HSeas, t \in T. \quad (4.23)$$

Some assortments can be further separated into other assortments, again subject to co-production. This co-production distribution is only partially constrained by upper and lower limits

$$v^{Har,O}_{l,hType,hSeas,w,t} \leq s^{Spl,U}_{l,w} \cdot \sum_{\hat{w} \in m_w^{-1}(w_p): spl_{\hat{w}} > 0} v^{H,O}_{l,hType,hSeas,\hat{w},t}$$
$$\forall w \in W, l \in OHar, hType \in HType, hSeas \in HSeas, t \in T \quad (4.24)$$

and

$$s^{Spl,L}_{l,w} \cdot \sum_{\hat{w} \in m_w^{-1}(w_p): spl_{\hat{w}} > 0} v^{H,O}_{l,hType,hSeas,\hat{w},t} \leq v^{Har,O}_{l,hType,hSeas,w,t}$$
$$\forall w \in W, l \in OHar, hType \in HType, hSeas \in HSeas, t \in T. \quad (4.25)$$

Due to phenomena such as thaw, some sites are accessible only during certain weather conditions. Harvesting locations are aggregations of several sites and thus harvesting volume from each harvesting location is expected to follow a given distribution of harvesting seasons

$$\sum_{hSeas \in HSeas} v^{Har}_{l,hType,hSeas,t} \geq s^{HSeas,L}_{l,t,hSeas} \cdot (1 - s^{HSeas,T}) \cdot \sum_{h\hat{S}eas \in HSeas} v^{H}_{l,hType,h\hat{S}eas,t}$$
$$\forall l \in OHar, hType \in HType, t \in T \quad (4.26)$$

and

$$\sum_{hSeas \in HSeas} v^{Har}_{l,hType,hSeas,t} \leq s^{HSeas,U}_{l,t,hSeas} \cdot (1 + s^{HSeas,T}) \cdot \sum_{h\hat{S}eas \in HSeas} v^{H}_{l,hType,h\hat{S}eas,t}$$
$$\forall l \in OHar, hType \in HType, t \in T. \quad (4.27)$$

Supply of roadside purchases is constrained for each location and assortment

$$\sum_{t \in T} v^{Rsid}_{l,w,t} \leq v^{Rsid,U}_{l,w} \quad \forall l \in OHar, w \in W. \tag{4.28}$$

In B2B purchasing and sales, supply and demand are considered along with special constraints for partners who are involved in both purchasing and sales. Purchasing supply is constrained, and the model is additionally allowed to abandon purchased wood

$$v^{Pur}_{l,w,p,t} + v^{Pur,O}_{l,w,p,t} \leq v^{Pur,U}_{l,w,p,t} \quad \forall l \in OPur, w \in W, p \in P, t \in T. \tag{4.29}$$

Sales are compared to demand and all deviations are tracked using unsatisfaction and oversatisfaction variables

$$v^{Sal}_{l,w,p,t} + v^{Sal,\downarrow}_{l,w,p,t} - v^{Sal,\uparrow}_{l,w,p,t} = v^{Sal,U}_{l,w,p,t} \quad \forall l \in DSal, w \in W, p \in P, t \in T. \tag{4.30}$$

For trade partners, i.e. partners involved in both purchasing and sales, the wood sold and wood purchased are expected to approximately match potential supply and demand volume up to proportionality, e.g., purchasing 50% of supply from trade partner p necessitates filling approximately 50% of the wood demand from p

$$u^{P,L} \leq u^P_p \leq u^{P,U} \quad \forall p \in P_t, \tag{4.31}$$

$$(1 - u^{P,T}) \cdot u^P_p \cdot v^{Pur,U}_{l,w,p,t} \leq v^{Pur}_{l,w,p,t} + v^{Pur,O}_{l,w,p,t} \leq (1 + u^{P,T}) \cdot u^P_p \cdot v^{Pur,U}_{l,w,p,t} \quad \forall l \in OPur, w \in W, p \in P_t, t \in T \tag{4.32}$$

and

$$(1 - u^{P,T}) \cdot u^P_p \cdot v^{Sal,U}_{l,w,p,t} \leq v^{Sal}_{l,w,p,t} \leq (1 + u^{P,T}) \cdot u^P_p \cdot v^{Sal,U}_{l,w,p,t} \quad \forall l \in DSal, w \in W, p \in P_t, t \in T. \tag{4.33}$$

Import supply is constrained and its utilization is required to remain consistent over time

$$v^{Imp}_{l,w,t} = u^{Imp}_{l,w} \cdot v^{Imp,U}_{l,w,t} \quad \forall l \in OImp, w \in W, t \in T. \tag{4.34}$$

The sourcing network's flows are gathered in a single set of constraints. Essentially, inflows, production, purchasing and storage level changes should correspond to outflows, sales and consumption

$$\text{inflow}_{l,t}+\text{harvesting}_{l,t}+\text{roadside}_{l,t}+\text{B2Bpurchasing}_{l,t}+\text{byproduction}_{l,t}+\text{storagedelta}_{l,t} = \text{outflow}_{l,t} + \text{B2Bsales}_{l,t} + \text{consumption}_{l,t} \ \forall l \in L, t \in T, \quad (4.35)$$

where

$$\text{inflow}_{l,t} = \sum_{o\in O}\sum_{m\in TMod} Trns_{o,l,m} \cdot f_{o,l,m,w,t}$$

$$\text{harvesting}_{l,t} = \begin{cases} \sum\limits_{hType\in HType}\sum\limits_{hSeas\in HSeas} v^{Har,O}_{l,hType,hSeas,w,t} & \text{for } l \in OHar \\ 0 & \text{otherwise} \end{cases}$$

$$\text{roadside}_{l,t} = \begin{cases} v^{Rsid}_{l,w,t} & \text{for } l \in OHar \\ 0 & \text{otherwise} \end{cases}$$

$$\text{B2Bpurchasing}_{l,t} = \begin{cases} \sum\limits_{p\in P} v^{P}_{l,w,p,t} & \text{for } l \in OPur \\ 0 & \text{otherwise} \end{cases}$$

$$\text{byproduction}_{l,t} = \begin{cases} v^{BPr}_{l,w,t} & \text{for } l \in DCon \\ 0 & \text{otherwise} \end{cases}$$

$$\text{storagedelta}_{l,t} = \begin{cases} v^{Str}_{l,w,t} - v^{Str}_{l,w,t+1} & \text{for } l \in S \\ 0 & \text{otherwise} \end{cases}$$

$$\text{outflow}_{l,t} = \sum_{d\in D}\sum_{m\in TMod} Trns_{l,d,m} \cdot f_{l,d,m,w,t}$$

$$\text{B2Bsales}_{l,t} = \begin{cases} \sum\limits_{p\in P} \left[v^{Sal}_{l,w,p,t}\right] & \text{for } l \in DSal \\ 0 & \text{otherwise} \end{cases}$$

$$\text{consumption}_{l,t} = \begin{cases} v^{Con}_{l,w,t} & \text{for } l \in DCon \\ 0 & \text{otherwise} \end{cases}.$$

Storage level limits are given per integrate area and primary assortment

$$v^{Str,L}_{l,w_p,t} \leq \sum_{s \in S: m_I(s) \in l, w \in m_w^{-1}(w_p)} v^{Str}_{s,w,t} \leq v^{Str,U}_{l,w_p,t} \quad \forall l \in LInt, w_p \in W_p, t \in \hat{T}. \tag{4.36}$$

Storage target levels are respectively given per integrate area and primary assortment

$$v^{Str,D}_{lInt,w_P,t} = v^{Str,Trgt}_{lInt,w_p,t} - \sum_{s \in S: m_I(s) \in lInt} \sum_{w \in m_w^{-1}(w_p)} \left[v^{Str}_{s,w,t} \right] \quad \forall lInt \in LInt, w_p \in W_p, t \in \hat{T}. \tag{4.37}$$

Storage at each terminal is limited by its storage capacity

$$\sum_{w \in W} v^{Str}_{s,w,t} \leq v^{Str,T}_{l} \quad \forall s \in STerm, t \in T. \tag{4.38}$$

Consumption is compared to demand and all deviations are tracked using unsatisfaction and oversatisfaction variables

$$\sum_{w \in m_i(i)} v^{Con}_{l,w,t} + v^{Con,\downarrow}_{l,i,t} - v^{Con,\uparrow}_{l,i,t} = v^{Dem,U}_{l,i,t} \quad \forall l \in DCon, i \in DItem, t \in T. \tag{4.39}$$

Unsatisfied and oversatisfied demand are restricted to a fraction of the total demand

$$0 \leq v^{Con,\downarrow}_{l,i,t} \leq s^{Dem,\downarrow,U} \cdot v^{Dem,U}_{l,i,t} \quad \forall l \in DCon, i \in DItem, t \in T \tag{4.40}$$

and

$$0 \leq v^{Con,\uparrow}_{l,i,t} \leq s^{Dem,\uparrow,U} \cdot v^{Dem,U}_{l,i,t} \quad \forall l \in DCon, i \in DItem, t \in T. \tag{4.41}$$

For certain kinds of consumption it is required for the consumption of a certain subset of assortments to form a minimum share of the consumption of a set of assortments, e.g. a pulp mill might consume a minimum share of softwood chips compared to all consumed softwood

$$s_{i,\hat{\imath},l}^{Dem,L} \cdot \sum_{w \in m_i(\hat{\imath})} v_{l,w,t}^{Con} \leq \sum_{w \in m_i(i)} v_{l,w,t}^{Con} \leq s_{i,\hat{\imath},l}^{Dem,U} \cdot \sum_{w \in m_i(\hat{\imath})} v_{l,w,t}^{Con}$$

$$\forall l \in DCon, i, \hat{\imath} \in DItem, m_i(i) \subset m_i(\hat{\imath}), t \in T. \quad (4.42)$$

By-products are created according to consumption and the given by-product coefficient

$$\sum_{w \in W} v_{l,w,t}^{Con} \cdot s_{l,w,\hat{w}}^{BPr} = v_{l,\hat{w},t}^{B} \quad \forall l \in DCon, \hat{w} \in W, t \in T. \quad (4.43)$$

4.6 Complexity Reduction Measures and Performance

Using a 12 month time horizon and the full planned geographical scope, the problem size becomes large. Some measures were considered in trying to reduce the number of constraints and variables in the problem formulation. In the above formulation, especially the transportation network and harvesting opportunities were found to form a significant share of the variables and constraints in the model. Therefore reducing the size of the transportation network and the harvesting decision space were identified as promising candidates for reducing the overall problem size and computation time.

When all routes between all locations are considered, the number of edges in the transportation network is $\left(\sum_{o \in L} \sum_{d \in L} \sum_{m \in TMod} Trns_{o,l,m}\right) \cdot |W|$. To reduce the number of decisions $f_{o,d,tMod,w,t}$, either reducing the number of time steps or the size of the transportation matrix is required. As depicted by Figure 3.5 there are a limited number of types of transportation opportunities:

- Forwarding from harvesting sources to roadside storage
- Truck and external transportation from purchasing sources to terminals, mill stocks and sales destinations
- Truck, ship and train transportation from import sources to mill stocks
- Truck transportation from roadside storage to terminals, mill stocks and sales destinations

- Railway, ship and float transportation from terminals to mill stocks
- Conveyor and other short transportation from mill stocks to mills
- Truck transportation from sawmills and plywood mills to other mill stocks and sales destinations.

Of these edges, a large share is formed by truck transportation opportunities from roadside stocks to sales destinations, mainly driven by the relatively large sizes $SRoad$ and $DSal$. Demand in sales destinations is however often limited to a few assortments per location and therefore for all $o \in SRoad, dSal \in DSal, tMod \in TMod, w \in W, t \in T$ where $\sum_{p \in P} v^{Sal,U}_{dSal,w,p,t} = 0$, all $f_{o,dSal,tMod,w,t}$ can be disregarded reducing the number of flows to consider.

In addition to considering demand for wood assortments, the network can be pruned by setting a maximum unit transportation cost to consider. For instance, transportation of pulp wood from Northern Finland to Lappeenranta on the road network may be physically possible but prohibitively expensive. The upper limit can be set globally for all transportation opportunities, but defining the upper limit for each transportation opportunity type separately allows for pruning the network further. Consider for instance direct truck transportation from sources to mill stocks and sales destinations and truck transportation from sources to terminals. Here wood transported to terminals will incur additional transportation costs before reaching its end destination, while direct truck transportation includes all transportation costs included in the mill gate price, suggesting that truck transportation to terminals should be comparatively cheaper.

Similarly, harvesting activities only produce wood among a subset of all possible assortments. Therefore for all $l \in OHar, hType \in HType, hSeas \in HSeas, w_p \in W_p, t \in T$ where $w \in m_w^{-1}(w_p)$ and $s^{Har}_{l,hType,w_p} \cdot v^{Har}_{l,hType,hSeas,t} = 0$, all $v^{Har,O}_{l,hType,hSeas,w,t}$ can be discarded. However, due to roadside purchases there is no guarantee that flow from $OHar$ is limited to harvested assortments meaning that the transportation network cannot be pruned on the same basis.

These effectiveness of the pruning measures were assessed using the 12 month indicative dataset. The measures were found to reduce the variable count before any presolve passes by roughly 66% and the constraint count by roughly 16%. This highlights the facts, that a naïve formulation of the problem may lead to unnecessary complexity, and that the complexity can be reduced by pruning the data.

The model was implemented using the AMPL modeling language and solved for each scenario using the barrier algorithm of the Gurobi optimizer. A laptop with an Intel i5-4300U CPU and 12 gigabytes of memory was used to evaluate solution times. In performance tuning experiments, the parallelizable barrier algorithm was found to outperform both the primal and dual simplex methods. With the selected hardware and problem complexity, the solver was further found to be CPU bound. This suggests that running the solver on more powerful hardware, such as on a virtual compute instance, could improve solution times. Table 4.4 displays the number of variables and constraints as well as the amount of solver time required to solve optimal plans for time horizons of various lengths. As evident from the description in Section 4.3, the model contains only a small number of variables and constraints that are not time-dependent. This leads to variable and constraint counts to increase almost proportionally to the planning horizon length. However, the solution time is found to increase non-linearly. Notably, the full 12-month planning horizon results in solving times in excess of the targeted time of a few minutes. Nevertheless, while falling short of the performance target, the model can still be considered usable.

Table 4.4: Problem complexity for various planning horizons, expressed in absolute and per-month quantities

Months	1	3	6	12
Variables	207 876	506 998	960 512	1 876 269
Constraints	181 466	407 445	746 429	1 424 537
Time (s)	5,59	31,8	152,4	1 249,8
Variables/ month	207 876	≈ 169 000	≈ 160 085	≈ 156 356
Constraints/ month	181 466	≈ 135 815	≈ 124 405	≈ 118 711
Time/ month (s)	≈ 5,59	≈ 10,6	≈ 25,4	≈ 104,15

Chapter 5

Results and Discussion

In this chapter, the output from the model using a test dataset is presented and discussed. The dataset constructed for this purpose is realistic enough for assessing the model's behavior and performance, but it should be only considered to be indicative of the data finally used in planning. Hence all outputs presented here should be only considered to be likewise indicative.

After the base case, the input data is modified according to selected example cases that illustrate the model's behavior under different environments. The cases have been drafted to correspond to possible future scenarios, where the planning system should support decisions in the planning process by adapting the generated plan to account for the changed environment. The developed scenarios can be roughly divided into changes in supply and changes in demand. On the demand side, the impacts of an increase in demand and a production line conversion are assessed. On the supply side, the effect of an import cost increase is analyzed. In order to capture both local and system-wide effects, the analyses focus both on individual mill gate prices and catchment areas[1] as well as on the components of the overall objective function. The computational performance, optimal objective value and optimal decisions are used to assess the feasibility of the results. The results' suitability for decision support is also demonstrated using results from the scenario analyses.

The mill gate price is a central measure for sourcing costs, and it is also used in this discussion to summarize the cost of wood for each individual mill. Figure 5.1 shows the principle of allocating sourcing costs at every source location to transport destinations proportionally to the planned transportation

[1]Catchment area is the area from which wood is supplied to a particular mill.

flow volume. Like direct flows to mills and sales destinations, planned wood flows to terminals are used to allocate costs to terminals. These costs are further allocated to consuming mills and sales destinations where the wood is finally transported. All volumes and costs are summed over time to mitigate the effect of stock level changes.

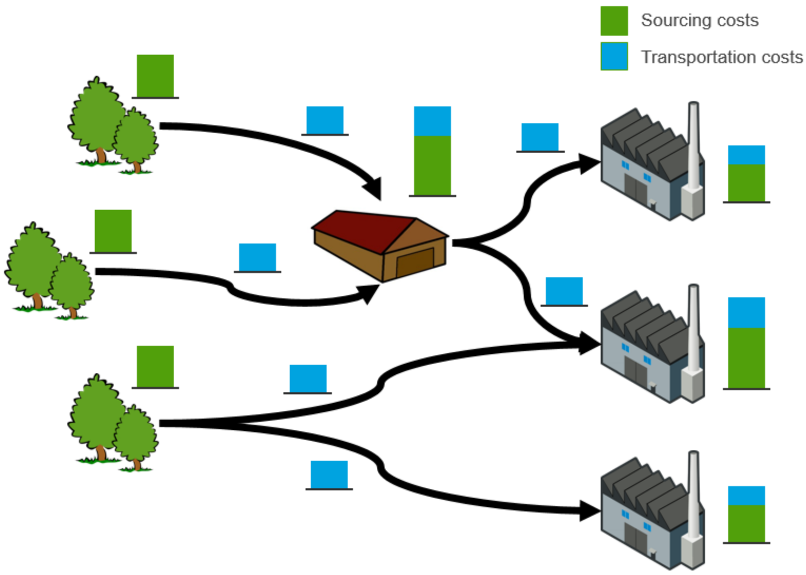


Figure 5.1: Allocation of sourcing and transportation costs to mills

5.1 Base Case

The base case is first used to illustrate the general characteristics of the planning problem and the resulting optimized plan. This discussion consists of descriptions of overall computation time and objective function components as well as snapshots into flows and mill gate prices for individual mills or regions, describing in part the optimal sourcing plan.

The optimal plan is characterized by its objective value and the corresponding optimal decisions. Figure 5.2 shows the base case objective function divided into components as defined in (4.4) as a percentage of the total objective value. The components are grouped into direct sourcing costs, net trade balance from B2B purchasing and sales as well as different penalties. Comparing the objective breakdown to the industrial roundwood removals as shown in Figure 2.7, roadside costs are found to form a relatively small portion of all related costs, while stand purchases and harvesting costs related to stand trades are emphasized. In order to meet demand, wood sourced through stand purchases, roadside purchases, import and B2B purchasing are all utilized to large extent, showing how the current business environment necessitates the use of all types of wood sources. Most penalty terms are maintained on a minor level, indicating that most demand is fulfilled cost effectively and that harvesting deadlines and storage targets are respected.

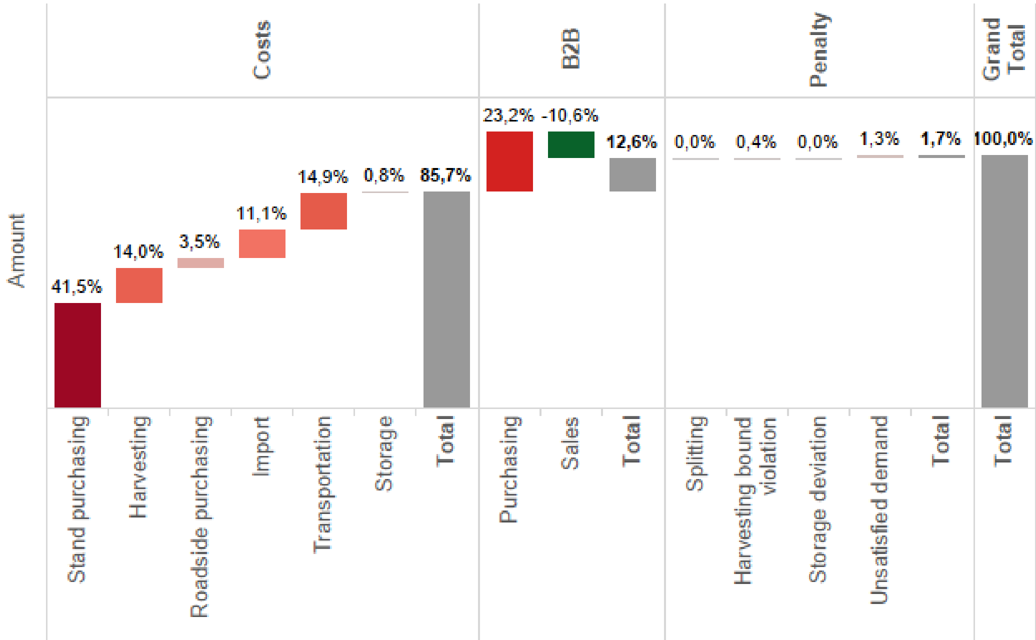


Figure 5.2: Objective function components as a percentage of the total objective value

The quality of the optimal decisions can be assessed by analyzing the optimal catchment areas. Figure 5.3 exhibits a snapshot of how harvested wood is transported from two neighboring districts in eastern Finland during a single month. A darker shade of green indicates a higher volume of wood. It should be noted, that the transportation destinations only include mill stocks and sales destination and exclude wood flows to terminals. Even with this exclusion, the figure shows how wood is mainly transported to locations in the vicinity of harvesting locations in trying to minimize transportation costs.

However, co-production of wood in harvesting operations and limitations on wood assortments in consumption also affect catchment areas. It is entirely plausible for wood from the same location to be allocated to several different destinations. For instance, harvesting operations producing both logs and pulp wood often have the logs delivered to a saw mill or a plywood mill and the pulp wood delivered to a pulp mill or a paper mill elsewhere.

Figure 5.4 in turn shows direct flows to four similar mills during a single month. In terms of areas of different mills, the preference of local forests over remote ones is an expected outcome. In addition, there is some overlap between catchment areas, which corresponds to allocating wood from a single location to several destinations as also indicated in Figure 5.3.

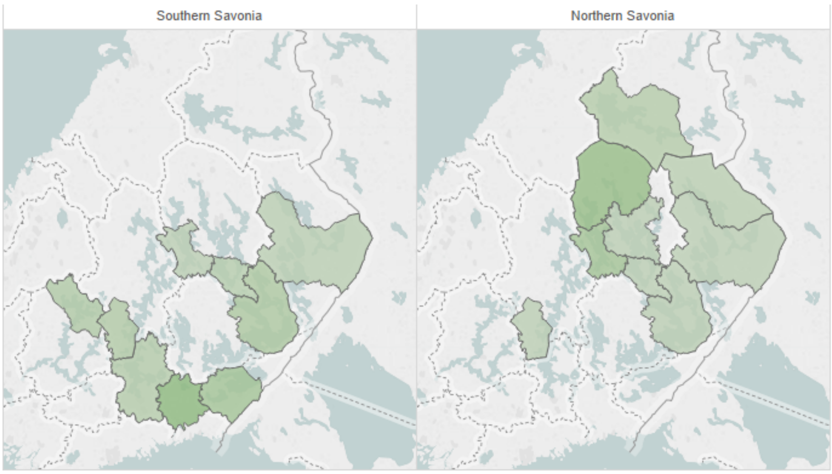


Figure 5.3: Distribution of consuming destinations from roadside stocks in the regions of Southern and Northern Savonia during a single month

Another way to analyze the optimal plan is to draw the planned mill gate price curves of each mill. Figure 5.5 displays the cost curves of two mills, indicating how different combination of sourcing wood (e.g., direct standing and roadside or standing and roadside via terminals) are associated with a unit mill gate price. Each individual source of wood is drawn as a rectangle whose width denotes the volume of the sourced wood and whose height denotes the average unit mill gate price. The total area of each rectangle then represents the total cost at mill gate for wood from that source. Arranging the blocks for each source in the order of ascending unit mill gate price yields an estimate of the realized cost curve.

It should be noted that the cost curves of the mills are dependent, and changing the consumption at one mill may affect the realized cost curves

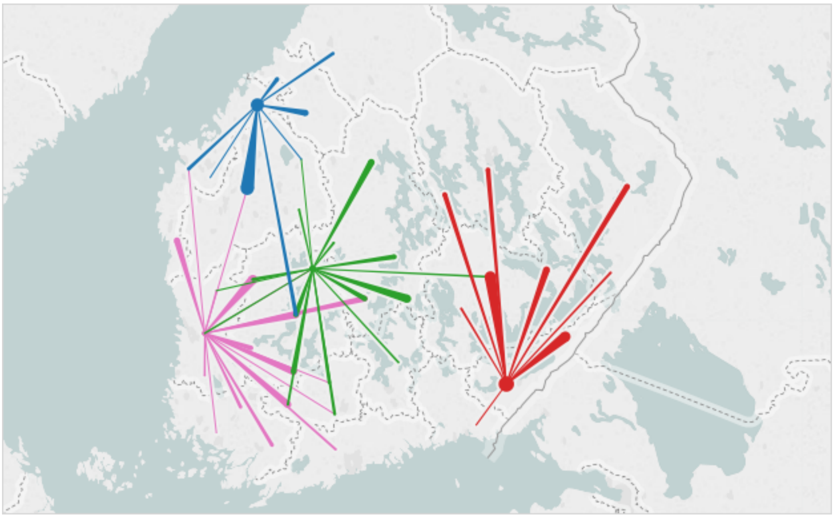


Figure 5.4: Direct transportations to four similar mills during a single month, with volume indicated by line width

at other mills. Essentially, decreasing demand at one mill might result in allocating wood that was previously delivered to that mill to be delivered somewhere else in the new optimum. This reduces the expected savings at the mill that reduced demand, while possibly reducing costs at mills that did not reduce demand. Likewise, increasing demand at one mill might result in allocating wood that was previously delivered to another mill to be now delivered to the mill with more demand, increasing the price for other mills in the process. In addition, co-production constraints and changes in demand may change optimal harvesting plans throughout, since the feasibility of a harvesting decision is determined by the demand for all yielded assortments.

Figure 5.5 also differentiates between different sourcing methods, showing how standing and roadside purchasing wood delivered via terminals tend to be the cheapest sourcing methods for both mills, while purchasing, standing and roadside purchasing batches with direct delivery tend to have higher unit costs. The lower mill in addition benefits from a large import opportunity representing a large fraction of all sourced wood. In its right end the mill is exposed to a very expensive purchasing batch, suggesting a reduced marginal profit for that last batch of wood.

In summary, the base case planning model is found to use all allowed wood sources to satisfy given demand, with quantities resembling historical trends. The small penalty term values imply that the soft constraints are

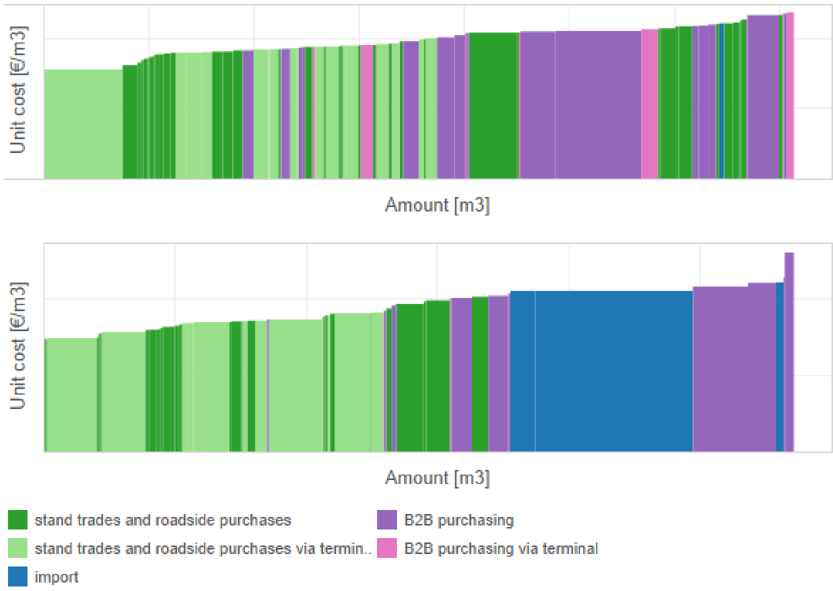


Figure 5.5: Realized cost curves of two mills in the base case

not violated to a major extent and catching area snapshots imply that the optimal solution tends to favor local wood sources. The realized cost curves describe the wood sources used to satisfy demand and highlight particularly expensive deliveries of wood.

5.2 Illustrative Example Scenarios

The base case is further varied according to three scenarios that affect either supply or demand in the system. The scenarios are compared to the base case using the objective function breakdown and relevant mill gate price and catchment area snapshots. The resulting differences are then discussed. The scenarios are described as follows:

Increase in consumption Additional production capacity is installed in one of the mills, leading to a sustained increase in demand. Several demand increments are assessed to create a cost curve beyond the original consumption. The mill gate price for the mill in question is found to only partially cover the total cost increase in the sourcing network.

Production line conversion A product line at a mill is converted to only consume one of two demand items, leading to a sustained increase in demand of one demand item and a corresponding decrease in demand for the other. Both conversions are found to increase the total objective value due to partially different reasons, suggesting that barring any changes in the business environment, a mix between the two should be used.

Import cost increase Cost of imported wood is significantly and indefinitely increased for instance due to exchange rate or tariff cost changes. A production line conversion is assessed as a response to the cost increase. The cost increase is expectedly found to result in a higher objective value, and against expectations the conversion response is found to further increase costs.

5.2.1 Increase in consumption

In the first set of scenarios, consumption in a pulp mill is increased in 20% increments from 20% to a 80% total increase. As a consequence of the price elasticity of supply, it is expected that increasing consumption also increases the average unit mill gate price. The direct effect on the mill gate price for demand increasing mill is shown in Figure 5.6, where demand increases induce an accelerating growth in average mill gate price and an 80% demand increase ultimately leads to a roughly 12% higher price.

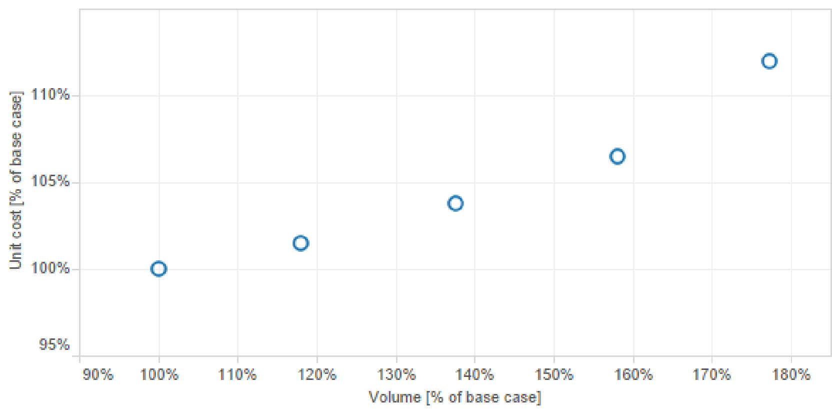


Figure 5.6: Increases in average unit mill gate price as a function of increasing consumption volume at the case mill

To further decompose the price increases into more detail, Figure 5.7 shows the volume and cost increases by wood type and sourcing method.

Purchasing and import volumes show no sensitivity to demand and the additional volume is rather sourced from standing and roadside purchases, implying that additional purchasing and import volume is either not available or is prohibitively expensive. At first the relatively cheap pulp assortments are used to satisfy increased demand. In order to satisfy further increases in demand, much more expensive logs are brought in, leading to accelerating price increases.

In addition to increasing the mill gate price at the mill with increased demand, the price elasticity of supply causes the demand increase to also affect prices throughout the system. Figure 5.8 shows the relative price increase at the pulp mill and at another nearby mill that follows its base case demand. Increasing demand at the pulp mill forces the nearby mill to source more expensive wood, leading to increased mill gate price. The catchment area comparison in Figure 5.9 is consistent with the mill gate price changes. The other mill bears a share of the increased costs by also increasing its catchment area in response to the pulp mills demand increase. This suggests that the total sourcing cost is minimized by spreading the impact of the demand increase across several mills.

In order to get a clear picture of the demand increase's impact, the change in the total objective value needs to be assessed. Figure 5.10 revisits the cost increase assessment from Figure 5.5 and additionally displays the increase in *reallocated unit cost* that allocates the total objective function change to the pulp mill whose demand has been increased, thus giving another perspective into the the cost implications of the demand increase. The reallocated unit cost increases are found to be up to 6 times the direct mill gate price increases depending on volume increase.

This highlights the fact that when planning for increased demand, both mill-wise and system-wide price changes need to be assessed. In the case example here it was found that the system tends to absorb the majority of the cost increase, making the mill-wise assessment an inadequate proxy in assessing the total price impact for the system.

5.2.2 Production line conversion

In the second set of scenarios, the sourcing cost effect of converting a production line at a mill is assessed. In the base case, the mill in question consumes mostly softwood and hardwood only to a limited extent. The conversions

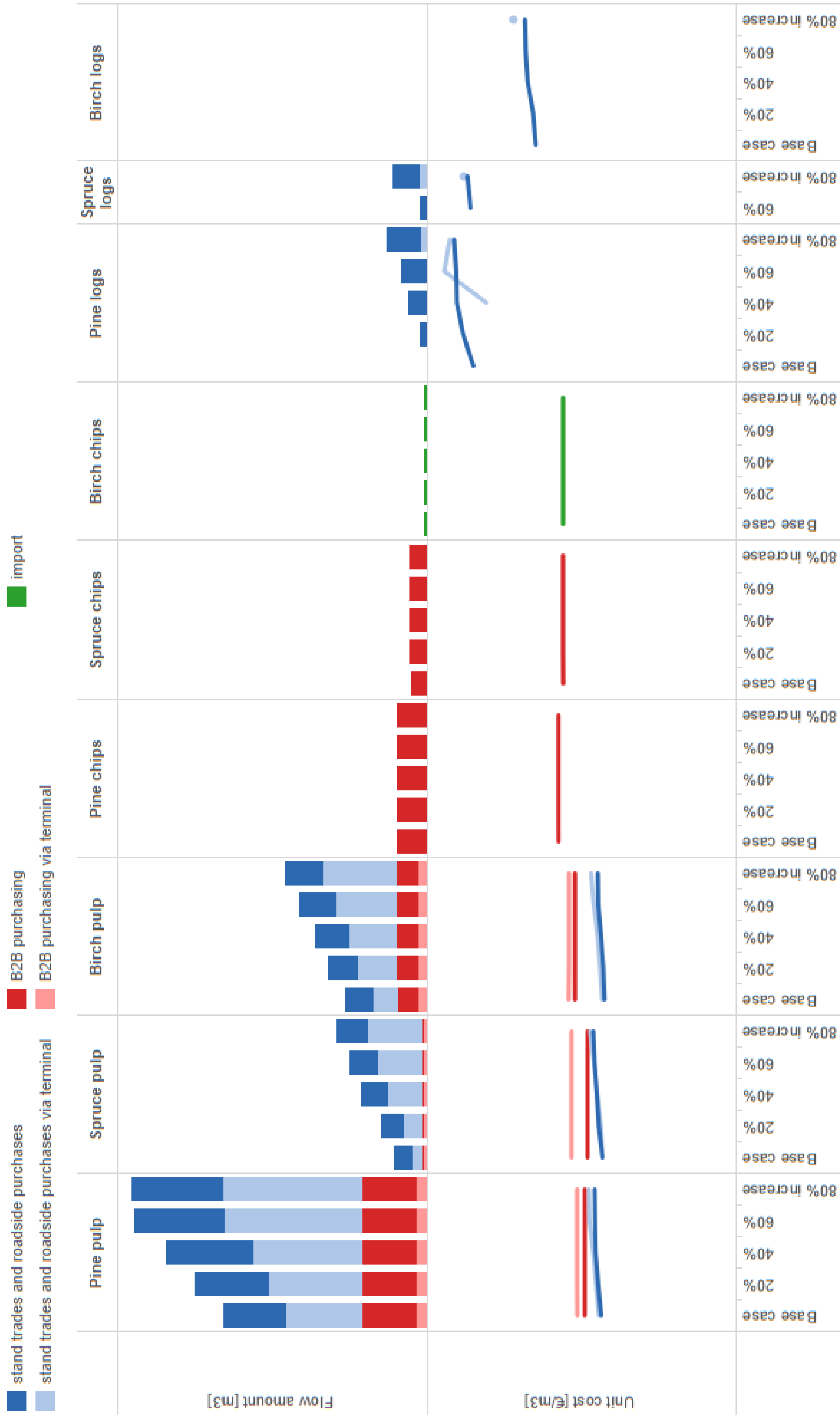


Figure 5.7: Sourcing volume and average unit mill gate price increases at the case mill by wood source and assortment

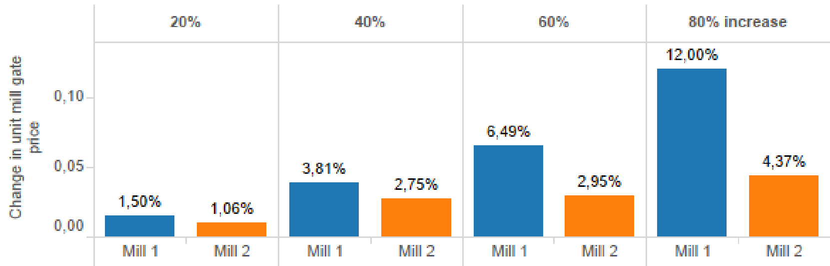


Figure 5.8: Relative mill gate price increase at the pulp mill (mill 1) and another nearby mill (mill 2)

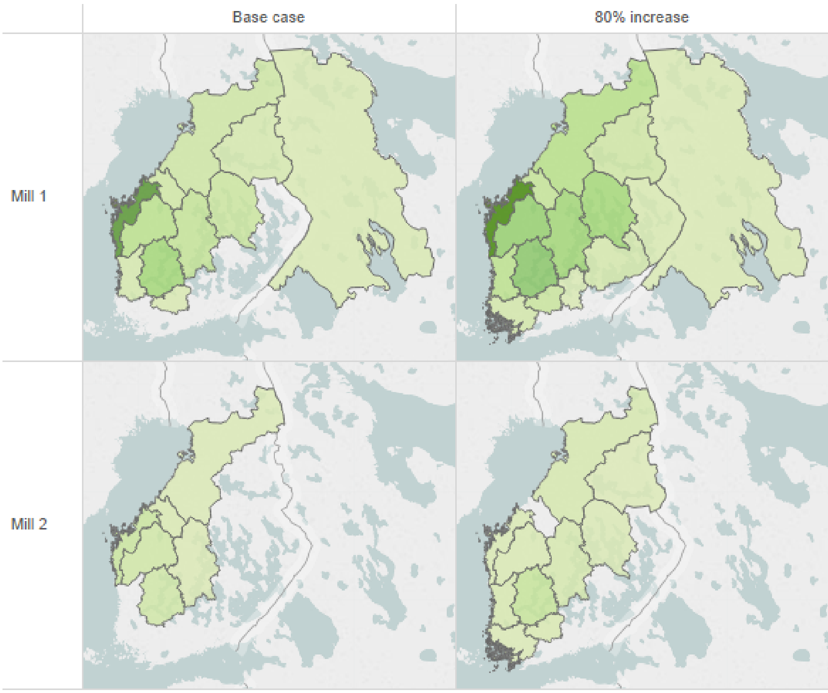


Figure 5.9: Catchment area comparison of the pulp mill (mill 1) and another nearby mill (mill 2) under the base case and under 80% pulp mill demand increase

shift demand at the mill from one demand item to another. Since different production methods consume raw material at different rates, this also changes the total demanded volume to some extent. Here two options are assessed: either converting one production line at the mill to consume only hardwood or only softwood. The former option results in a more balanced mix between the types of demand while the latter results in pure softwood demand.

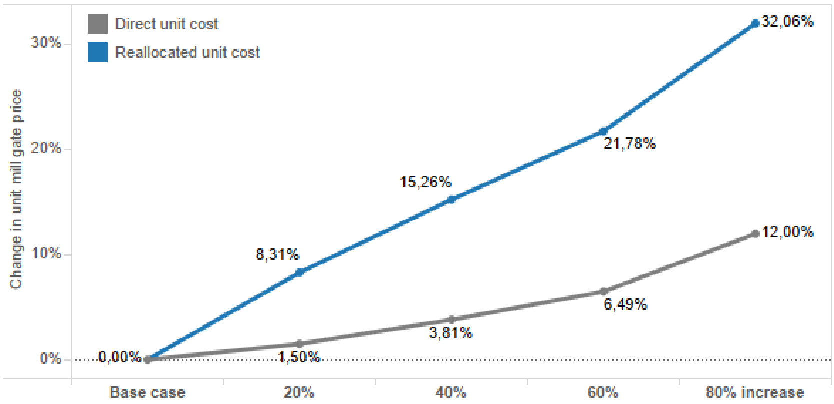


Figure 5.10: Comparison between increases in direct mill gate price increases and reallocated mill gate price increases

Figure 5.11 shows the resulting optimal hardwood and softwood flows as a percentage of the total base case flow for each scenario. The softwood conversion results in the total wood flow volume to increase by approximately 3,9% and direct mill gate price by 4,3%, whereas the hardwood conversion *decreases* the total flow volume by 6,0% while slightly *increasing* the direct unit price, implying that the hardwood supply exhibits significantly steeper price elasticity.

Figure 5.12 in turn show the catchment area for hardwood and softwood for the base case and both conversion scenarios. In all scenarios, hardwood is sourced from a wider area that also includes imports, while softwood is sourced from a smaller, focused catchment area. Expectedly increasing the demand for either type of wood grows the respective catchment area and decreasing demand respectively shrinks it. As previously noted in the demand increase analysis, catchment area changes for a single mill often cause the catchment areas of other mills to change. This raises the question of whether the simple flow and direct mill gate price analysis above is sufficient to assess the impact from the production line conversions.

As a means to assess the complete effect of the mill conversions, Figure 5.13 shows the objective value breakdown of each scenario in question, showing how both hardwood and softwood conversions lead to increases in the total objective value. The total increase however comes from partly different sources for either conversion. Both conversions result in increases in harvesting, stand purchases and wood flow costs. The hardwood conversion results however in a lower net cost from B2B trades while partially offsetting

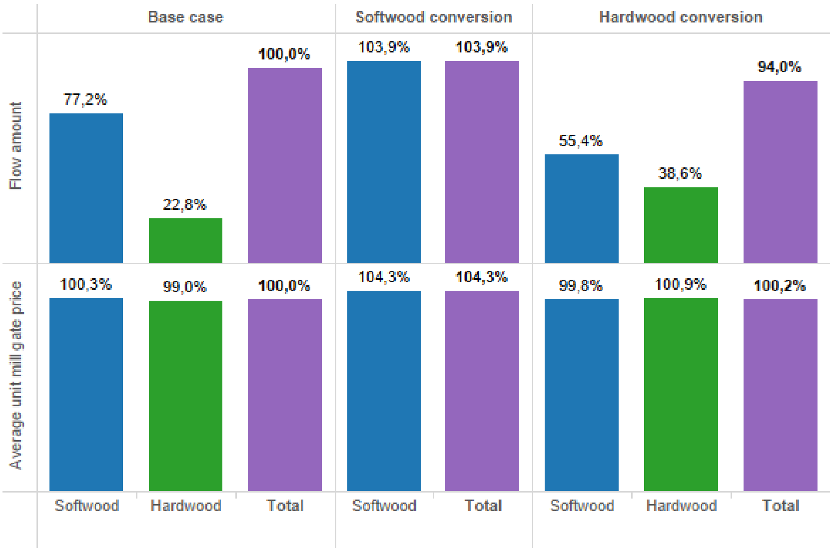


Figure 5.11: Flow amounts as a percentage of total base case flow and respective average unit mill gate price as a percentage of average base case price

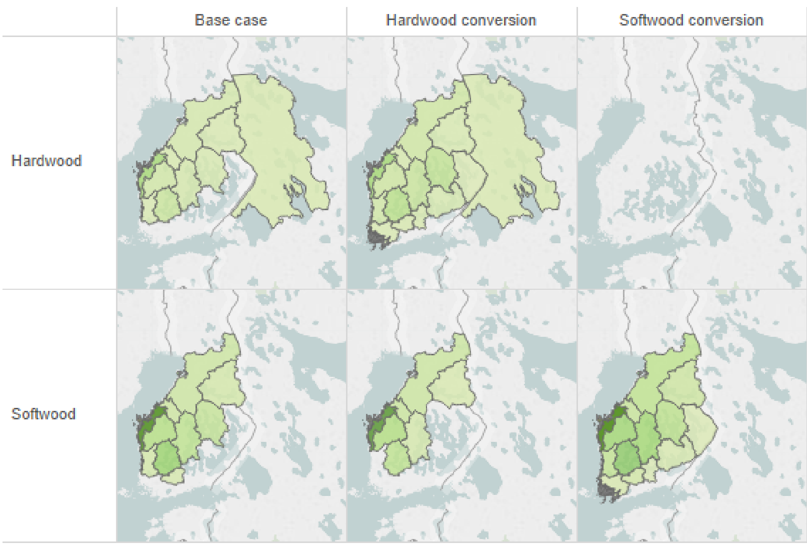


Figure 5.12: Catchment areas of the converted mill for hardwood and softwood for the base case and both production line changes

this with an increase in demand unsatisfaction. Therefore it is implied that the conversions are expensive for different reasons: the softwood conversion results in higher mill gate prices due to increased volume and price elasticity effects, while the hardwood conversion fails to source enough wood to satisfy demand in an economically feasible way. It should be pointed out that only sourcing costs are assessed here, and the increased sourcing costs should be compared to respective revenue changes to assess the profitability of the conversions.

Figure 5.13: Objective value breakdown for the base case and both conversion scenarios as a percentage of base case total

5.2.3 Import cost increase

In the final set of scenarios, the effects of a significant import cost increase are assessed. The unit import costs over the planning horizon are increased by 50% to simulate a scenario, where for instance the Ruble significantly appreciates in value or export tariffs are introduced. The assessment is conducted from the perspective of a mill that is much dependent on imports, as well as considering the system's total cost. As can be expected, an import cost increase leads to higher sourcing costs. Hence a response, where in an attempt to mitigate this effect, the mills production lines are converted in a similar manner as above, is also assessed.

Figure 5.14 shows a comparison of catchment areas for hardwood and softwood for the import dependent mill under the base case, import cost increase and conversion response scenarios. In the base case, both hardwood and softwood are sourced via importation, while softwood is to some extent also sourced domestically. The picture changes in the cost increase scenario as especially softwood sourcing is now shifted from imports to domestic sources. This suggests that there is ample supply for softwood from different sources while hardwood needs to be imported even at a high cost.

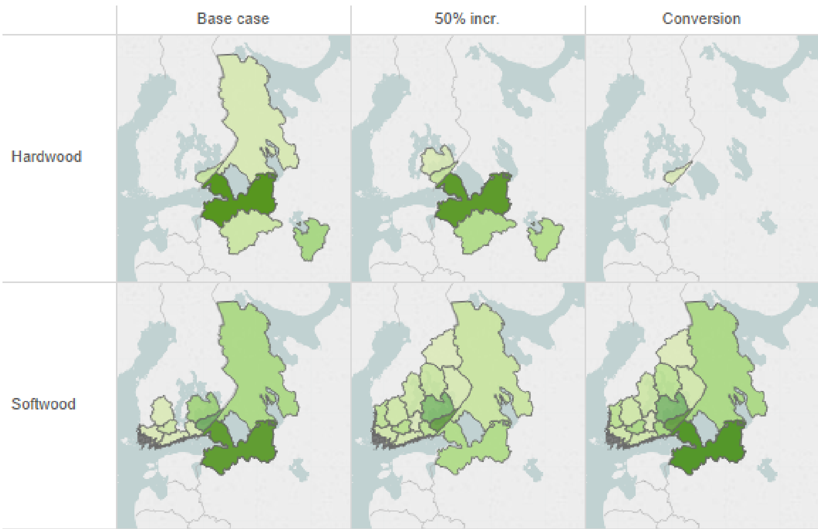


Figure 5.14: Catchment areas for an import dependent mill for the base case, cost increase and conversion response scenarios

Figure 5.15 shows the flow amounts and direct mill gate prices of hardwood and softwood for the base case, cost increase and conversion response scenarios. In comparison to the base case, the import cost increase causes a minor decrease in the mill's consumption as all demand cannot in this instance be satisfied in an economical manner. It is also notable that the average unit mill gate price for hardwood is increased by more than 30% whereas the softwood costs only see a minor price increase, which is consistent with the catching area shift in Figure 5.14.

The inability to shift hardwood sourcing from import sources and the resulting high hardwood prices now raise the questions of whether it would be economically beneficial to alter the import dependent mill's consumption. Based on the cost increase scenario, softwood is widely available domestically

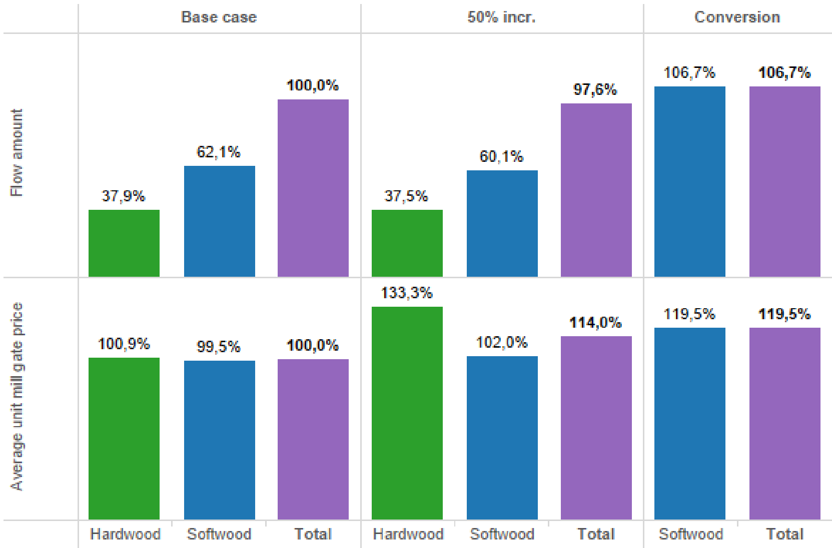


Figure 5.15: Flow amounts as a percentage of total base case flow and respective average unit mill gate price as a percentage of average base case price

and could potentially be cheaper to consume. On the other hand, softwood is also subject to increasing marginal mill gate prices, suggesting that a major demand increase might lead to large unit cost increases.

The conversion scenario shown in Figures 5.14 and 5.15 expectedly results in hardwood imports to seize completely. However, domestic softwood sourcing turns out to be insufficient in satisfying the higher demand. As a result, softwood imports are needed to fulfill demand and subsequently the mill sees a 19,5% increase in average unit mill gate price when compared to the base case. This makes it even *more* expensive than the cost increase case where no changes to demand were made.

As in the cases above, the effects of the changes are not only evident in costs and catchment areas of single mills, but also in the total objective value. Figure 5.16 shows the objective value breakdown for each scenario, showing a similar trend as in the individual mill figures. While the import cost increase leads to a 4,9% objective value increase overall, the conversion reaction leads to an even higher 7,7% overall increase. This together with the mill analysis suggests that the conversion is not an appropriate response to the price increase. Interestingly, the objective value increase in the import cost increase scenario is caused mostly by stand purchases and B2B trade balance changes. This is consistent with the catchment shift in Figure 5.14: it is cheaper to shift sourcing to domestic sources instead of maintaining the more expensive import volumes. Again, while the direct impact of the price change targets only mills using imported wood, the cost minimizing plan for the whole system leads to other mills to absorb a part of the effect.

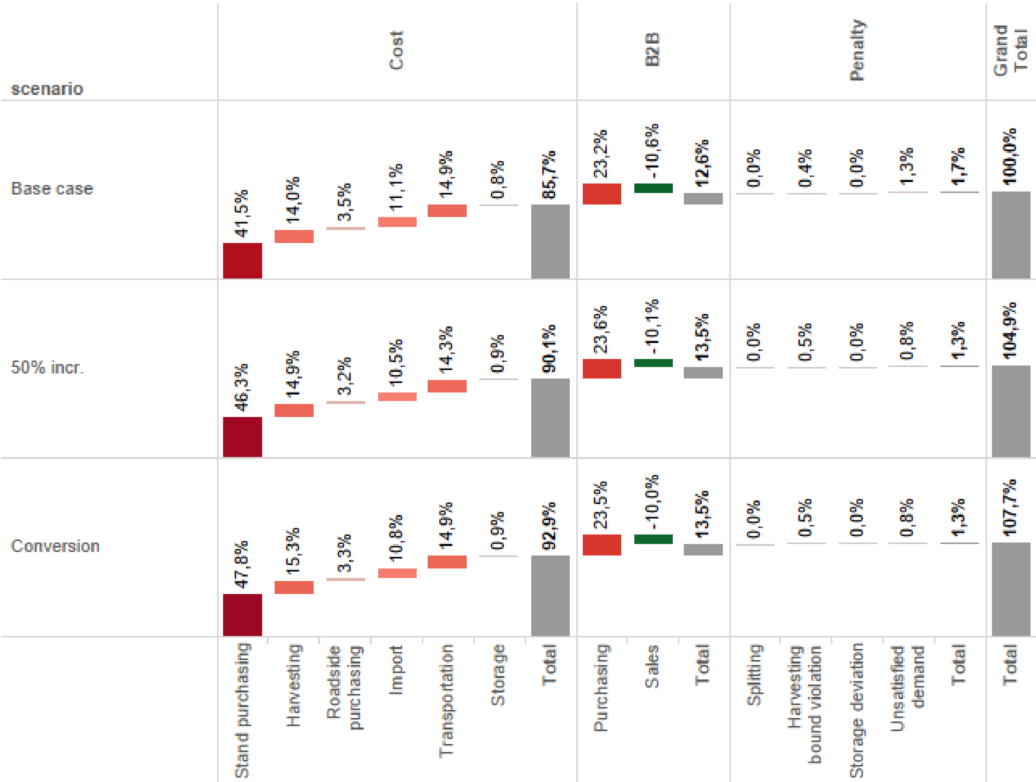


Figure 5.16: Objective value breakdown for the base case, cost increase and conversion response scenarios as a percentage of base case total

Chapter 6

Conclusions

This thesis presented an optimization model that produces decision support as a part of a larger planning system for tactical wood sourcing. The model was developed for the case company's operations in Finland, and it takes into account the significant idiosyncrasies of the local business environment. The model provides support for the purchasing, trading, storage and transportation of wood. In doing so, the model accounts for features characteristic of the forest industry on the whole, namely assortment co-production, demand substitution and by-product generation. The model additionally considers seasonal availability of harvesting sites and transportation modes as well as B2B wood trades and wood imports, that are very pertinent to the Finnish forest industry. The developed formulation also improves upon the model currently in use by considering the problem on a monthly resolution instead of as a single period problem and enabling the use of piecewise-linear unit costs. When integrated into the new planning system, the combination is also expected to improve the accuracy of the planning process and to reduce the amount of manual work that it involves as a whole.

The model's complexity was assessed in an effort to increase performance. The initial model generated using an indicative data set was found to be large and several complexity reduction measures were investigated to improve performance by reducing the problem size. Pruning the transportation network and harvesting opportunities significantly reduced the variable count in the problem. The full 12 month planning horizon was nevertheless found to require more solver time than the targeted value of a couple of minutes.

Illustrative instances of the planning problem were constructed to examine the model's behavior under several scenarios, and ad-hoc reporting tools were devised to summarize and visualize the model's output. In the base case, the model's results were expected and logical, preferring local wood sources over remote ones. Penalty terms in the objective function were also maintained on a low level. Scenarios, in which demand was altered highlighted the fact that changes in demand for individual mills have consequences across the whole supply chain. Direct impact on mill gate price are small compared to the total price increase incurred by the whole sourcing network. In addition, a proposed consumption shift as a response to the import price increase was found to further increase prices over the base case costs. The case studies indicate that the model yields reasonable results and provides insight in situations where the operating environment changes.

Some avenues for further studies exist. First, reformulating and tuning the model should be explored in order to further reduce computation time and better enable ad-hoc analyses. Second, provided that performance can be improved, further integrating the planning process across the supply chain and planning horizons could be assessed. Using the given formulation and a normal laptop, the computation time was found to fall behind expectations. CPU boundedness and swiftly increasing solving time per solved month suggest that increasing computing power and decomposing the problem might improve performance. Bredström et al. (2004) successfully implemented a column generation strategy for solving an LP relaxation of a supply chain problem, and Gunnarsson and Rönnqvist (2008) implemented a rolling horizon heuristic for a multi period forest supply chain problem, indicating that such approaches could be beneficial.

At present, the optimization model only supplies a cost and penalty minimizing solution for given demand and linear lack cost. In terms of planning horizon, the model is also limited to mid-term analysis and subsequently assumes strategic decisions as given and ignores operational details of the supply chain. For instance, modeling production units and end product sales with possibly fewer periods could enable scenario analysis for future production location selection. Alternatively, the accuracy of route optimization could be improved in order to enable route planning of disaggregated sources and destinations. Therefore improving computational performance not only enables better analysis in the current state of planning, but also enables potential integration of planning tasks in the supply chain matrix.

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