

Improving Cut-to-length Operations Management in Russian Logging Companies Using a New Decision Support System

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Abstract

The article introduces the operational-tactical-strategic context of wood supply in Russian logging companies. In this context, the transition to cut-to-length means that multiple assortments may be produced at multiple locations in the supply chain for numerous destinations. Harvesting-forwarding and transportation are the key activities in this context. This article gives an overview of the mathematical models implemented in a new decision support system (DSS) for these companies. The DSS consists of a number of modules, including optimization of routes for the fleet of harvester-forwarder teams and truck transport. The optimization of routes is based on a two-phase algorithm where a heuristic optimization method is used for choice of best transportation paths, and dynamic programming is used for choice of daily tasks and vehicle routing. The article presents the results of three cases where the DSS has been tested. The cases selected concern daily (operational), monthly (tactical) and yearly (strategic) transport planning where planning horizons were 4 days, 3 months and 1 year, respectively. The studies have all been made in logging companies located in Northwest Russia with annual harvest levels of about 250,000 m³ per company. The studies include from 4 to 9 harvester-forwarder teams, 5 to 24 trucks, 8-10 assortments, 4-129 supply points and 4-5 demand points. The results show that the DSS can be used to support a wide range of planning decisions at company level including truck routing, fleet utilization and choice of transport method under new infrastructure assumptions. The potential cost savings calculated range from 14 to 25%.

Key words: cut-to-length harvesting, decision support system, dynamic programming, logistics, Russia

Introduction

Wood harvesting and transportation in Russia are typically conducted by logging companies with leased forests and in some cases, contractors. Technological development and environmental demands motivate the continued development of the supply chain for fully mechanized cut-to-length (CTL) harvesting. An illustration of the CTL supply chain for a Russian logging company is shown in Figure 1.

The assortments obtained from harvesting are classified according to their use. Sawlogs, pulpwood, energy logs and logging by-products are the main groups of assortments. Each group is divided into several subgroups according to their species, qualities and dimensions. After harvesting, sawlogs, pulp-

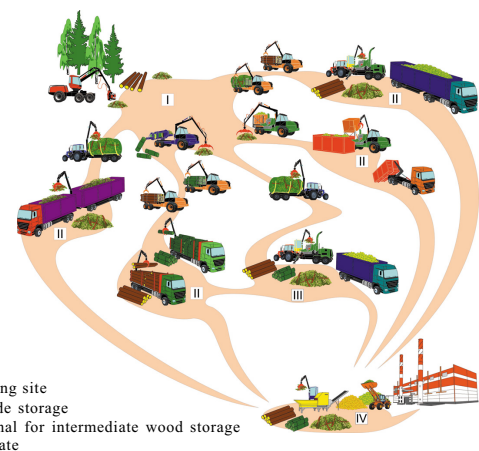


Figure 1. The different components of the cut-to-length supply chain with energy assortments included

wood and energy logs are transported directly to mills either by truck or via rail. These assortments can also be transported to a terminal for intermediate storing before transportation to the mills. The roundwood harvesting leaves some by-products in the form of tops and branches. This woody biomass is collected and extracted to roadside storages for drying and later chipping and/or transporting to heating plants.

The planning of CTL operations requires the comparison of many different potential combinations of decisions. Optimization is therefore an established approach to support decisions in CTL wood supply. The applications range from long-term problems related to company development to short-term problems such as harvesting scheduling or real-time wood transportation routing (D'Amours et al. 2007). There are typically three distinct levels in traditional forest planning which are associated with the planning horizon (Rönqvist 2003, Weintraub and Romero 2006). The *strategic* level often includes decisions that concern several years or decades. *Tactical* planning is often connected to annual decisions, but can also concern shorter or longer periods. *Operative* planning can span a couple of months or involve daily planning (Gunnarsson 2007). The difference in time for each level is not uniquely defined and depends on the type of problem. In general terms, strategic decisions involve setting goals and developing resources to fulfil these, while tactical decisions focus more on the ordered arrangement of elements. It is first at the operational level that resources are identified and scheduled. Specifically, in the context of Russian logging companies (Table 1), *yearly (strategic) planning* typically involves decisions from a year up to a decade and includes investment and infrastructure planning. *Monthly (tactical) planning* spans from a quarter of year to a year and includes annual production planning related to the budget process, wood flows and equipment utilization. *Daily (operational) planning* includes decisions up to three months such as detailed production planning and truck routing and scheduling. These

varying planning horizons make varying demands to decision support systems.

Focusing on transport decisions in wood supply, the strategic level considers decisions of one year or longer. Examples of DSSs for strategic decisions including transport system development and wood flow planning are documented by Lukka (1994) and Forsberg et al. (2005). The tactical level considers decisions from a few months down to a few weeks and an example is documented by Carlsson and Rönqvist (1998). The operative level often involves daily decisions about vehicle routing and scheduling. Several studies have been made within this area in different countries. These include, for example, Rönqvist and Ryan (1995) in New Zealand, Weintraub et al. (1996) in Chile, Karanta et al. (2000) in Finland, and Palmgren et al. (2003) and Andersson et al. (2008) in Sweden. Complete DSSs for transport decisions at various levels in Finland are documented by Linnainmaa et al. (1994) and Savola (2004).

In wood supply, the integration of yearly (strategic), monthly (tactical) and daily (operational) decisions is a challenge due to the sheer size of the tasks involved. At the same time, studies have shown that the integrated planning of supply chain operations from the stump to customer has contributed to considerable improvements in economic performance at company level. The challenges to a complete integration, however, can be compounded when operating in state-owned forests because of the configuration of leasing conditions. According to recently approved forest legislations, the daily (operational) – monthly (tactical) – yearly (strategic) context of forestry in a Russian logging company with leased forests is regulated by the Forest Development Project (FDP) of wood harvesting (Russian Federation 2006, Karvinen et al. 2011). The FDP is compiled on the basis of Regional Forest Plan and District Forestry Regulations, which are reviewed every 10 years. The FDP includes the list and location of forest areas designated for harvesting and their harvesting methods in accordance with

Planning level	Horizon	Harvesting decisions	Road decisions	Transport decisions
Yearly (strategic)	1-10 yrs	Leasing area harvest potentials Choice of harvesting method Equipment investments	Infrastructure investments Equipment investments	Choice of transport method Equipment investments
Monthly (tactical)	3 months-1 yr	Annual harvesting volumes Harvest unit scheduling Choice of equipment utilization level	Temporary truck access roads Upgrading and maintenance of permanent road	Transport delivery plan Choice of equipment utilization level
Daily (operational)	1 day-3 months	Detailed harvesting plan		Truck routing

Table 1. Planning levels, time horizons and typical decisions for operations management in wood supply for a Russian logging company

the approved rules of cuttings. The FDP is developed after the establishment of annual allowable cuttings for a leasing period and also specifies the sequencing of stands projected to be harvested during the coming revision period. The individual characteristics of each harvest area and the allocated harvesting technology are important parameters for the achievement of multiple objectives within ecology, forest protection, and work safety (Karvinen et al. 2011). The FDP is therefore a key component of the wood supply planning process.

At present, the successful implementation of the FDP procedure relies on the personal experience and knowledge of supervisors or professionals engaged in the logging company. This process is time consuming and access to professional capacities is a bottleneck to selecting the best options within the planning process. The challenge is further compounded by a rapidly changing economic situation, leading to the need for daily (operational) adjustments of the FDP. A number of business rules present some unique restrictions for managing wood supply operations in Russia. These include:

- Annual delivery plans are fulfilled according to the annual contracted volume; however, the monthly deliveries are flexible depending on many factors such as seasonal conditions, market situation, infrastructure etc.
- Seasonal intermediate storages in the forest or at a central processing yard are common practice
- Logging companies own equipment for wood harvesting and transport, and manage forest operations themselves. Outsourcing and entrepreneurship is not common practice
- Limitations for the maximal truck axle loads on public roads and bridges. The use of heavy trucks are restricted in many places
- The condition of roads, bridges and even sections of the same road may vary between periods.

The conditions encourage the development of a DSS designed specifically for the context of the Russian logging company.

Aim of the study

Due to the lack of formal analysis of harvesting and transport within wood supply at the logging company level, the objective of the study was to present the typical daily (operational) – monthly (tactical) – yearly (strategic) problems of three individual Russian logging companies and develop an integrated DSS for their logistics planning. This paper presents the DSS and illustrates its potential with three test cases in daily (operational), monthly (tactical) and yearly (strategic) planning of wood transport.

Material and methods

A full range of optimization methods are used to support the planning problems within wood supply however, different contexts present different demands to solution times. Daily (operational) problems, for example, need to be solved rapidly, within minutes, while a long-term yearly (strategic) planning problem can take many hours. Daily (operational) problems are therefore typically solved with heuristics and network approaches while monthly (tactical) and yearly (strategic) planning problems are better served with mixed integer programming and stochastic programming methods (D'Amours et al. 2007).

The core functionality of the DSS developed in the study is routing and scheduling of all resources within the individual logging company. Examples of dynamic programming approaches for handling such problems in other sectors are documented by Kok et al. (2010) and Novoa and Storer (2009). Dynamic programming was the method chosen for this study in order to serve a complete range of company planning problems by searching for strategic goals and tactical concepts based on operationally efficient resource allocations.

Dynamic programming is among the most powerful methods for designing algorithms for optimization problems. Companies with large forestland areas have utilized dynamic programming in their management planning (McDill 1999), however, because of its complexity the method has not yet been widely adopted in forestry in Russia. The DSS in this study aims to solve large scale optimization problems and we focus on discrete optimization problems for which a set or sequence of decisions are made to optimize some function of the decisions. Numerous methods exist to solve discrete optimization problems where each method has advantages and disadvantages, as discussed in other publications (Taha 2011, Lew and Mauch 2007). The most prominent of alternative methods is linear programming. Linear programming with its variants and extensions (some that allow nonlinearities) have been used to solve many real world problems. This is in part because of the earlier availability of software development tools (based on the simplex method). In contrast, fewer tools have been available for the more general method of dynamic programming (Lew and Mauch 2007) and an important criterion for this project was to develop a tool for solving dynamic programming problems which was both general and easy to use.

The DSS is integrated with application-specific databases for all the information needed for the models and GIS for visualizing the input data and results. An overview of the DSS structure and its most impor-

tant components is presented in Figure 2. The Data Module handles information about roads and their characteristics, locations of logistic management units and their characteristics. The Logistic Management Unit Module manages relevant facilities involved in supply, such as harvesting areas, roadside storages, wood processing mills, depots (garages) or railway terminals. In the Graph Module, the user can generate a set of layers for roads and logistics management units. Within the Wood Harvesting Optimization Module, production output of harvesting machines is simulated per assortment by the Wood Harvesting Simulation Sub-module as a function of average tree size, tree species, forwarding distance etc. A scheduling function in the Harvest Scheduling Sub-Module arranges the sequence of harvest areas for the planning period with consideration to growing stock, the state of the road network and seasonal restrictions.

The functionality focused on in this study is found within the Wood Transport Optimization Module where daily tasks, routing and scheduling are found for each truck with the help of dynamic programming. The

Wood Transport Optimization Module solves the planning problem at two consecutive stages; first the optimization of paths (the Paths Sub-module); and second, the optimization of routes and their corresponding schedules (the Routes Sub-module). The Paths Sub-module helps the user to search for the best paths between any unit and facility. Two approaches have been used when searching for optimal paths. The Dijkstra algorithm (Cormen et al. 2009) is used for the optimal paths during the generalized search for all possible paths (i.e., the best paths among all logistic management units at the same time). However, when finding a path between only a pair of points, a quicker heuristic algorithm was developed based on the Dijkstra algorithm documented by Gerasimov et al. (2011). Dijkstra's algorithm is used as a base, and the heuristic is an option for local changes in the graph (for example, a new customer) when the user needs to re-calculate a small number of paths.

Finally, the Reporting Module generates plans of routes and schedules for all trucks per garage. The plan indicates the points of pick-up and delivery, the

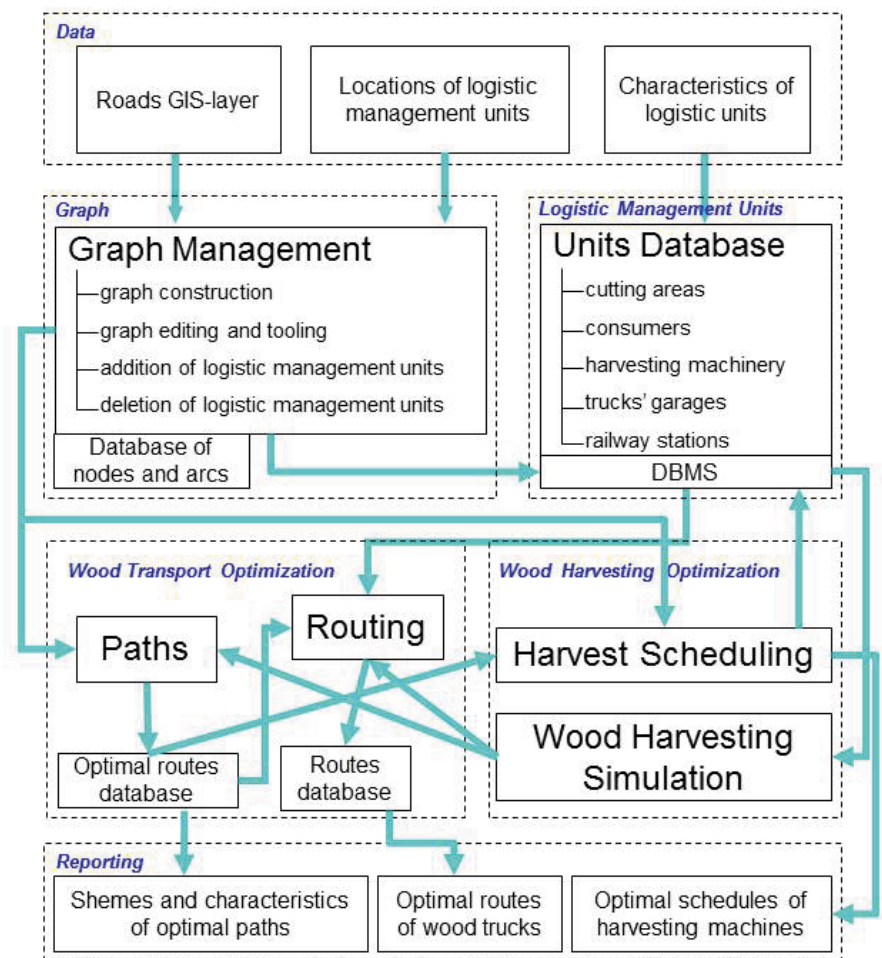


Figure 2. The structure of the DSS developed for routing and scheduling of logging company resources. The modules include Data, Graph, Logistics Management Units, Wood Harvesting Optimization, Wood Transport Optimization and Reporting Scheme

distances between them, times of arrival and departure, as well as the characteristics of the transported timber. Further documentation can be found in Gerasimov et al. (2008, 2010), Sokolov et al. (2010, 2012), and Sokolov and Gerasimov (2011).

Adapting the VRP to a logging company DSS

The core function of the DSS concerns finding solutions for daily (operational) scheduling, monthly (tactical) concepts and yearly (strategic) goals based on the most efficient allocation of transport resources. At the centre of efficient allocation of transport resources is the vehicle routing problem (VRP). The VRP can be defined as a problem of finding the optimal routes of collection or delivery from one or several *depots* to a number of *customers*, while satisfying some constraints. Much research effort has been devoted to studying the VRP since 1959 where Dantzig and Ramser have described the problem as a generalized version of the Travelling Salesman Problem (Liong et al. 2008). In a classical VRP, the customers are known in advance. Moreover, the driving time between the customers and the service times at each customer are known (Madsen et al. 1995). The classical VRP can be defined as follows (Laporte 1992): Let $G = (V, A)$ be a graph where $V = \{v_0, v_1, \dots, v_n\}$ is a set of vertices representing *customers* with the *depot* located at vertex 0, and $A = \{(v_0, v_1), \dots, (v_{n-1}, v_n)\}$ is the set of arcs. With every arc (i, j) $i \neq j$ is associated a non-negative distance matrix $C = (c_{ij})$, where i and j are the vertex numbers. In some contexts, c_{ij} can be interpreted as a *travel cost* or as a *travel time*. When C is symmetrical, it is often convenient to replace A by a set E of undirected edges. In addition, assume there are m available vehicles based at the depot. If m_L and m_U are lower and upper bounds on m , when $m_L = m_U$, m is said to be *fixed*. When m is not fixed, it often makes sense to associate a fixed cost f on the use of a vehicle. The VRP consists of designing a set of least-cost vehicle routes in such a way that:

- each customer in $V \setminus \{0\}$ is visited exactly once by exactly one vehicle;
- all vehicle routes start and end at the depot;
- some side constraints are satisfied.

The problems that need to be solved in timber transport are usually more complicated than the classical VRP. Karanta et al. (2001) give an overview of the key differences between the timber transport vehicle routing problem (TTVRP) and the classical VRP for Nordic conditions. Regardless of the context, a typical assumption of the VRP is that an empty vehicle has to start a route from a depot (or operator's home base) and come back at the end of a shift. This problem is a modification of the well-known VRP with back-

hauls (VRPB) as described by Bianchessi and Righini (2007) and Ropke and Pisinger (2006). According to the VRP with backhauls, the problem can be divided into two independent VRPs; one for demand points and one for the supply points. In this context, Ropke and Pisinger (2006) originally defined a demand point (rail terminal or mill) as a *linehaul* customer, while a supply point (harvesting site) was defined as a *backhaul* customer. The use of the term backhaul in the this context is therefore somewhat broader than the definition often used in roundwood trucking (see Carlsson and Rönnqvist 1998) where backhauling is associated with exploitation of opposing wood flows to form complex routes reducing the proportion of empty travel (and where a simple route is defined as when the loaded travel distance from forest to mill is identical to the unloaded travel distance from mill to forest).

The problem description for the VRP with backhauls as it is used in the DSS is explained below. The fleet of V vehicles departs from a depot to perform only sequential deliveries of A types of assortments from B supply points (harvesting sites) to L demand points (mills). The planning period is N shifts within D days and M months. Mills' demands follow monthly contracted volumes of each assortment. The supply volumes at supply points follow known initial stock and daily production of each assortment at a harvesting site. They (initial stocks and daily productions) are assumed to be statistically independent of each other. Variables u_{abd} and u_{alm} (defined below) describe the supply and demand for each supplier and customer. Exact supply volume for a supply point is revealed only when the vehicle arrives at the harvesting site for the first time. A vehicle route is assumed to fail when the end of a shift occurs. Considering changes in supply or demand, a vehicle route is assumed to fail when the remaining volume for a supply or demand point for the considered assortments is under a full vehicle load. The last condition is particular for the Russian industrial context. Wood harvesting in Russian companies concentrates in large-scale clear-cutting areas and the situation when the available supply is less than a full truckload rarely occurs. In this context, the DSS offers two options, to enter a "light" truck into the fleet or to merge several small piles of assortments into one delivery. Upon route failure, the vehicle returns to the depot to change drivers and wait for the next shift. The routing solution also allows vehicles to return to the depot before the vehicle scheduled time is depleted (i.e. proactive return).

The objective is to find routing solutions where the demand at each mill is satisfied with minimal travel costs. Assuming constant truck costs under full utilization, cost minimization is achieved through maximizing transport volumes per shift.

The problem can be formulated as follows:

$a = \{1, 2, \dots, A\}$ is a set of assortments

$v = \{1, 2, \dots, V\}$ is a set of vehicles

$l = \{0, 1, 2, \dots, L\}$ is a set of demand points, node

0 represents the depot

$b = \{0, 1, 2, \dots, B\}$ is a set of supply points, node

0 represents the depot

q_{va} is the vehicle v load capacity associated with assortment a , m^3 (vehicles can have different load capacities)

$t(l, b)$ is delivery time between demand point l and supply point b , h

u_{alm} the maximum loads of assortment a that can be transported to demand point l during month m , m^3

u_{abd} the maximum loads of assortment a that can be transported from supply point b during day d , m^3

u the shift duration, h

r_{abd} remaining supply of assortment a associated with supply point b within day d , m^3

r_{alm} remaining delivery of assortment a associated with demand point l within month m , m^3

t_{vd} remaining time to the end of shift associated with vehicle v within day d , h

X_{dvabl} the number of deliveries of assortment a made by vehicle v from supply point b to demand point l within day d

X_{mvabl} the number of deliveries made by vehicle v from supply point b to demand point l of assortment a within month m .

The mathematical formulation of the problem is then:

$$\sum_{d=1}^D \sum_{v=1}^V \sum_{a=1}^A \sum_{b=1}^B \sum_{l=1}^L q_{va} X_{dvabl} \rightarrow \max \quad (1)$$

Subject to

$$r_{abd} = \sum_{v=1}^V q_{va} X_{dvabl} \leq u_{abd}$$

for $a = 1, \dots, A, b = 1, \dots, B, l = 1, \dots, L$ and $d = 1, \dots, D$ (2)

$$r_{alm} = \sum_{v=1}^V q_{va} X_{mvabl} \leq u_{alm}$$

for $a = 1, \dots, A, b = 1, \dots, B, l = 1, \dots, L$ and $m = 1, \dots, M$ (3)

$$t_{vd} = \sum_{b=0}^B \sum_{l=0}^L t(l, b) X_{dvabl} \leq u$$

for $a = 1, \dots, A, v = 1, \dots, V$ and $d = 1, \dots, D$. (4)

The objective function (1) is the volume of assortments, which is delivered by the fleet of vehicles during the planning period. The constraint (2) ensures that the total daily collection volume from a supply site does not exceed the maximum supply for each assortment associated with each day. The constraint (3) ensures that the total monthly delivery to a demand point does not exceed the maximum demand capacity for each assortment associated with each month. The constraint (4) ensures that the total time that a vehi-

cle is in use during the shift, which includes driving, loading and unloading, does not exceed the shift duration.

The VRP algorithm developed for the DSS

The VRP was formulated as a dynamic programming problem. The algorithm maximizes each vehicle's volume of wood transportation per shift, which corresponds directly to a minimization of time, subject to constraints (2-4). For each load the critical time of truck arrival at the demand point is determined by the formula:

$$t_c(s) = T - t_l - t_r(s) \quad (5)$$

where

$t_c(s)$ – the critical time of truck arrival at the demand point, h

s – the number of the system state corresponding to truck location at this demand point,

T – duration of the shift, h

t_l – time of unloading, h

$t_r(s)$ – moving time from this demand point to the garage, h.

In the conditional optimization at each step of dynamic programming, the next point to be visited is determined for each current point based on minimizing the total time elapsed from the beginning of the shift to arrival at the current point.

The problem of conditional optimization is solved for the current demand point:

$$\tau_i(s) = \min\{\tau_{i-1}(u) + t(s, u) + t_l\} \quad (6)$$

where

$\tau_i(s)$ – the time from the beginning of the shift to the arrival at the current demand point, h

i – step number of dynamic programming

s – the number of the system state corresponding to the truck location at the current demand point,

$\tau_{i-1}(u)$ – conditionally minimum time from the beginning of the shift to arriving at the supply point u , obtained in the previous step of dynamic programming, h

u – the desired conditional optimal action (the supply point from which, at the given step, conditionally optimally delivers the timber assortment to the current demand point)

$t(s, u)$ – moving time from the supply point u to the current demand point, h.

The problem of conditional optimization is solving for the current supply point:

$$\tau_i(s) = \min\{\tau_{i-1}(u) + t(s, u) + t_l\} \quad (7)$$

where

$\tau_i(s)$ – the time from the beginning of the shift to the arrival to the current supply point, h

i – the step number of dynamic programming
 s – the number of the system state corresponding truck location at the current supply point,
 $\tau_{i-1}(u)$ – conditionally minimum time from the beginning of a shift to arriving at demand point u , obtained at the previous step of dynamic programming, h
 u – the desired conditional optimal action (the demand point from which a conditionally optimal decision, at this step, would be to make a run to the supply point)
 $t(s, u)$ – moving time from the customer u to the current supply point, h .

In the unconditional optimization (maximum number of delivered loads), the end of the initiated route is scanned. If there are several alternative routes with the same number of delivered loads, the alternative closest to the garage at the end of the shift is selected.

In the case of alternative timber assortments intended for delivery from the optimum harvesting area to an optimal mill the timber assortment with the highest priority is selected. Priority is set in the interface dialogues that define the characteristics of the mill and the harvesting area.

All available vehicles are included in the overall list. In the beginning, the route for the first truck in the list is defined, then – for the second (for the remaining volume of undelivered wood), then the third, etc. In this case the first truck listed is given the highest priority. This is set in the user interface dialogue for garages. If there are several garages, the first truck from the first garage is selected; then the first truck from the second garage, etc. After this come the second trucks, third trucks and so forth until all the trucks are considered or all available wood is delivered.

The scheduling function to arrange the sequence of harvest areas

The Wood Harvesting Optimization Module (see Figure 2) manages the wood supply information for harvest areas and harvesting teams. The Wood Harvesting Simulation Sub-module calculates harvesting team production and their output of harvested assortments as well as determining the optimal path and relocation time between the harvest areas. Harvesting teams can be set to include harvester-forwarder chains or conventional feller-buncher-skidder-processor chains. The Module requires initial information including harvest area characteristics, assortments and planning period (Figures 3-4). Productivity models were developed for CTL harvesting over a broad range of Russian stand and site conditions and are documented by Gerasimov et al. (2012).

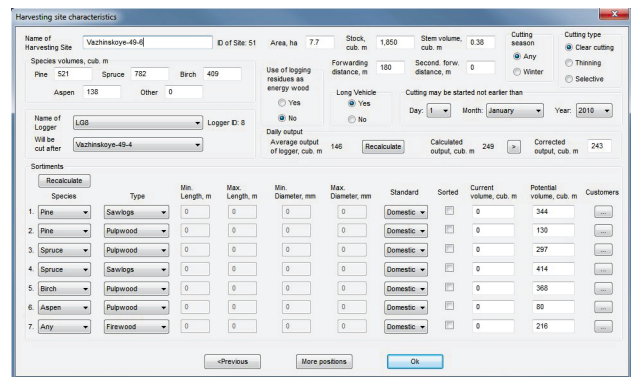


Figure 3. The user dialog for entering the characteristics of the harvest areas

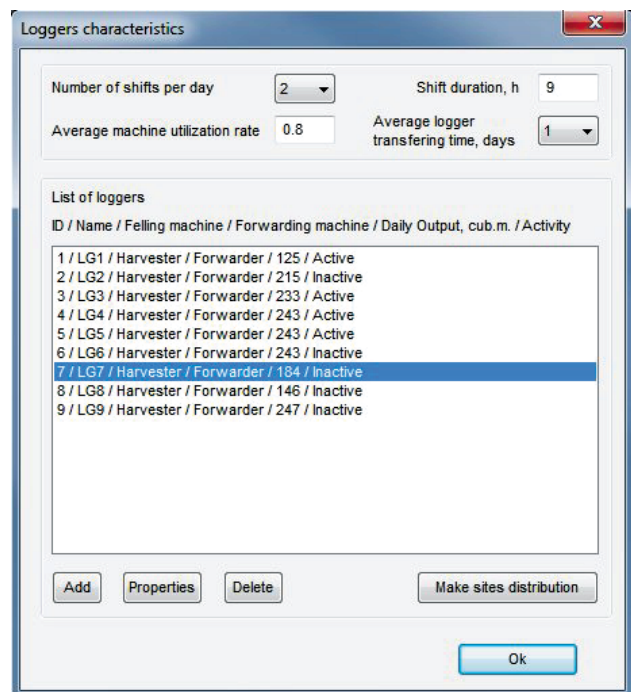


Figure 4. The user dialog for entering the characteristics of the harvesting teams

The simulation of wood harvesting requires the sequence of harvest areas designated for felling per harvesting team. An earlier version of the DSS offered the user the option to input the sequence of harvest areas manually. This did not represent any inconvenience in daily (operational) or monthly (tactical) planning tasks, because the user deals with a reasonable number of actual harvest areas. These are accurately known since some of them are already harvested and while the remaining areas are to be harvested in the near future in accordance with the harvesting plan. Yearly (strategic) planning tasks, however, require in-

put of a large number of harvest areas (sometimes over a hundred), which are not yet accurately known due to a lack of specific felling designations. The only available information this far ahead of time is the list of potential harvest areas from the FDP.

The selection of the best harvest areas from the potential ones, their sequencing, designation for felling and matching with the available harvesting teams for a long period is a complex and time consuming task because of the number of factors taken into consideration. This problem is further complicated by the pronounced seasonality of harvesting, which leads to uneven supply during the year. Harvesting volumes peak during the winter and reach their lowest levels during the spring (typically April and May). The capacity requirements and number of involved harvesting teams is therefore different for different periods. The degree of seasonal influence is different for different companies and depends mainly on soil conditions at the harvest areas, the availability of forest truck roads. As a result, the harvest areas are broken down into two categories. The first of them includes the harvest areas available for harvesting regardless of the season (year-round) and the second includes harvest areas only available during the winter.

The problem of selection of harvesting areas designated for felling is designed as the maximization of assortment value according to ExWorks (EXW) prices (Incoterm for wood price at roadside). The mathematical formulation of the problem is then:

$$\sum_{i=1}^N x_i \sum_{j=1}^n \sum_{k=1}^m V_{ij} h_{jk} C_{jk} \rightarrow \max \quad (8)$$

Subject to

$$\sum_{i=1}^N x_i \sum_{j=1}^n V_{ij} \leq T \sum_{r=1}^M P_r;$$

$$x_i = 0, \text{ for } s_i \neq S; i = 1, 2, \dots, N;$$

$$x_i \in \{0, 1\}; i = 1, 2, \dots, N,$$

where

N – the total number of potential harvest areas

x_i – controlled variable taking the value 1 if the i -th harvest area is included in the harvesting plan, and 0 – otherwise

n – the number of tree species

m – the number of assortments produced at the harvest areas

V_{ij} – the wood volume of j -th tree species at the i -th harvest area

h_{jk} – the average proportion of the k -th type of assortment obtained from the j -th tree species

C_{jk} – the average EXW price of the k -th type of assortment obtained from the j -th tree species

T – the duration of the planning period, days

M – the number of harvesting teams

P_r – the average performance of the r -th harvesting team, $\text{m}^3 \cdot \text{day}^{-1}$

s_i – a seasonal factor in the i -th harvest area

S – a seasonal factor in the planning period.

The problem of sequencing of harvest areas, including the matching with specific harvesting teams, is designed as a minimization of the relocation costs for harvesting teams. The assumption was made that the relocation costs between the harvest areas was directly proportional to moving time. The moving time between the harvest areas is determined on the basis of the distances between these points on the graph of the road network and average speeds for each section of road. The Optimal Routes Database Sub-module is the source for the necessary data regarding optimal distances and average speeds (see Figure 2). The mathematical formulation of the optimization problem is then:

$$\frac{1}{2} \sum_{r=1}^M \sum_{i=1}^N \sum_{j=1}^N y_{ijr} t_{ij} \rightarrow \min \quad (9)$$

Subject to

where

$$\frac{1}{P_r} \sum_{i=1}^N z_{ir} V_i \leq T; r = 1, 2, \dots, M;$$

$$z_{ir} = \begin{cases} 1, & \text{if } \sum_{j=1}^N (y_{ijr} + y_{jir}) > 0; \\ 0, & \text{if } \sum_{j=1}^N (y_{ijr} + y_{jir}) = 0 \end{cases}; i = 1, 2, \dots, N, r = 1, 2, \dots, M;$$

$$y_{ijr} \in \{0, 1\}; i = 1, 2, \dots, N, j = 1, 2, \dots, N, r = 1, 2, \dots, M;$$

$$\sum_{r=1}^M y_{ijr} = 1; i = 1, 2, \dots, N, j = 1, 2, \dots, N;$$

$$\sum_{r=1}^M z_{ir} = 1; i = 1, 2, \dots, N,$$

y_{ijr} – controlled variable taking the value 1 if the harvesting plan for the r -th harvesting team includes the movement from the i -th harvest area to the j -th one, and 0 – otherwise

t_{ij} – the moving time from the i -th harvest area to the j -th area, h

z_{ir} – controlled variable taking the value 1 if the harvesting plan for the r -th harvesting team includes the harvesting of the i -th harvest area, and 0 – otherwise

V_i – the total harvested volume from the i -th harvest area, m^3 .

The problem is solved as a multiple travelling salesman problem with two stages. The first stage determines the sequence of harvest areas included in the harvesting plan after the solution of Eq. (8) with-

out any reference to the specific harvesting teams. This sub-problem is solved as the classical traveling salesman problem with Prim's minimum spanning trees algorithm by introducing a restriction on the number of edges belonging to the same vertex (Cormen et al. 2009). The second stage determines the matching of harvest areas with the harvesting teams based on their specific performance. Since the number of harvesting teams simultaneously working at an average logging company in Russia rarely exceeds 10, the optimal matching of harvest areas with harvesting teams is

arranged by a complete enumeration of all possible combinations using the algorithm for generating permutations as described by Lipsky (1988).

The generalized algorithm of the Harvesting Scheduling Module for solving the optimization problems above is shown in Figure 5.

The DSS test cases

The potential improvement enabled by the DSS for daily (operational), monthly (tactical) and yearly (strategic) planning was tested in three transport-related

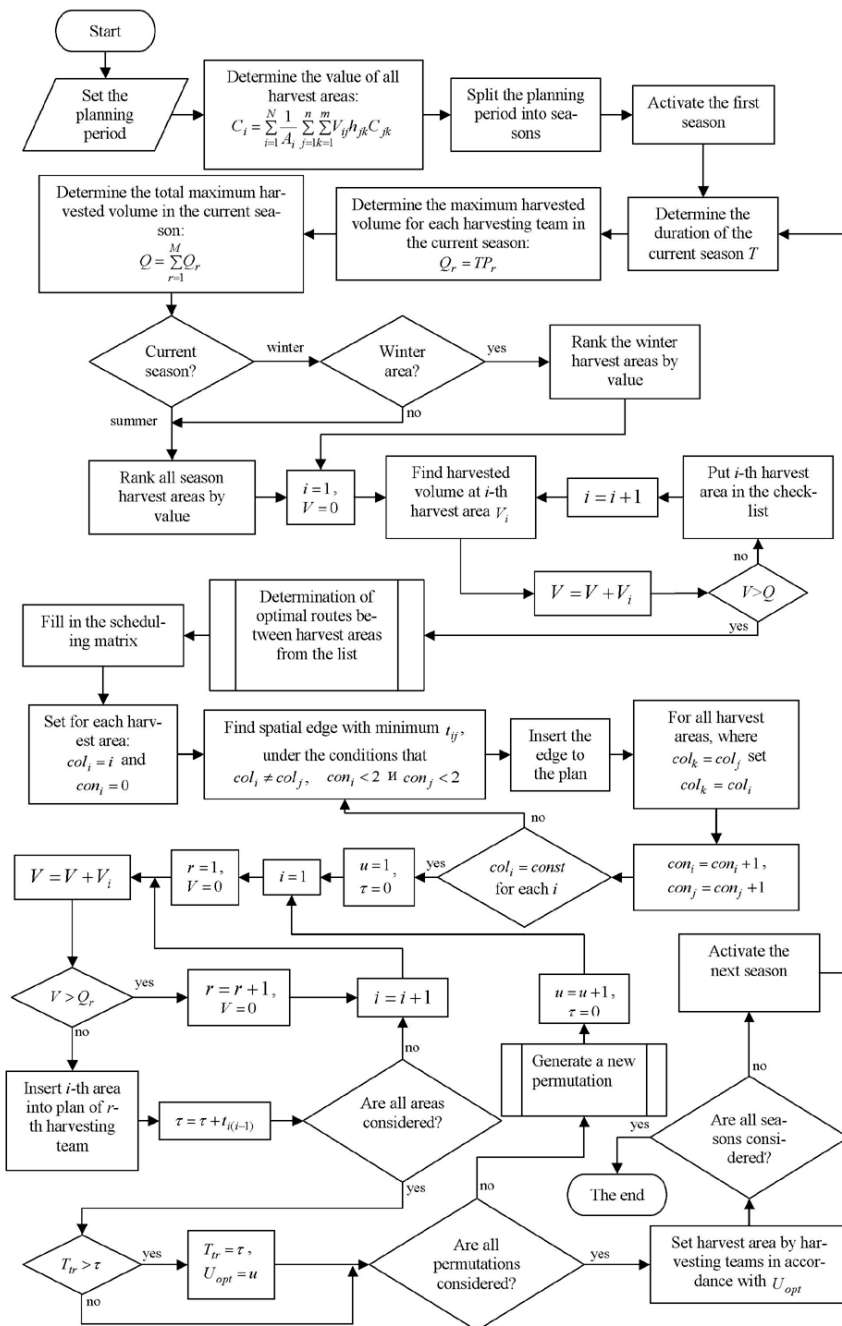


Figure 5. Generalized optimization algorithm of Harvest Scheduling Sub-module

case studies in the Republic of Karelia and the Leningrad region (Table 2). Each case study was done at a different logging company. The first case (operational decision support) examined the potential for improved routing of logging trucks. The second case (tactical concept) examined the effects of different fleet sizes on overall fleet utilization. The third case (strategic goals) examined the effect of different transport infrastructure assumptions on transport operations. Each is described in more detail below. All calculations have been performed on a standard personal computer. A number of key variables are used to compare routing solutions. These include total work time (hours), total distance (km), total number of truck loads, total volume of wood transportation (m³), total loaded distance (km), required number of trucks and fleet utilization rate per shift. Two other key performance indicators were also used to judge transport efficiency: the loaded distance index (percentage of total distance travelled with load), and delivery index (number of m³ delivered per km of truck travel). These are calculated from grand totals for all trucks and shifts for the entire period studied.

Table 2. An overview of the three case studies tested in the DSS

	Case 1	Case 2	Case 3
Planning level	Daily (operational)	Monthly (tactical)	Yealy (strategic)
Problem	Truck routing	Alternative fleet utilization levels	Transport with or without storage at intermediate terminals
Time horizon	4 days	3 months	1 year
Total supply volume, 1000 m ³	3	80	272
Number of harvesters/forwarders	4/4	7/7	9/9
Number of trucks	5	13	24
Number of assortments	10	9	8
Number of supply points	4	63	129
Number of demand points	4	5	5
Number of intermediate wood terminals	-	-	6

Case study 1: Daily (operational) planning

The daily (operational) planning case study used the DSS to generate daily routing and scheduling for the company’s logging trucks. The optimal solution was then compared to the existing manual solution. The company selected for this case study operates in the Republic of Karelia with an output of about 250,000 m³ of round wood per year. All wood comes from the company’s leased forests located in the southern part of Karelia (Figure 6). The company undertakes forest operations with CTL harvesters and forwarders and transport using self-loading trucks. Most of the coniferous sawlogs are delivered to two local sawmills while pine pulpwood goes to a local pulp mill and birch and spruce pulpwood to the company’s terminal at a railway station for further export to Finland. The case

study covers five trucks based in one garage, four supply points (harvesting areas) and four customers (three mills and one wood terminal) as shown in Table 2. The load capacities for the CTL trucks vary between 50 and 52 m³. The daily outputs of harvesting and forwarding are 140-420 m³, depending on the site, and the volume cut per harvesting area is 5,000-15,000 m³. Half of the actual cut is coniferous sawlogs, including 9% small-size spruce sawlogs. The rest consists of 18% coniferous pulpwood, 22% birch pulpwood and 10% energy wood.

Three routing solutions were made for four working days assuming two shifts per day. These included the typical manual routes and two different variants of optimal routes. The manual routes were planned using traditional methods without DSS support. The two types of optimal routes were then constructed with the DSS support; the first assumes that the trucks return to the garage to change operators and the second assumes that the operators are changed without returning to the garage every shift.

Case study 2: Monthly (tactical) planning

The monthly (tactical) planning case used the DSS to estimate the required fleet size for roundwood transport trucks given a more optimal utilization of resources. The optimal solution for the reduced fleet was compared to the optimized solution for the existing fleet. The company selected for this case operates in the Leningrad region with an output about 250,000 m³ per year. All wood comes from the company’s leased forests located in the eastern part of the Leningrad region. Most of the coniferous sawlogs are delivered to two local sawmills, birch sawlogs to a plywood mill, and pulpwood to the company’s terminal at a railway station for export to Finland. The company outsources both the harvest and transport services. The company’s contractors use harvester-forwarder chains in wood harvesting and a variety of self-loading trucks in transport.

Two routing solutions were generated with the DSS using different CTL vehicle fleets under the same conditions. The Basic plan is done for an existing vehicle fleet (seven harvesters, seven forwarders, 13 trucks) with DSS support. The Advanced plan of the routes is obtained with the DSS for a reduced fleet of six trucks. The optimal routing was done for a three-month period during the winter using two shifts per day. There were 63 supply points (harvesting areas) and five demand points (four sawmills and one wood terminal). The load capacities for short-wood trucks were 30-50 m³ depending on the individual truck type. Daily outputs of harvester-forwarder teams were 60-90 m³ depending on the site.

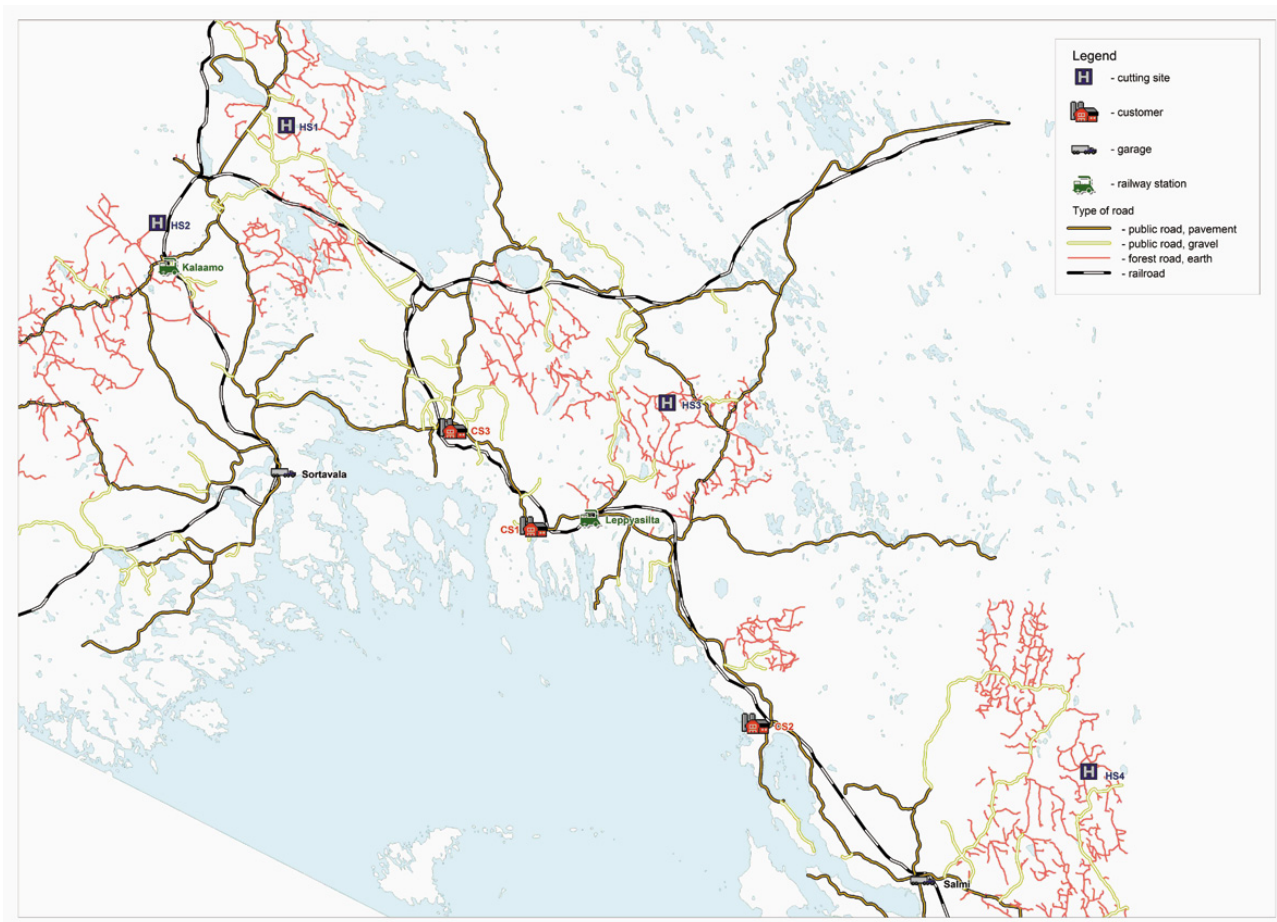


Figure 6. The layout of the logistical management units in the test of the DSS on operational transport planning in Case 1 (Karelia)

Case study 3: Yearly (strategic) planning

The yearly (strategic)-planning case used the DSS to study the choice of transport systems given different infrastructure assumptions over a planning horizon of one year. An optimal solution was generated by the DSS for immediate direct transport to the mill (assuming a complete network of year-round roads) and this was compared with the existing solution (with intermediate storage at terminals). The company selected for this case study operates in the Leningrad region with an output of approximately 270,000 m³ of wood per year. All wood comes from the company's leased forests located in the northern part of the Leningrad region. Most of the spruce sawlogs are delivered to local sawmills, and pine sawlogs and pulpwood to the company's terminals at railway stations and a river port for further export to Finland. Wood is typically transported to 6-8 intermediate wood terminals on all-weather roads during the winter time (Table 2). Fully mechanized cut-to-length systems are used for harvesting while Russian self-loading trucks are used

for transport. The company purchases additional harvesting and transport services during the winter.

Complete routing solutions were generated for the two different transport systems. The first system includes the use of intermediate terminals during the winter, while the second system excludes the use of these. While this change enables more efficient transport solutions (reduced extra handling and transport for intermediate storage) it assumes an upgrading of 100 km of forest roads with a total investment cost of approximately €1 million (10 € per m). The basic delivery plan with intermediate terminals is generated by the DSS for the existing vehicle fleet (nine harvesters, nine forwarders, 24 trucks). The advanced delivery plan is generated with the DSS for an optimal fleet in wood transport (eight trucks) avoiding intermediate wood terminals in winter time (direct transport from harvesting areas to customers). The delivery plans are created for a one year horizon using two shifts per day. There are about 130 supply points and five demand points (one sawmill, three wood terminals at railway

stations, and one wood terminal at a river port). The load capacities of short-wood trucks were 26-33 m³ depending on the individual truck type. The daily outputs of harvester-forwarder teams were 125-250 m³ depending on the site.

An overview of conditions for Cases 1, 2 and 3 are presented in Table 2.

Results

An overview of the main results for each of the three cases is shown in Table 3.

Table 3. Overview of the results from the three case studies on operational, tactical and strategic transport planning decisions

Plan	Required trucks [units]	Total working time [hr]	Total distance [km]	Number of truck loads	Total volume [m ³]	Total loaded distance [km]	Fleet utilization rate	Loaded distance index	Delivery index [m ³ ·km ⁻¹]	Transport cost [€·m ⁻³]
Case study 1: Daily (operation) level										
Basic	5	307	7,382	53	2,740	2,212	0.754	0.300	0.371	5.6
Advanced 1	5	255	7,382	58	2,996	2,697	0.728	0.365	0.406	5.1
Advanced 2	4	239	5,743	58	3,000	2,872	0.895	0.499	0.526	4.0
Case study 2: Monthly (tactical) planning										
Basic	13	13,474	622,453	2170	80,025	308,211	0.858	0.495	0.129	7.3
Advanced	6	10,349	449,648	1728	80,325	223,389	0.864	0.497	0.179	6.3
Case study 3: Yearly (strategic) planning										
Basic	24	37,231	709,898	10869	314,031	296,217	0.477	0.417	0.380	6.0
Advanced	8	30,222	584,310	8184	270,072	252,143	0.636	0.432	0.462	4.5

Case study 1: Daily (operational) planning

Case study 1 involved a comparison of the manual and optimized vehicle routing solutions for five trucks over four days. The optimization of the routes according to the Advanced plan 1 shows that the total delivered wood volume increased from 2,740 m³ to 2,997 m³ (+9%) compared to the manual Basic plan. The total travel distance was the same, but the total working time decreased by 17%. The required fleet was the same; five CTL trucks. The fleet utilization rate decreased slightly (-4%) while the loaded distance index increased by 22%, and the delivery index (m³·km⁻¹ of truck travel) increased by 9%.

The optimization of the routes according to the Advanced plan 2 shows that the total delivered wood volume increased from 2,740 m³ to 3,000 m³ (+10%) compared to the manual Basic plan. The total travel distance decreased from 7,382 km to 5,743 km (-22%), and the total working time decreased from 307 hrs to 234 h (-22%). This reduced the required fleet from five to four trucks. The fleet utilization rate increased by 19%, the loaded distance index increased by 30%, and the delivery index (m³ per kilometre of truck travel) increased by 42%. The potential cost reduction through

optimized routing is estimated as 9 % and 29 % with Advanced 1 and Advanced 2, respectively.

Case study 2: Monthly (tactical) planning

Case study 2 involved a comparison of the existing vehicle fleet with a reduced but more optimal fleet. The comparison of the performance indexes for the existing and optimal vehicle fleets is presented in Table 3. The optimization of routes using the DSS according to the Advanced plan shows that for the same total delivered wood volume (80 thousand m³) the total travel distance decreased from 622,453 km to 449,648

km (-28% compared to the Basic plan with the existing fleet) and the total working time decreased from 13,474 h to 10,349 h (-23%). According to these results, the optimization gives the possibility to reduce the required fleet from 13 to six trucks. The fleet utilization rate increased, the loaded distance index increased slightly, and the delivery index (m³ per kilometre of truck travel) increased by 39%. The Advanced plan decreased the transport cost by 1.0 €·m⁻³ or 250,000 € per year. The reduced fleet, however, left a higher volume at roadside during the end of the 3-month period (Figure 7) than the existing fleet. The initial stocks at the beginning of the optimization were equivalent to approximately 3 days production. The stock size at the end of the optimization was equivalent to approximately 3.7 days production for the reduced fleet and 1.4 days production with the existing fleet.

Case study 3: Yearly (strategic) planning

Case 3 involved the comparison of two different transport systems, one with and one without the use of intermediate terminals in wintertime. The second system avoided the use of intermediate terminals by assuming a higher seasonal availability of the road network.

Figure 7. Results of from Case study 2 for the existing fleet (Basic, 13 trucks) and reduced fleet (Advanced, 6 trucks). The figure shows the daily harvested volumes, transported volumes, and the development of the roadside stocks (m³) for both the existing and reduced fleet over the three-month period.



The monthly schedule for harvester-forwarder teams (LG1-LG9) over the year is shown in Figure 8.

Team	1	2	3	4	5	6	7	8	9	10	11	12
LG1	█	█										
LG2			█	█								
LG3				█	█							
LG4						█	█	█	█	█	█	
LG5							█	█	█	█	█	█
LG6												█
LG7												
LG8												
LG9												

Figure 8. Monthly activity schedule (1-12) for harvester-forwarder teams (LG1-LG9) over the year in Case study 3

The comparison of the harvested and transported volumes as well as stock volume development for the two transport systems is presented in Figure 9. The Basic plan with the existing fleet and terminals shows a high stock before the spring thaw and high transport volumes after the spring thaw. The Advanced plan with optimization of routes using direct transport shows that the total transport distance decreased from 709,898 km to 584,310 km (-18%) compared to the Basic plan, and the total working time decreased by 7,000 h. The more even rate of transport enabled a reduction of the required truck fleet from 24 to eight trucks. The fleet utilization rate and the loaded distance index increased only slightly. The delivery index (m³ delivered per km

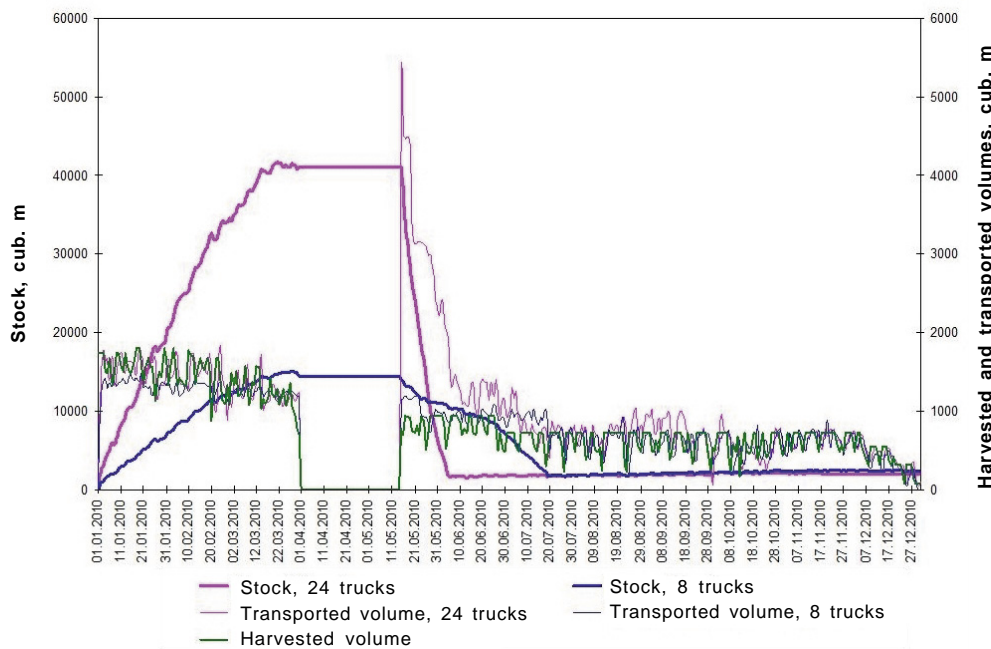


Figure 9. Results from Case study 3 on strategic transport planning decisions. The figure shows daily harvested volumes, transported volumes and the development of the roadside stocks (m³) for two systems. The existing system (Basic, 24 trucks) uses intermediate storages to compensate for seasonal road closures. The alternative system (Advanced, 8 trucks) assumes an improved road network availability to enable direct transport to the mills

of truck transport) increased by 22%. The Advanced plan decreased the transport cost by 1.5 €·m³ or about € 0.4 million per year.

Discussion and conclusion

The core of the CTL system is a deeper penetration of mill requirements upstream into the supply chain and the transition to CTL influences therefore the planning and control processes in wood supply. Since both harvesting and transport operations must separate the flows of different assortments, this places new demands to management and the need for integrated decision support. Approaches for managing CTL operations are not yet developed in Russia, and software from other countries is not directly applicable. This work may, therefore, be regarded as an initial support to the introduction of CTL harvesting systems in Russian logging companies. The DSS controls both the supply (harvested volumes on daily base) and demand (contracted volumes on monthly base). The integration routing and scheduling for both harvesting and of transport planning demands a combination of both theoretical and heuristic solutions. The solutions are customized to the industrial context are therefore novel. The use of the dynamic programming approach offers a solution to this complex challenge.

The cases presented in this study focus on the VRP function. The goal function used to solve the VRP (maximization of transported volume, which generally corresponds to time and cost minimization) avoids much of the potential complexity inherent to other timber transport vehicle routing studies. For complete cost minimization of the TTVRP, Karanta et al. (2000) specifies many parameters which are assumed to be known for complete calculation of both direct costs (different speeds and fuel consumption for respective loaded and unloaded driving) and indirect costs (arising from contracting conditions). In this respect, the solution used in this study is less detailed and by-passes specific cost parameters by focusing on transport production. The large amount of input data and high degree of detail has been one difficulty operational optimization of timber transport in routing and scheduling, which this study partially overcomes. However, this study also excludes some aspects handled in other studies, such as the modelling of costs for the roundwood customer's mills. This is because the context of the study concerns single logging companies with goals of scheduling own resources and not necessarily minimizing the total costs or maximizing the total profit for an integrated forest products company. Lukka (1994) shows more complete models for studying the effects of different delivery programs on mill

stock development for different degrees of freshness and mill production planning, however, without handling operational transport planning. Linnainmaa et al. (1994) shows an integrated wood supply DSSs with a structure clearly separating the hierarchies of decisions involving wood flow from the more operational decisions on vehicle routing. The same structure is also reflected in the later efforts (Savola et al. 2004). Most Nordic transport DSSs have included load clustering, which precedes the actual vehicle routing. This is generally necessary under Nordic conditions because of the large proportion of wood procurement sourced through small private forests with their typical "less-than-truckload" supply volumes per assortment. The current prototype TTVRP tool being tested in Sweden (Palmgren et al. 2003, Andersson et al. 2008) built on a hierarchical structure where the wood flow problem is solved first by pairing clustered pick-up and delivery points into whole load deliveries and the routing problem is solved secondly as a sequencing of the paired pick-up and delivery points.

Interestingly, Karanta et al. (2000) refer to the Finnish context right across the border from the Russian case studies involved in the current study. The experiences so far on the organization of forest operations management in the Russian forest tenure system suggest that a revision of the earlier Nordic experiences is clearly required for the Russian context. Given these contrasts, a direct comparison of improvement potential made possible by the DSS in the three cases of this study and other Nordic studies is difficult. Case 1, however, with its comparison of a manual solution to optimized solutions, is organized in a similar way to Andersson et al. (2008). This gives us a framework for further discussion. Table 4 shows Case 1 has fewer trucks (five compared to 10-12) and a longer period (five compared to three days). Andersson et al. (2008), however, distinguishes between two situations: 1) wood flows were identical between the manual and optimized solution and 2) the optimization is allowed to change the historical wood flow patterns during the study period. Noting this, the potential improvement estimated for better routing (alone) by Andersson et al. (2008) varied between 2% and 16%. These figures, however, assume that operator switches between shifts are made at points agreed on by the operators themselves that is similar to Advanced 2 in Case 1. The limited restrictions to wood flow offered in Case 1, however, present a context more like the adjustable flow variants in Andersson et al. (2008). Given these assumptions, we can say that the potential improvement calculated by the DSS in Case 1 is greater than indicated by Andersson et al. (2008) in two of three Cases.

Table 4. A comparison of improvement potential (%) enabled by optimized truck routing in Russian and Swedish studies

Case study 1 (5 trucks, 4 days)		Andersson et al. 2008 (3 days)		
Advanced 1	Advanced 2	Case	With identical flow	With adjustable Flow
9 %	29 %	SE (12 trucks)	1.84-7.72 %	22.18-37.77 %
		NE (10 trucks)	0.8-3.4 %	5.1 %
		Mid (10 trucks)	10.5-16.4 %	18.7 %

In general, comparisons between actual and optimized transport present a risk for overestimation of improvement potential. This is because it is very difficult to capture all the relevant restrictions, which influence landings, trucks, roads and mills during each day. The limited complexity of Case 1 (four landings and four mills) reduces the risk for such an overestimation. On the other hand, the lower number of mills (four as compared to 8-22 in Andersson et al. 2008) and lower demands to delivery precision in Case 1 gives a greater degree of freedom to maximize truck capacity utilization. The management of delivery rates with monthly and weekly contractor quotas, which is typical of Nordic conditions (Lindström 2010), also restricts the freedom to maximize capacity utilization.

One deviation between Case 1 and Andersson et al. (2008) concerns the levels of the loaded index. Having to start and end the working day at a central garage in Case 1 demands considerable empty driving as indicated by the loaded index, which in only one treatment comes up to 50 %. Where Andersson et al. (2008) present this variable (case SE in Table 4); it drops below 50 % in only one of 16 alternatives. Another case presented by Andersson et al. (2008) involving 110 trucks over 5 days estimates that no fixed location for change of drivers resulted in a potential cost reduction of 9 %. Clearly, the more flexible work organization as simulated by alternatives Advanced 2 vs. Advanced 1 in Case 1 is important to achieve in practice.

The integration of harvesting and transport offered by the developed DSS enables high-resolution analysis over longer periods. The opportunity to analyse actual harvesting and transport operations captures the variations in respective daily, weekly and seasonal operating conditions and production balance for the respective operations which are required to reflect reality. The extensive data required for longer studies makes a direct comparison to a manual solution difficult, but the simple heuristics developed for the specific context makes the comparison of alternatives computationally feasible.

The use of the DSS in case studies 2 and 3 also gave the opportunity to examine aspects other than transport costs. Both case studies involve changes in wood flow patterns for which consequences are im-

portant to evaluate for receiving mills. Case 2 shows improved transport efficiency (see delivery index and transport cost in Table 3) but the reduced transport volumes could also result in increased stock costs for wood not delivered and service penalties from the mills not receiving these volumes. The opposite effect is demonstrated in Case 3 where the potential for higher truck capacity utilization is enabled by a more even wood flow over time. In this case, the reduced storage times for roundwood and corresponding reduction of stock costs enabled by direct transport to the mill is particularly important for industrial processes requiring fresh roundwood. As mentioned earlier, the modelling of aging with different transport systems is discussed by Lukka (1994) and these effects are important for the competitive ability of mills in the forest products market.

In this study, the daily (operational)-monthly (tactical)-yearly (strategic) approach, supported by the GIS-based DSS, gives the logging company comprehensive information about the benefits and limitations of different CTL options. Improvement of the economic feasibility of CTL operations is important for further development of forestry in Russia and the developed DSS assists logging companies in making comprehensive decisions on options for CTL harvesting and logistics giving immediate benefits.

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СОВЕРШЕНСТВОВАНИЕ УПРАВЛЕНИЯ СОРТИМЕНТНОЙ ЗАГОТОВКОЙ ДРЕВЕСИНЫ НА ЛЕСОЗАГОТОВИТЕЛЬНЫХ ПРЕДПРИЯТИЯХ В РОССИИ С ИСПОЛЬЗОВАНИЕМ НОВОЙ СИСТЕМЫ ПОДДЕРЖКИ ПРИНЯТИЯ РЕШЕНИЙ

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Резюме

Представлена лесозаготовительная деятельность российских предприятий в оперативно-тактическом-стратегическом контексте, предусматривающим переход на сортиментную технологию заготовки с использованием харвестеров, форвардеров и автомобилей-сортиментовозов. Внедрение сортиментного метода требует большего внимания логистике, ввиду существенного увеличения номенклатуры, производимой на лесосеке продукции в виде сортиментов, которые напрямую поставляются нескольким потребителям. В статье дается обзор математических моделей, реализованных в новой системе поддержки принятия решений (СППР) для этих предприятий. СППР состоит из нескольких модулей, в том числе оптимизации маршрутов для парка лесосечных и лесотранспортных машин. Оптимизация маршрутов выполнена на базе двухэтапного алгоритма, где эвристический метод оптимизации используется для выбора лучшего пути транспортировки, а динамическое программирование используется для выбора ежедневных задач и маршрутизации транспортных средств. В статье представлены результаты тестирования СППР на трех предприятиях на примере оперативного, тактического и стратегического планирования вывозки, где горизонты планирования были 4 дня, 3 месяца и 1 год соответственно. Все исследования были сделаны в лесозаготовительных компаниях Северо-Запада России с ежегодной заготовкой около 250 000 м³ в каждой. Исследования включают от 4 до 9 комплексов харвестер-форвардер, от 5 до 24 автомобилей-сортиментовозов, 8-10 сортиментов, 4-129 лесосек и 4-5 потребителей. Результаты показывают, что СППР может быть использована для поддержки широкого спектра планировочных решений на уровне предприятия, в том числе маршрутизация сортиментовозов, уровни использования парка машин и выбор метода транспортировки в соответствии с новыми возможностями по развитию дорожной инфраструктуры. Расчеты показали, что возможно получить снижение затрат от 14 до 25%.

Ключевые слова: Россия, логистика, сортиментная заготовка, система поддержки принятия решений, динамическое программирование