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Detailed scheduling of harvest teams and robust use of harvest and transportation resources

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ABSTRACT
Planning activities of harvest teams (harvesting and forwarding) and transportation is critical for efficient procurement of roundwood from forests to mills. The planning process involves many integrated decisions that consider process, spatial and temporal aspects. The spatial aspect concerns which area to harvest, which machine team to use, the mill to which the timber should be allocated and where to store the timber. The process decisions involve which bucking instruction to use. The temporal aspect concerns when to harvest, when to transport in order to meet specific demand at mills, and when to store the timber. Temporal decisions also include determining a detailed schedule for each harvest team. Such a schedule includes starting time and movement time between harvest areas. This is complicated by the harvest team having different home bases and different machine systems with their specific performance description and capacities. The overall planning problem can be formulated into one optimization model, but such a model is too large for practical use and cannot be solved in a reasonable time. We propose a decomposition scheme where a sequence of aggregated models, or limited parts of the model, is solved to find high-quality solutions quickly. We test the scheduling in cases involving two large Swedish forest companies.

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Introduction

Producing long-term operational plans for harvesting is difficult, because of the changing and uncertain environment. At the same time, it is very important to ensure that tactical plans balance resources over a long period to ensure optimal use of all resources. These resources include harvesting areas, harvesting teams and transportation capacity. We aim to establish detailed short-term schedules for harvesting teams, while ensuring that they follow a more long-term and balanced tactical plan. A typical operational plan may cover a few weeks, and a typical tactical plan several months up to one year.

Operational and tactical harvesting relates to all activities associated with harvesting forests (Epstein et al. 2007; Marques et al. 2014). The process involves all operations, beginning with cutting and bucking the trees through to delivering logs to primary and secondary customer destinations. The plans stipulate when and how the operations are to be performed (the means and the timing). In this respect, technical issues relating to the forest operations, and characteristics and limitations of the machine systems, are important. The plans also rely on detailed information about the site conditions and the material resources available locally. The process typically starts with a given set of potential harvest areas to cut over a limited planning period. Each area has particular characteristics in terms of size, volume, species composition, average tree size, ground structure, terrain and road accessibility.

Harvesting is carried out by a set of teams with their own machines that have different performances and capacities. Each team has a home-base location and skills that makes it suitable for certain operations, such as thinning, final felling or harvesting in steep terrain. Operations are planned in order to satisfy a demand from a set of customers, such as sawmills, pulp and paper mills and heating plants. Demand is often specified through a combination of fixed contracts and estimated orders over the planning period. Transportation and inventory are important parts of the logistic operations, and transportation planning must include information on road accessibility. One of the difficult aspects is that there are several sources of uncertainty that may necessitate the transportation plan being continuously revised during the course of operations. For example, rainy weather may make roads difficult or even impossible to use, and demand is not fully known until customer orders are confirmed. A third source of uncertainty relates to the volume of different assortments available. Often this is not known until the harvesting is completed. Operational planning is often carried out by experienced planners using support systems containing parts, or all, of the information needed. Most, if not all, support systems for operational harvesting contain no advanced planning tools based on operations research.

Harvesting problems in forestry are widely considered in the literature. Detailed descriptions on operational and tactical harvesting are provided in two book chapters by Marques et al. (2014) and Audy et al. (2016). The first describes

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operational and planning activities and the second focuses more on the decision-support systems (DSSs) designed for planning. A more general description on different planning levels in forestry can be found in D'Amours et al. (2008). A recent description of the current status of and challenges in forest planning is given in Rönnqvist et al. (2015). Two open problems identified in this article are connected with the problem considered in this paper:

(OPEN PROBLEM 2) How can we model and solve the scheduling of jointly detailed daily or weekly harvesting and transportation decisions?

(OPEN PROBLEM 4) How can we synchronize operational sorting, harvesting and transportation decisions for large-sized forest problems?

Tactical planning of harvest operations has been studied in Bredström et al. (2010). The authors consider an annual planning problem of allocating harvest areas to harvest teams. Each team consists of a harvester and a forwarder, both of different sizes and capacity. Four seasons are used as planning periods in the optimization model. The problem is solved in two phases. In the first, an allocation problem is solved to efficiently allocate teams to harvest areas. Harvest areas are not sequenced within each season in this phase. Sequencing is considered in the second phase, where a sequence is determined for each team and for each season using a traveling salesman person heuristic. The case study reported has 968 harvest areas and 23 teams. A similar application is studied in Karlsson et al. (2004), where monthly time periods are used. The harvest teams are not scheduled, and the case study involves 5 teams and 437 harvest areas.

More short-term scheduling of teams is described in Karlsson et al. (2003), where each team is allocated a detailed schedule over four to six weeks. Another aspect to manage is the age of the logs; the value of certain products (spruce pulp in this case) falls considerably after a few weeks in storage. The potential schedules are generated by a greedy heuristic, based on distances between areas. The case involves 6 teams and 41 harvest areas. The main decisions are the allocation of teams to harvest areas, but transportation and inventory handling are key factors in making the correct decisions. Transportation can be planned with a DSS. One example is the FlowOpt system described in Forsberg et al. (2005) and Carlsson and Rönnqvist (2007). An application where harvesting is integrated with more strategic logistic planning using an extension of FlowOpt is described in Broman et al. (2009). Routing problem involves finding detailed routes over the next day or week. One such application is given in Andersson et al. (2008) where a truck scheduling system developed for Swedish forestry is described.

Planning for more than one year often integrates harvest planning and road maintenance (or road building). One such application is described in Flisberg et al. (2014). The application includes 6022 harvest areas and 4012 road links that can be upgraded to different road quality levels. The planning period is five years, with annual sub-periods. Due to the size of the resulting model, the authors propose a methodology that solves a sequence of mixed integer programming (MIP) problems. Each problem is based on solving a problem with only two time periods, a business and an anticipation period. The business period represents the first year and the anticipation period represents an aggregation of the remaining years. The solution uses a rolling horizon approach to solve the problem. In each stage, one year is fixed and the problem then considers the remaining years but with a new business period and new aggregation. Once a feasible solution to the full model has been found, it is possible to restart the optimization to find improved solutions.

A similar idea with business and anticipation periods is used in Troncoso et al. (2015). The problem considered in the study is to devise a comprehensive forest management plan over a full rotation. The case is from Chile. The planning period is 25 years and includes 1226 harvest areas, 5 mills, 7 log types and 8 final products. In addition to the long-term plan, a harvest plan must be found that considers the industrial capacity over the next five years. A five-year period is used because it is very hard to estimate demand over a longer period. The model developed uses annual planning periods for the business period (five periods for years 1–5) and five-year plans for the anticipation periods (four periods for years 5–25). Only decisions made in the business periods are expected to be implemented in practice. For the business periods, decisions are made on which areas to harvest and when, which bucking pattern to use in each area, and the transportation flows along the entire value chain from forests to customers.

Many models and solution methods have been developed for integrated harvesting and transportation problems, but these often miss a number of important aspects. Firstly, supply often exceeds the actual demand. This enables the solution to use creaming, that is, to use the best-located areas and leave the worst, but this means that the situation deteriorates every time the problem is resolved. A second aspect is that a very detailed level of the solution is only needed for short-term planning, as the problem is constantly replanned on a rolling horizon. A high level of details for the entire planning period results in very large model that cannot be solved in a reasonable time. A third aspect is that the situation changes continuously, for example, the weather can change and new customer orders can be confirmed. Another consideration is the need to easily connect or be integrated with the Enterprise Resource Planning systems used by the forest companies.

In this paper, we propose a model and solution methodology designed to include all the aspects described above. We use business and anticipation periods, where modeling in the business periods is at a detailed level, but at a less detailed level in the anticipation periods. By using the anticipation periods, we can ensure that we balance resources over a long period. The level is such that harvesting covers several periods in the business period horizon, and several harvesting operations can be carried out in each anticipation period. In each business period, we decide on the most suitable bucking price list to use to match customer orders, and on detailed transportation and inventory levels. We use different aggregations of the full planning model to find solutions quickly. We have tested the approach in cases involving two Swedish forest companies.

Materials and methods

Model

The proposed model is described below, divided into the following parts: sets and input data, decision variables and model formulation (including objective function and constraints).

Sets and input data

The sets are described below. Some sets are defined to simplify the model descriptions.

Notation	Description
I	Set of harvest areas
M	Set of teams
J	Set of industries
L	Set of terminals
O_j	Set of orders at industry j
H	Set of assortments
G	Set of group assortments
C_i	Set of bucking price lists for harvest area i
Q	Set of harvest operations (e.g. final felling and thinning)
T_B	Set of business periods ($\bar{t}_B$ = last business period)
T_A	Set of anticipation periods ($\underline{t}_A$ = first anticipation period)
T	Set of periods $T = T_B \cup T_A$
I_m	Set of potential harvest areas for team $m \in M$
M_i	Set of teams that can harvest area $i \in I$
I_q^Q	Set of harvest areas for harvest operation $q \in Q$
H_g	Set of assortments that can be used to fulfil demand of group assortment g
G_h	Set of group assortments that can be fulfilled by assortment h.
n_{mit}^B	All periods that team m can start harvesting in area i and still be harvesting the same area in period t (in business periods)
F^T	Set of harvest areas i that have to be harvested by team m in period t using bucking price list c.

The data coefficients are defined as follows.

Notation	Description
c_{mi}^p	Operation cost (harvesting, forwarding and traveling) for team m in harvest area i
t_{mi}^i	Operating time for team m in harvest area i
t_{mit}^B	Operating time used for machine m in harvest area i when starting in business period t until the last business period
t_{mt}^t	Available time for machine m in period t
a_{mq}	Minimum level (proportion) of harvest operation q for machine m
s_i^{AB}	Volume at harvest area i
s_{hic}^A	Volume of assortment h in harvest area i when using bucking price list c
$s_{hmictt'}^B$	Volume in period t′ of assortment h in harvest area i when using machine system m with bucking price list c when the harvesting starts in period t
p_{it}	Percentage availability at harvest area i in period t
c_{hij}^f	Transportation cost for assortment h from harvest area i to demand point j
c_{hit}^i	Inventory cost for assortment h at point i (harvest area, terminal or demand point) at the end of period t
d_{gjot}	Accumulated demand goal for group assortment g at demand point j of order o in period t
$\underline{d}_{gjot}$	Accumulated lower demand level of group assortment g at demand point j of order o in period t
$\bar{d}_{gjot}$	Accumulated upper demand level of group assortment g at demand point j of order o in period t
$\underline{d}_{hgjot}^h$	Accumulated lower demand level of assortment h in group assortment g at demand point j of order o in period t
$\bar{d}_{hgjot}^h$	Accumulated upper demand level of assortment h in group assortment g at demand point j of order o in period t
$c_{gjot}^{\underline{d}}$	Cost to supply below goal value of demand for group assortment g at demand point j of order o in period t

(*Continued*)

Continued.

Notation	Description
$c_{gjot}^{\bar{d}}$	Cost to exceed goal value of demand for group assortment g at demand point j of order o in period t
$c_{ghjot}^{\underline{dh}}$	Cost to supply below goal value of demand for group assortment g using assortment h at demand point j of order o in period t
$c_{gjot}^{\bar{d}h}$	Cost to exceed goal value of demand for group assortment g using assortment h at demand point j of order o in period t
n_m^m	Maximum number of allowed moves for machine m
c_m^m	Penalty cost for each move exceeding the maximum allowed number of moves for machine m
c_{mt}^i	Cost for idle time for team m in period t ($\bar{t}_B$ corresponds to idle time in all business periods together
v_i^i	Value if harvest area i is not harvested during the planning horizon
v_{ghj}^s	Value of fulfilling assortment group g at industry point j with assortment h
b_{ij}	Distance between point i (harvest area or terminal) and point j (terminal or industry point)
$\bar{b}_t$	Maximum transport work allowed in period t
c_t^b	Cost for exceeding allowed transport work in period t
c_{mit}^c	Compression cost for team m harvesting harvest area i in period t

The compression cost is used to penalize the selection of harvest areas far away from the home base. The further away the harvest area selected, the higher the compression cost. Our use is similar to the compression factor used in Bredström et al. (2010), where different versions were tested.

The main decisions concern harvesting and transportation. A central idea is to divide the planning horizon into *business* periods (detailed short term) and*anticipation* periods (aggregated long term). This is illustrated in Figure 1. In our tests, we use daily periods for the business periods and monthly periods for the anticipation periods. Business periods are used to produce detailed scheduling where the time taken to harvest an area covers several business periods. Anticipation periods are not used for scheduling purposes, and several harvest areas can typically be harvested in one anticipation period. It is important to note that decisions from the business periods comprise operational decisions, and decisions from the anticipation periods comprise possible plans for the future.

The definitions of the decision variables are as follows:

y_{mict}	$=\begin{cases} 1, \text{ if machine } m \text{ starts in harvest area } i \text{ applying bucking price list c at period } t \\ 0 \text{ otherwise} \end{cases}$
o_{mit}	$=\begin{cases} 1, \text{ if machine } m \text{ continues to harvest } i \text{ in the period after } t \\ 0, \textit{ otherwise} \end{cases}$
v_{mict}	=Time needed in periods after period t for machine m to finish harvesting area i using bucking price list c
x_{hijt}	=Flow of assortment h from harvest area i to demand point j in period t
s_{gjot}^l	=Volume below accumulated goal value of demand of group assortment g at demand point j of order o in period t
s_{gjot}^u	=Volume above accumulated goal value of demand of group assortment g at demand point j of order o in period t
s_{ghjot}^{hl}	=Volume below accumulated goal value of demand of group assortment g using assortment h at demand point j of order o in period t
s_{ghjot}^{hu}	=Volume above accumulated goal value of demand of group assortment g using assortment h at demand point j of order o in period t
I_{hit}	=Inventory of assortment h at point i (harvest area, terminal or demand point) at the end of period t
u_{hgjot}	=Fulfilled demand of group assortment g from assortment h at demand point j of order o in period t
s_m^m	=Number of moves exceeding allowed number for machine m
s_{mt}^i	=Idle time for team m in period t
s_t^b	=Transport work above allowed level in period t

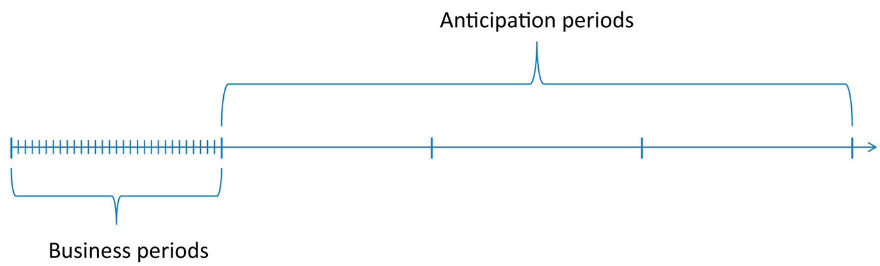

Figure 1. Illustration of business and anticipation periods.

We have eight cost components and two value components in the objective function. We choose to minimize the total cost minus revenues. The first cost component is the production cost, including harvesting and forwarding. The second is the transportation cost. The third is the inventory cost. The fourth is a cost when any teams are idle. These first four components are associated with actual and real costs. The fifth is a balancing cost to keep the selected harvest areas for a team close to the home base. The parameter is set by the planners based on experience or through "what-if" scenarios. By displaying the crew movements visually for several values it is possible to find a suitable level of the balancing parameter. The sixth is a penalty cost for exceeding the limit of the transport work. The seventh is a penalty cost for exceeding the maximum number of moves for a team. The eighth is a penalty cost for not meeting the target demand given by orders. These three components are used to control the quality of data and to guarantee the feasibility of the model, if needed. The values of the penalty parameters are chosen high in order to only identify problems with feasibility. If there is any penalty value, it is important to revise the data accordingly as theses should not be included in the model for a real solution. We could have omitted them in the model as they do not impact the real solution but our experience is that they are important for practical usage. The first value component is the sales value, and the second is the net present value (NPV) of the harvest areas not selected. The latter is the standing value of the non-harvested areas.

$$z_{\text{production}} = \sum_{m\in M}\sum_{i\in I_m}\sum_{c\in C_i}\sum_{t\in T} c^p_{mi} y_{mict}$$

$$z_{\text{transport}} = \sum_{h\in H}\sum_{i\in I\cup L}\sum_{j\in L\cup J}\sum_{t\in T} c^f_{hij} x_{hijt}$$

$$z_{\text{inventory}} = \sum_{h\in H}\sum_{i\in I\cup L\cup J}\sum_{t\in T} c^i_{hit} l_{hit}$$

$$z_{\text{idleTime}} = \sum_{m\in M}\sum_{t\in T_A\cup \bar{t}_B} c^i_{mt} s^i_{mt}$$

$$z_{\text{compression}} = \sum_{m\in M}\sum_{i\in I_m}\sum_{c\in C_i}\sum_{t\in T} c^c_{mit} y_{mict}$$

$$z_{\text{transportPenalty}} = \sum_{t\in T} c^b_t s^b_t$$

$$z_{\text{exceedingMoves}} = \sum_{m\in M} c^m_m s^m_m$$

$$z_{\text{demandPenalty}} = \sum_{g\in G}\sum_{j\in J}\sum_{o\in O_j}\sum_{t\in T}\Bigg(c^d_{gjot} s^l_{gjot} + c^{\bar{d}}_{gjot} s^u_{gjot} + \sum_{h\in H_g}\left(c^{dh}_{ghjot} s^{hl}_{ghjot} + c^{\bar{d}h}_{ghjot} s^{hu}_{ghjot}\right)\Bigg)$$

$$v_{\text{sale}} = \sum_{g\in G}\sum_{h\in H_g}\sum_{j\in J}\sum_{o\in O_j}\sum_{t\in T} v^s_{ghj} u_{hgjot}$$

$$v_{\text{NPV}} = \sum_{i\in I} v^i_i \left(1 - \sum_{m\in M_i}\sum_{c\in C_i}\sum_{t\in T} y_{mict}\right)$$

The full model can be stated as follows:

$$\begin{aligned}\min z = {} & z_{\text{production}} + z_{\text{transport}} + z_{\text{inventory}} + z_{\text{idleTime}} \\ & + z_{\text{compression}} + z_{\text{transportPenalty}} + z_{\text{exceedingMoves}} \\ & + z_{\text{demandPenalty}} - v_{\text{sale}} - v_{\text{NPV}} \\ & s.t.\end{aligned}$$

$$\sum_{m\in M_i}\sum_{c\in C_i}\sum_{t\in T} y_{mict} \le 1, \quad i \in I, \tag{1}$$

$$\begin{aligned}&\sum_{m\in M}\sum_{i\in I_m}\sum_{c\in C_i}\sum_{t\in T_B : p_{it}<100} 1/p_{it} s^{AB}_i y_{mict} \\ & -1/100 \sum_{m\in M}\sum_{i\in I_m}\sum_{c\in C_i}\sum_{t\in T_B} s^{AB}_i y_{mict} \le 0,\end{aligned} \tag{2}$$

$$\begin{aligned}&\sum_{m\in M}\sum_{i\in I_m : p_{it}<100}\sum_{c\in C_i} 1/p_{it} s^{AB}_i y_{mict} \\ & \quad - 1/100 \sum_{m\in M}\sum_{i\in I_m}\sum_{c\in C_i} s^{AB}_i y_{mict} \\ & \quad \le 0, \\ & t \in T_A,\end{aligned} \tag{3}$$

$$\sum_{m\in M}\sum_{i\in I_m : p_{it}=0}\sum_{c\in C_i} y_{mict} = 0, \quad t \in T, \tag{4}$$

$$\sum_{i\in I_m}\sum_{c\in C_i}\sum_{t'\in n^B_{mit}} y_{mict'} \le 1, \quad m \in M, \quad t \in T_B, \tag{5}$$

$$\begin{aligned}&\sum_{t\in T_B} (t^i_{mi} - t^B_{mit}) y_{mict} = v_{mic\bar{t}_B}, \\ & m \in M, \quad i \in I_m, \quad c \in C_i,\end{aligned} \tag{6}$$

$$\sum_{i\in I_m}\sum_{c\in C_i}\sum_{t\in T} y_{mict} \le n^m_m + s^m_m, \quad m \in M, \tag{7}$$

$$\sum_{t\in T_B} t^t_{mt} - \sum_{i\in I_m}\sum_{c\in C_i}\left(\sum_{t\in T_B} t^i_{mi} y_{mict} - v_{mic\bar{t}_B}\right) = s^i_{m\bar{t}_B}, \quad m\in M, \tag{8}$$

$$\sum_{i\in I_m}\sum_{c\in C_i}(v_{mic(t-1)} + t^i_{mi} y_{mict} - v_{mict}) = t^t_{mt} - s^i_{mt}, \quad m\in M,\ t\in T_A, \tag{9}$$

$$o_{mit} - o_{mi(t-1)} \le \sum_{c\in C_i} y_{mict}, \quad m\in M,\ i\in I_m,\ t\in T_A, \tag{10}$$

$$t^i_{mi} o_{mit} \ge \sum_{c\in C_i} v_{mict}, \quad m\in M,\ i\in I_m,\ t\in T_A\cup\bar{t}_B, \tag{11}$$

$$\sum_{i\in I_m} o_{mit} \le 1, \quad m\in M,\ t\in T_A\cup\bar{t}_B, \tag{12}$$

$$l_{hi(t-1)} - l_{hit} + \sum_{m\in M_i}\sum_{c\in C_i}\sum_{t'\in n^B_{mit}} s^B_{hmict't} y_{mict'} = \sum_{j\in J\cup L} x_{hijt}, \quad h\in H,\ i\in I,\ t\in T_B, \tag{13}$$

$$l_{hi(t-1)} - l_{hit} + \sum_{m\in M_i}\sum_{c\in C_i} s^A_{hic} y_{mict} + \sum_{m\in M_i}\sum_{c\in C_i} s^A_{hic}/t^i_{mi} v_{mic(t-1)} - \sum_{m\in M_i}\sum_{c\in C_i} s^A_{hic}/t^i_{mi} v_{mict} = \sum_{j\in J\cup L} x_{hijt}, \quad h\in H,\ i\in I,\ t\in T_A, \tag{14}$$

$$l_{hi(t-1)} + \sum_{j\in I} x_{hjit} - \sum_{j\in J} x_{hijt} - l_{hit} = 0, \quad h\in H,\ i\in L,\ t\in T, \tag{15}$$

$$l_{hj(t-1)} + \sum_{i\in I\cup L} x_{hijt} - l_{hjt} - \sum_{g\in G_h}\sum_{o\in O_j} u_{hgjot} = 0, \quad h\in H,\ j\in J,\ t\in T, \tag{16}$$

$$\sum_{h\in H_g}\sum_{t'\in 1..t} u_{hgjot'} + s^l_{gjot} \ge d_{gjot}, \quad g\in G,\ j\in J,\ o\in O_j,\ t\in T, \tag{17}$$

$$\sum_{h\in H_g}\sum_{t'\in 1..t} u_{hgjot'} - s^u_{gjot} \le d_{gjot}, \quad g\in G,\ j\in J,\ o\in O_j,\ t\in T, \tag{18}$$

$$s^l_{gjot} + \underline{d}_{gjot} \le d_{gjot}, \quad g\in G,\ j\in J,\ o\in O_j,\ t\in T, \tag{19}$$

$$\bar{d}_{gjot} - s^u_{gjot} \ge d_{gjot}, \quad g\in G,\ j\in J,\ o\in O_j,\ t\in T, \tag{20}$$

$$\sum_{t'\in 1..t} u_{hgjot'} + s^{hl}_{ghjot} \ge \underline{d}^h_{hgjot}, \quad h\in H,\ g\in G,\ j\in J,\ o\in O_j,\ t\in T, \tag{21}$$

$$\sum_{t'\in 1..t} u_{hgjot'} - s^{hu}_{ghjot} \le \bar{d}^h_{hgjot}, \quad h\in H,\ g\in G,\ j\in J,\ o\in O_j,\ t\in T, \tag{22}$$

$$\sum_{c\in C_i}\sum_{t\in T}\left(\sum_{i\in I^Q_q} t^i_{mi} y_{mict} - a_{mq}\sum_{i\in I_m} t^i_{mi} y_{mict}\right) \ge 0, \quad m\in M,\ q\in Q, \tag{23}$$

$$\sum_{h\in H}\sum_{i\in I\cup L}\sum_{j\in J\cup L} b_{ij} x_{hijt} \le \bar{b}_t + s^b_t, \quad t\in T, \tag{24}$$

$$y_{mict} = 1, \quad (mict)\in F^{\mathrm{T}}, \tag{25}$$

$$y_{mict}\in\{0,1\}, \quad \forall m\in M,\ i\in I_m,\ c\in C_i,\ t\in T, \tag{26}$$

$$o_{mit}\in\{0,1\}, \quad \forall m\in M,\ i\in I_m,\ t\in T_A\cup\bar{t}_B, \tag{27}$$

$$x_{hijt}, v_{mict}, l_{hit}, s^i_{mt} \ge 0, \tag{28}$$

$$s^l_{gjot}, s^u_{gjot}, s^{hl}_{ghjot}, s^{hu}_{ghjot}, u_{ghjot} \ge 0. \tag{29}$$

Constraint set (1) states that each harvest area can only be harvested once. Sets (2) and (3) state the limits for harvesting in business and anticipation periods, respectively. Set (4) describes areas that are not available in a certain period, that is, cannot be harvested that period. Set (5) states that only one operation can be run in each business period. Set (6) describes that overtime is needed if there is not enough time left in business periods to finish an operation. The total number of moves for a machine is limited in set (7). Sets (8) and (9) limit the available time for each machine in business and anticipation periods, respectively. Set (10) states that the operation carrying over to the next period must have been started in this period (or started in earlier periods and still be running). The connection between binary and continuous variables for overtime is modeled in (11). Set (12) states that only one operation can carry over to the next period. Sets (13) and (14) state flow balance in harvesting areas for business and anticipation periods, respectively. Sets (15) and (16) state flow balance at terminals and demand points, respectively. Sets (17–20) fulfil aggregated demand with goal value and max and min, respectively. The same for assortment demands is given in sets (21) and (22). The minimum proportion of different harvest types for each machine is stated in set (23). Set (24) states the maximum allowed transportation work. Where there is a requirement that a specific team must harvest an area in a specific period, this is given in set (25). Sets (26,27) and (28,29) state the binary and non-negativity restrictions, respectively.

Solution methodology

The model is an MIP model and, for practical applications, it will be large and difficult to solve directly within short solution times. The solution approach proposed is based on applying decomposition and aggregation techniques to solve the full model in a stepwise manner. This is a heuristic approach in three phases and will not guarantee an optimal solution.

The idea is not to make any detailed decisions in a particular phase. Instead, we make decisions that, for example, a harvest area should be harvested in the business periods and not in the anticipation periods. The solution can be interpreted to form a basis for making overall balancing decisions before more detailed decisions are made. One phase, phase 2, is devoted to formulating the detailed scheduling that is later fixed to solve the full model in the final phase. In phase 1, we make an allocation of stands either to the business periods (i.e. first month) or the anticipation periods (i.e. the remaining months). This is to balance the characteristics of all harvest areas over the entire year. Given the areas allocated to the first month, we make a detailed scheduling of these harvest areas in Phase 2. Given the fixed schedule, we can solve the entire problem in Phase 3. Each of the problems solved in the three phases is relatively small as compared to the full problem and more computationally tractable. Examples of the size of the problems and solution times are given in the numerical tests. The overall solution approach is described below.

Algorithm 1 Overall solution approach

Phase 1:

Assumptions: Two planning periods only. All business periods are aggregated into the first period and all anticipation periods aggregated into the second.

Solve Problem P1 (aggregated Master problem)

Output: Allocation of stands to aggregated business periods and aggregated anticipation periods, i.e. we know which stands are to be harvested in the first month.

Comments: The purpose is to allocate areas to either the aggregated business periods or the aggregated anticipation periods. Here we can find a balance between the periods to ensure that no creaming is done in the first period (i.e. the first month in our case). In this model we include inventory and flows between areas and industry. All aggregations are based on the full model so all relevant constraints are included.

Phase 2:

Assumptions: Selected stands to business periods from Phase 1.

Solve Problem P2 (Master problem with original business periods only)

Output: Allocation of stands to teams and starting harvesting times in business periods, i.e. initial schedule in business periods.

Comments: Since we know which areas are to be harvested in the first month, we solve the full model, but only for the business periods. We obtain detailed scheduling of the harvesting, together with flows and inventories.

Phase 3:

Assumptions: Detailed schedule (harvest decisions) in business periods from Phase 2.

Solve Problem P3 (Full Master problem with fixed schedule for teams (not flows and inventories) in business periods)

Output: Full detailed plan in business and anticipation periods.

Comments: We solve the full problem, but the schedule in the business periods is fixed. The scheduling is one of the most difficult parts from an optimization perspective, but is already solved so the remaining model is relatively easy to solve.

Case study

The study comprises two cases from two large Swedish forest companies, BillerudKorsnäs and Holmen Skog. BillerudKorsnäs is a leading provider of renewable packaging material. Its forestry department manages the company's supply of fiber raw material and forest biomass for energy, and is responsible for all harvest activities. Holmen Skog is the forestry department of Holmen, a large manufacturer of printing paper, paperboard and sawn timber. Both companies operate over much of Sweden, but mostly in the north of the country. Forest operations activities are similar in both companies, and are typical of most Swedish forest companies.

The current manual planning process can be described as follows. Company activities are geographically divided into regions, typically 2–4 per company. Each region is divided into districts, typically 2–6 per region. A district represents an area for which the company defines target harvest volumes per assortment and month. Trees can be harvested in forests owned by the company itself and/or in forests owned by private forest owners who sell standing wood to the company. Information on each harvest area, either in the company 's own forests or in private forests, is collected by forest planners and collated in a register. The information comprises composition of tree species, average stem diameter and volume, presumed forwarding distance, total volume to harvest, ground structure, bearing class, etc., which are all used when planning the harvesting activities.

Companies aim to have enough areas in the register to cover 1–3 years of harvesting. Hence, the number of areas in the register depends on the size of the company. Sometimes the register has substantially less areas, covering only 3–6 months of harvesting. The register is replenished continuously as more areas are surveyed but normally is at its peak every fall, after the ordinary planning season. The reason is that the majority of the surveys are done in the summer. When considering a time horizon of up to one year in planning, as in the case studies, several areas are not known when harvest scheduling is done as they are added continuously during the year. This is one reason why the planning is revised on a monthly basis with only one month scheduling ahead. Another reason is that the conditions, for example the demand situation or the stand and road accessibility, can change rapidly forcing the schedule to be changed. With the proposed approach, we make a revised plan each month but covering a full year in the planning.

Planning the harvesting activities includes not only scheduling the harvesting crews, but also ensuring that the harvested volume matches current demand from the mills for roundwood. This is done by first choosing the right areas to meet the demand for saw timber and then to meet the demand for pulp wood. Typically, there is one harvest production manager in each district, responsible for 8–16 different harvesting teams, and responsible for producing the right amount of saw timber and pulp wood to roadside. From roadside to mill, responsibility for the wood lies with the transportation manager, who normally works very closely with the production managers. The harvesting teams vary in many ways. Machine size, shifts and operator skills are factors that must be considered when scheduling the teams. The machines vary a lot in size and each machine has its preferred harvest area parameters, often depending on average stem volume.

Choosing a bad assignment of harvest team to a specific harvest area can be costly, bearing in mind that small machines are normally more efficient than large machines in areas with small-diameter trees, and vice versa. Another consideration is the harvesting type, such as final felling or thinning, and which type of bucking pattern is to be used, depending on mill demands (different bucking patterns for different mills). The production manager tries to devise reasonable routes for each team by studying maps of the available harvest areas. Some managers aim to minimize the number of moves that require trailers for moving the machines, while others focus on producing the right assortments according to mill demands.

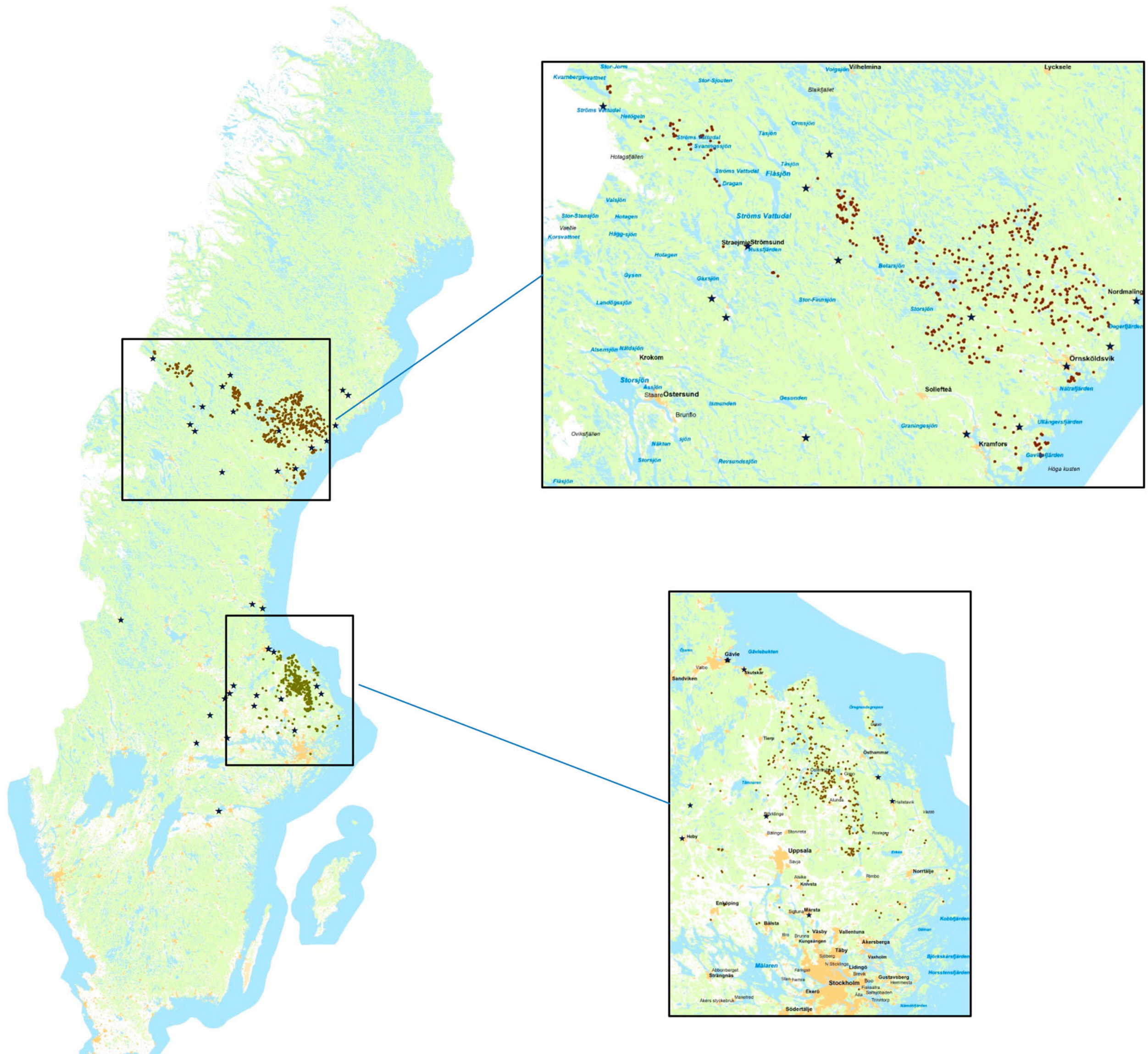

Figure 2. Geographical location of the two cases in Sweden. The northern is from Holmen Skog (Case B) and the southern BillerudKorsnäs (Case A).

For each case, called cases A and B, we have extracted production information for harvest areas, harvested volumes, harvest machines and teams, and transported volumes from planning systems at each of the companies. The data from BillerudKorsnäs (case A) apply to 12 months in 2013, and for Holmen Skog (case B) the data applies to 9 months in 2014. The geographical locations of the two cases are shown in Figure 2.

Table 1. Information on the two cases regarding the dimension of the planning problem and historical data.

Aspect	Case A	Case B
Number of teams	14	26
Number of harvest areas	285	584
Number of industries	19	20
Demand at industries (m^3)	433,122	437,156
Supply available (m^3)	443,018	437,177
Number of harvest operations	7	3
Number of assortments	22	14
Number of group assortments	22	14
Average forwarding distance (m)	324	256
Average tree diameter (m)	0.41	0.21
Number of periods in the business period (days)	22	30
Number of anticipation periods (months)	11	8
Total planning period (months)	12	9

Table 2. Solution comparison (all cost components) between the manual and optimized solution for the two cases.

	Case A		Case B	
	Manual	Optimal	Manual	Optimal
Harvesting cost	19.60	17.05	24.97	24.80
Forwarding cost	21.66	18.11	12.20	11.97
Travel cost (teams)	0.55	0.72	0.61	0.49
Moving cost (equipment)	1.33	1.53	2.56	2.99
Transportation cost	29.19	28.53	25.44	24.57
Transportation cost (opt for manual)	28.44	–	24.53	–
Total cost	72.32	65.94	65.78	64.82
Average cost (SEK/m^3)	166.73	152.22	150.47	148.27
Harvested volume m^3	434,177	433,244	437,177	437,177
Transported volume m^3	433,122	433,122	437,156	437,156
Average harvesting and forwarding cost (SEK/m^3)	99.34	86.34	92.28	92.06
Average transportation cost (SEK/m^3)	67.39	65.87	58.19	56.20
Average transportation distance (km)	93.42	91.38	77.91	75.29

Note: All costs are given in SEK millions.

Table 3. Size of optimization models and solution times.

	Problem 1	Problem 2	Problem 3	Full problem
		Case A – manual		
Number of binary variables	111	1,058	4,404	31,917
Number of continuous variables	55,451	138,927	462,482	1.523,536
Number of constraints	3,641	19,113	47,985	122,653
Solution time (*s*)	3	6	31	
		Case A – optimized		
Number of binary variables	20,100	45,845	84,291	249,712
Number of continuous variables	119,116	352,530	684,260	1.591,694
Number of constraints	36,278	72,974	217,301	378,341
Solution time (*s*)	70	3,900	7,100	$> 86,400$
		Case B – manual		
Number of binary variables	17,282	5518	14,194	987,763
Number of continuous variables	158,882	392,715	578,924	1.972,341
Number of constraints	8,342	90,660	68,597	766,531
Solution time (*s*)	7	15	45	
		Case B – optimized		
Number of binary variables	90,306	155,916	288,585	1.245,962
Number of continuous variables	219,616	441,148	741,693	2.143,544
Number of constraints	141,642	179,624	616,102	1.281436
Solution time (*s*)	100	1140	500	$> 86,400$

Some key information on the two cases is shown in Table 1. For case A (BillerudKorsnäs), there are 8 sawmills and 3 pulp and paper mills. For case B (Holmen Skog), there are 11 sawmills, 3 pulp and paper mills and 4 terminals. The main harvest operations are final felling and thinning. We also take into account delivery wood, which is saw timber and pulp wood bought at roadside from forest owners. Consequently, no harvesting is needed and we are only considering the transportation part. For both of the cases, we use the major assortments, such as various types of pine and spruce timber and pine, spruce and birch pulp wood. There are only 22 periods for Case A in the business periods because weekends are not included in the planning.

Results

The model and solution approach is implemented in the modeling language AMPL, and we have used CPLEX 11 as the solver. All tests were carried out on a PC with 32 GB RAM and an i7-4770 processor.

A comparison with the full manual solution and proposed solution method is given in Table 2. We have information on

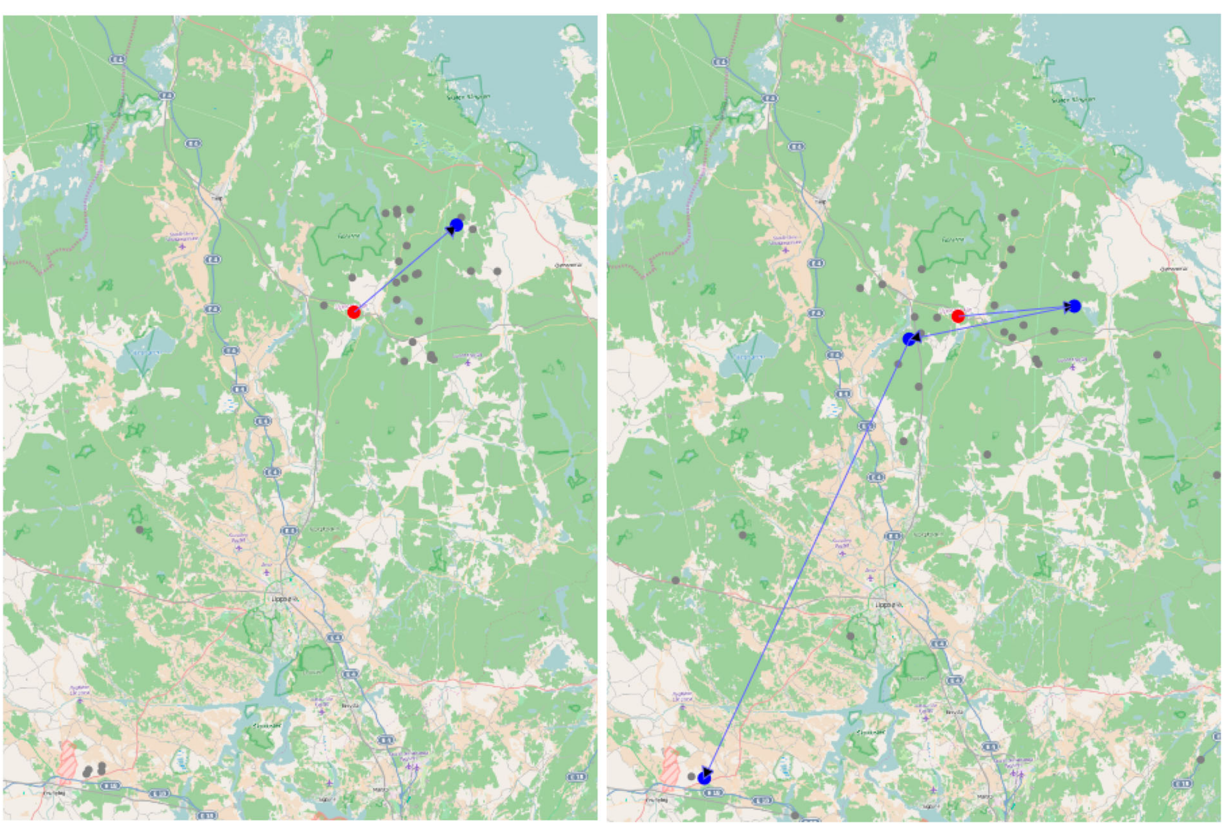

Figure 3. Examples of movements (lines) of a team between harvest areas and allocated areas (dots) in a manual solution (left) and an optimized solution (right).

different cost components, as well as average costs and distances. The transportation cost (opt for manual) is when we take the manual harvesting plan but make an optimal transportation plan.

One of the issues in making a comparison is that the manual solution is not necessarily feasible in the model. The performance functions may not be accurate and the harvest area may have been harvested faster or more slowly. In order to compare solutions which are feasible, we fix the schedule in the model but let the optimization adjust the manual plan so that it becomes feasible. This is one reason why we also solve an optimization model for the manual solution. The second reason is that we want to examine how good the manual transportation is compared to an optimal transportation plan, but given the manual schedule for all teams.

The size of the different optimization models in terms of the number of variables (binary and continuous) and constraints, and their solution times, are given in Table 3.

In Figure 3, we illustrate the areas allocated to a team and the movement in the business periods for the manual and optimized solution, respectively.

Discussion

The overall effect of using the proposed approach shown in Table 2 is that we can reduce the total cost by SEK 6.38 million (8.8%) in case A and by SEK 0.96 million (1.5%) in case B. A saving of 8.8% would considerably improve competitiveness. The harvesting and forwarding cost can be reduced considerably more in case A than in case B. The main reason is that, in case A, we have detailed production capacity for each team while, in case B, we only have the size of machines with similar performance curves. Since the production capacity for the same-sized machines is the same, it is difficult for the model to find better solutions. This also applies because the performance curves are very similar even for different sized machines. The relative difference in harvesting and forwarding costs between the two cases depends on the fact that 10 of the 26 teams in Case B have two harvesters and only one forwarder. Another explanation comes from the differences in average tree size and forwarding distance in the cases.

An interesting point is that it is worthwhile accepting a higher cost for team travel and moving equipment in order to more easily find the best allocations of teams and harvest areas. This aspect has also been observed in Bredström et al. (2010). The planner probably has a goal to reduce the travel cost by keeping the teams close, but misses out on the fact that it is important, in terms of cost, to find the best possible allocation.

It is clear that better transportation solutions can be found in both cases. The savings for case A are SEK 0.66 million (2.26%) and for case B SEK 0.87 million (3.42%). These levels are similar to those found in earlier case studies for transportation planning. As there are many supply and demand points for many assortments, finding an optimal transportation plan is known to be difficult. This is why a system like FlowOpt, Forsberg et al. (2005) have proved to be an efficient tool used by some companies (but not the companies in this study). In order to see whether these savings were due to the fact that we compared a manual harvesting plan with an optimized harvest plan, we also optimized the transportation plan for the manual harvest plan. The savings for the two cases were then 2.57% and 3.58% . These results show a similar difference compared to the optimized harvest plan firmly supporting that optimization can help producing better plans.

If we study the business periods, it is not possible to see whether any kind of creaming is done. In case A, the average transportation distance is lower than the average over the full planning period, but in case B the opposite applies. Nor do we have any exact information on which harvest areas were available in each monthly planning. In our cases, the proposed solution method is limited by the operations actually done. This of course limits the possibilities to find better solutions. With more harvest areas available, that is, the ones that were available in the manual planning, even better solutions could be found. The same is true for the demand description, as we use the actual transports to define the demand. Increased flexibility would enable the optimization to find better solutions.

It is clear from Figure 3 that the allocated areas are more dispersed in the optimized case, because longer moves are justified to get the right machine to the right area. Relative logging costs are affected very negatively if a harvester in a specific class (small/medium/large) is allocated to a stand outside the preferred working range for the machine. The preferred working range for a harvester is primarily determined by the mean stem volume in the stand.

Table 3 shows all the sizes of the models. Problem 1 has 20,100 binary variables for case A and 90,306 for case B. The numbers of continuous variables are 119,116 and 219,616, respectively. We are only interested in the optimized versions, as the manual are limited versions where many items are already fixed. The numbers of constraints are 36,278 and 141,642, respectively. These are large problems but the solution time is within two minutes in both cases. Problem 2 is about twice the size and takes about 20 times longer time to solve. Problem 3 is again about twice the size, but has a similar solution time. Both cases are solved within three hours. Even if the sizes of the models are relatively large, we can find good solutions with the proposed solution methods within limited computational time. The full model has 249,712 binary variables for case A and 1.24 million for case B. The numbers of continuous variables are 1.59 million and 2.14 million, respectively. The numbers of constraints are 378,341 and 1.28 million, respectively. When trying to solve case A directly using CPLEX, we could not find a feasible solution (i.e. without large penalty values) after 24 hours (86,400 seconds). This is considerably lower quality compared with the proposed method. We also tried to use the solution found by the proposed method as a starting solution for CPLEX in the full model. However, after 24 hours no improved solution could be found and the optimality gap was still 21%. Case B is even larger and the same weak performance also applies in this case.

One of the most important differences between manual planning and our approach is that the optimization model can take much more information into account when creating schedules. The proposed approach can better decide the timing when areas are harvested in order to make better allocation of logs to fulfil the mill demands. In a manual planning approach, the allocation is done based on the availability of harvest areas at the current moment. Even though the manual schedules are good, they cannot balance over the entire planning period. Also, the optimization can make better allocation of harvesting teams to the areas which is best suited for their machine capacity and performance. In the manual approach, there is more emphasis to allocate teams close to their home bases even if this is not the best allocation. This allocation is however very difficult to make manually as much information is needed for such assignments. Also, in manual scheduling areas often are clustered and then allocated to the teams in order to reduce moving costs, even though the machine performance might be less in some of the stands in the cluster. The optimization instead tries to use each machine where it has its highest performance.

The data used in the case study come directly from company databases. In case A, we use data directly from the forest planning system called VSOP, which is an operative business system developed by the international company CGI. Consequently, it is very easy to connect the optimization models in a module in direct communication with the overall planning system. This is an important aspect in developing a customized module for the optimization model.

In conclusion, we have proposed a solution methodology that meets many of the challenges described in the introduction. Our methodology can provide detailed schedules for the upcoming month on a daily basis, while maintaining a long-term balance on a monthly basis. This contrasts with many other studies where the planning periods are longer and constant throughout the planning period. The solution times of our models are within practical limits. As we solve the model on a rolling horizon, we can adjust the plans according to various random events, such as weather and demand. Creaming is limited, as we can balance over the entire planning period in each replanning. In our case, this is somewhat less critical, as the supply balances the demand over the full period. To study the effect of creaming on a longer period than one year with unbalanced demand and supply, we need to include additional harvest areas available. This is a very interesting topic for further research.

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Disclosure statement

No potential conflict of interest was reported by the authors.

References

Andersson G, Flisberg P, Liden B, Rönnqvist M. 2008. *RuttOpt – a decision support system for routing of logging trucks*. Can J For Res. 38:1784–1796.

Audy JF, Mobtaker A, Ouhimmou M, Marques AF, Rönnqvist M. 2016. Tactical planning and decision support systems in the forest-based value creation network, Chapter 10. In: D'Amours S, Ouhimmou M, Audy JF, Feng Y, editors. Forest value chain optimization and sustainability. CRC Press/Taylor & Francis, ISBN: 978-1-4987-0486-1.

Bredström D, Jönsson J, Rönnqvist M. 2010. *Annual planning of harvesting resources in the forest industry*. Int Trans Oper Res. 17(2):155–177.

Broman H, Frisk M, Rönnqvist M. 2009. *Supply chain planning of harvest operations and transportation after the storm Gudrun*. INFOR. 47 (3):235–245.

Carlsson D, Rönnqvist M. 2007. *Backhauling in forest transportation: models, methods and practical usage*. Can J For Res. 37:2612–2623.

D'Amours S, Rönnqvist M, Weintraub A. 2008. *Using operational research for supply chain planning in the forest product industry*. INFOR. 46:47–64.

Epstein R, Karlsson J, Rönnqvist M, Weintraub A. 2007. Harvest operational models in forestry. In: Weintraub A, Romero C, Bjørndal T, Epstein R, editors. Handbook of operations research in natural resources. New York: Springer; p. 365–377.

Flisberg P, Frisk M, Rönnqvist M. 2014. *Integrated harvest and logistic planning including road upgrading*. Scand J For Res. 29(1):195–209.

Forsberg M, Frisk M, Rönnqvist M. 2005. *FlowOpt - a decision support tool for strategic and tactical transportation planning in forestry*. Int J For Eng. 16(2):101–114.

Karlsson J, Rönnqvist M, Bergström J. 2003. *Short-term harvest planning including scheduling of harvest crews*. Int Trans Oper Res. 10:413–431.

Karlsson J, Rönnqvist M, Bergström J. 2004. *An optimization model for annual harvest planning*. Can J For Res. 34(8):1747–1754.

Marques AF, Audy JF, D'Amours S, Rönnqvist M. 2014. Tactical and Operational harvest planning, Chapter 7. In: Borges JG, Diaz-Balteiro L, McDill ME, Rodriguez LCE, editors. The management of industrial forest plantations. Dordrecht: Springer.

Rönnqvist M, D'Amours S, Weintraub A, Jofre A, Gunn E, Haight RG, Martell D, Murray AT, Romero C. 2015. *Operational research challenges in forestry: 33 open problems*. Ann Oper Res. 232:11–40.

Troncoso J, D'Amours S, Flisberg P, Rönnqvist M, Weintraub A. 2015. *A mixed integer programming model to evaluate integrating strategies in the forest value chain – a case study in the Chilean forest industry*. Can J For Res. 45:937–949.