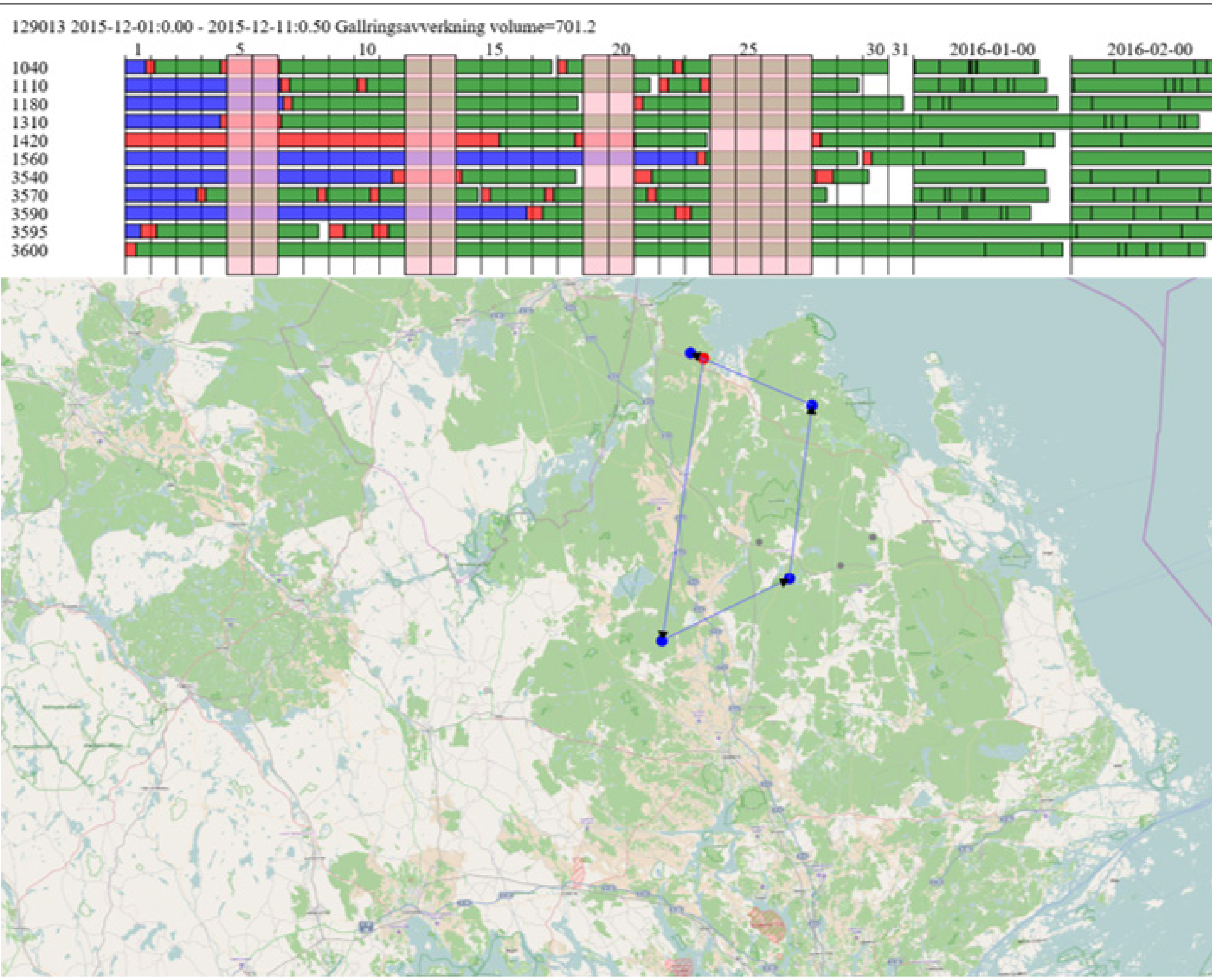
ARBETSRAPPORT 1018-2019 (English version of Arbetsrapport 930-2017)

Scheduling of harvesters

Order of planning



skogforsk

Authors
Patrik Flisberg, Mikael Frisk, Mikael Rönnqvist Erik Willén

Sammanfattning

Schemaläggning av avverkningsresurser och planering av vilka trakter som ska avverkas och i vilken ordning, är en viktig del i skogsbrukets planeringsprocess. Denna turordningsplanering är komplex, eftersom flera olika beslut måste fattas och en stor mängd detaljerad information måste bearbetas.

För att underlätta denna planering har Skogforsk utvecklat en planeringsmodell som ger förslag på vilka bestånd som ska avverkas när i tiden och av vilket maskinlag.

Kostnader för drivning, transport till industri, flytt av maskiner mellan trakter och personalens resor till och från trakterna, minimeras samtidigt som värdet på den avverkade skogen maximeras.

Utfallet från de avverkade bestånden matchas mot de leveranskrav som företaget har gentemot olika mottagningsplatser.

Resultatet utgörs av en schemalagd avverkningsplan som kan presenteras i befintliga beslutsstödsystem.

Modellen skapar detaljerad information om resursernas aktiviteter den närmaste månaden samt en översiktlig plan för upp till ett år framåt.

I fallstudier tillsammans med BillerudKorsnäs och Holmen Skog har modellen testats och utvärderats med goda resultat. Testerna gjordes med skarpa data för verklig planering vid sammanlagt fem tillfällen. Utvärderingen av optimerings¬modellens förslag till turordning visar att en stor del av förslagen var klart genomförbara och utgjorde en bra startpunkt för en operativ plan. De fall där modellens förslag inte var möjliga att överföra till praktiken kunde bland annat härledas till felaktig definition av när trakter var tillgängliga.

Fallstudierna har visat att modellen är lämplig att använda för att skapa förslag till turordningsplaner för avverkningslagen.

skogforsk

Uppsala Science Park, SE-751 83 Uppsala
skogforsk@skogforsk.se
skogforsk.se

 ISSN 1404-305X

Foreword

Scheduling involves deciding the order in which logging areas are allocated to harvest teams by forest company production managers. This report summarises development and demonstration of the project Scheduling of harvesters, which was run from 2014 to 2017. The project was carried out by Skogforsk in collaboration with Creative Optimization Sweden AB. Skogforsk's special programme for increased productivity with reduced environmental impact financed the project, together with participating forest companies.

Grateful thanks are extended to BillerudKorsnäs and Holmen Skog for their active participation, which enabled the demonstrations, and to the Örnnästet policy group, which continually provided valuable comments and prioritised the project for funding (Göran Andersson, BillerudKorsnäs [Chair], Gunnar Björkholm, Mellanskog, Jonas Eriksson, Holmen Skog, Mats Johansson, Södra, Veegard Haanaes, StoraEnso, and Per Österberg, SCA).

Validation of the developed models have been performed within the Efforte project. This project has received funding from the Bio Based Industries Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No 720712 with a project duration: 1.9.2016–30.8.2019. Coordinator: Natural Resources Institute Finland (Luke).

Thanks are also extended to CGI Sverige, which provided data from the companies' databases for the analyses.

Patrik Flisberg, Mikael Frisk, Mikael Rönnqvist and Erik Willén

Contents

Sammanfattning ... 2

Foreword ... 3

Summary ... 5

Background ... 6

Aim and objectives ... 8

Materials and methods ... 8
- Requirements for input data ... 8
- What the model can offer ... 9
- Solution method ... 11
- Case studies ... 11

Results ... 14
- Holmen Skog ... 14
  - Optimization results ... 14
  - Comments from production managers ... 16
- BillerudKorsnäs ... 17
  - Optimization results ... 17
  - Comments from production managers ... 18
- Identified and prioritised benefits ... 19

Discussion ... 21
- Input data ... 21
- Weighting of parameters and model requirements ... 22
- Evaluation ... 23
- Benefits ... 23
- Practical use of the model ... 24
- Towards implementation ... 25
- Further development ... 25

Conclusions ... 26

References ... 27

Summary

Scheduling harvest resources and planning which areas are to be harvested, and in what order, is an important part of the forestry planning process. Scheduling is complex, because many different decisions must be made, and a large amount of detailed information must be processed.

Skogforsk has developed a planning model that generates proposals about which stands are to be harvested, when, and by which harvest team. Costs of harvesting, transport to industry, movement of machines between areas, and work team movements to and from the area are minimised, while maximising the value of the harvested forest. The yield from the harvested stands is matched against the company's specific delivery requirements for different recipient points.

The result is a schedule for a harvesting plan that can be incorporated in existing decision-support systems. The model generates detailed information about use of resources in the forthcoming month, and a more long-term tactical plan for up to a year ahead.

The model has been tested and evaluated with good results in case studies involving two Swedish forest companies, BillerudKorsnäs and Holmen Skog.

The tests were based on authentic data for actual planning on five occasions. Evaluation showed that many of the scheduling proposals generated by the optimization model were feasible and formed a good basis for an operative plan. In those cases where the model's proposals were not feasible in practice, possible reasons included incorrect definition of when the harvest areas would be accessible.

The case studies showed that the model is suitable for generating scheduling proposals for harvest teams.

Background

Forestry supply chains depend on efficient harvest organisations that cost-effectively adapt timber harvest to delivery agreements between the organisation and mills.

Harvest planning involves many decisions, the most important of which are:

- Deciding which areas are to be harvested to match relevant delivery or production targets regarding volume per assortment and time of delivery.
- Deciding which harvest team to use in each area to minimise resource use and cost.
- How to match harvest and transport to industry to minimise transport distance.

The planning outcome is a schedule for all harvest teams for a certain period ahead, usually one month. However, planning for the forthcoming month is insufficient; planning must also integrate the subsequent 2-12 months to balance resource use.

Scheduling is a complex calculation and planning task with many variables, and information is needed about harvest areas and harvest team availability and productivity. A calculation model that can generate proposals for scheduling would considerably ease this work. A model would also be useful when there is a need to quickly revise planning because of unforeseen circumstances.

In the FlexWood project, an optimization model was developed for planning harvest activities, with the aim of minimising costs of harvest, movement and transport, while maximising the value of the harvested volumes and fulfilling a given industry demand (Flexwood, 2012). The model was developed and tested in 2015 at BillerudKorsnäs and Holmen Skog with good results. With historical data, the function and content of the model could be verified, thereby motivating further tests in authentic situations.

The aim of the optimization model was to generate scheduling plans. The optimization would produce data on which to base decisions on scheduling of harvest resources and allow scenario analyses if logging circumstances changed.

The model generates a proposal about which stands are to be harvested, when, and by which harvest team. Costs of harvesting, transport to industry, movement of machines between areas, and work team movements to and from the area are minimised, while maximising the value of the harvested forest. The yield from the harvested stands is matched against the company's specific delivery requirements for different recipient points. The result is a scheduled harvesting plan that can be incorporated in existing decision-support systems.

The model manages up to one year of planning, using a rolling horizon. Normally, the first month is specified with 28-31 periods (one per day) and subsequent months are specified as individual periods. This allows operational planning for the first month and tactical planning for the remaining months. However, the operational planning is not linked to every day in the first month; the planning period can be longer depending on practical circumstances.

The model must be able to describe the first month in detail and generate longer-term tactical planning for the subsequent months. Operational planning is important because of the need for accurate instructions regarding, for example, start date for harvesting, choice of bucking instruction for each area, and detailed flows to mills at day level. Tactical planning is important to avoid 'creaming', i.e. harvesting all the best areas at the start of the year, which would increase the cost and difficulty of operations later in the year.

The model therefore uses two periods:

- A shorter and more detailed operational planning period (business period). In this period, the model proposes decisions that will be implemented and used operatively.
- A longer-term tactical planning horizon (anticipation period) that is mainly used to evaluate the effect of decisions taken in the operative period.

One important difference is that, in operative planning, a schedule for harvesting is generated, but in tactical planning the only specification is the month in which harvesting will start. This type of planning is proposed in, for example, an article by Troncoso et al. (2015) for long-term strategic planning in Chile. In that model, the business period covered one year, while a five-year horizon applied for tactical planning in the anticipation period.

The objective of the optimization model for scheduling is either to:

A. Maximise profit in the operation, or
B. Minimise costs at a given demand.

These objectives give the same solution if demand is fixed. Even if the objective is to maximise profit by varying demand within a few intervals, much will depend on finding cost-effective logistics.

The model includes parameters to balance, for example, transport work over several time periods. These parameters can be interpreted as a cost for deviating from a target that can be an average. The model also uses penalty parameters and penalty variables to ensure a permitted solution. If any of these variables has a value, this indicates an error in the input data, so further analysis is necessary. The use of these penalties considerably facilitates troubleshooting in data.

The model comprises three parts:

- Decision variables
- Other conditions
- Target function

The model is described in more detail in Frisk et al. (2016). The model is a mixed whole-number problem (Lundgren, Rönnqvist & Värbrand, 2010), which means that only some of the variables are whole-number variables. Even for small issues, solution of these problems is known to be very difficult. A standard solution involves commercial optimization solvers, e.g. CPLEX[1)], which in turn use sophisticated tree-searching and plan sectioning methods, integrated with efficient pre-processing algorithms.

[1)] http://www-01.ibm.com/software/commerce/optimization/cplex-optimizer/

Aim and objectives

The aim of the project was to improve the efficiency of scheduling, by applying models based on available data on forest, industry and logging.

The aims were to:

- Carry out a user evaluation under realistic conditions.
- Test and develop the model so that, at the end of the project, the model could be implemented in the companies' operative planning.

Materials and methods

REQUIREMENTS FOR INPUT DATA

Demand in the model is described as a target volume of a certain assortment over a certain period (a calendar week) for a certain recipient. Deviation from a target volume is permitted by a certain percentage (both up and down) per week and per month. Permitted deviation at week level is normally greater than the permitted deviation per month. Demand is supplemented with price information, i.e. the price the recipient pays for each assortment. This allows the value to be maximized by ensuring correct destination of the volume from the harvest.

The company's contractual delivery requirements are assumed to be fulfilled, except when, for example, there is insufficient volume of a certain assortment. In such cases, the model can buy in these volumes from an external source and deliver to the recipient.

Resources (available assortment and volumes) are described as information about volume yield for all areas, together with detailed information about the harvest area. For each area, information is needed about total volume, mean stem size, forest transport distance, bearing capacity, and harvest type (final felling, thinning, seed tree felling, etc.). Capacity or time is determined by tree volume and machine size on each individual site. As the capacity also varies between different harvest teams (with otherwise the same conditions), the relative productivity of each harvest team can be compared with normal productivity.

Information is also needed about the coordinates of the site and whether the forest is owned by the company or the standing timber purchased.

The area properties are important for length of harvesting time, choice of harvest machine, and time of harvest. In the start position, the first period is linked to a certain date, for example to control when different harvest areas are available and when different harvest teams can work with consideration for holidays, planned maintenance downtime, etc. There must also be information that determines when in the year different bearing capacities apply, and availability information regarding all machine resources.

The harvest team is described with ID, type (employed or contracted), home base, action radius (maximum permitted distance between home base and harvest area), minimum and maximum time the team can work in each period, and any requirements regarding target volume. Every home base has a name and coordinates. Each harvest area must be described with a distance to the boundary of the home base area of each harvest team. If the site is within the area of the team's home base area, the distance is zero.

Description of harvest machines is associated with the description of the harvest teams. Each machine is described with ID, the harvest team to which it applies, machine type (harvester and forwarder), size (large, medium, small), available capacity per period, and cost per hour.

Other information needed is distances between all harvest areas, between areas and the harvest teams' home bases, and between areas and recipient points, as well as information about transport costs (timber transport and person transport), movement costs for machines, accessibility details for each bearing class, minimum distance for the movement cost to apply, time taken for movements between sites, maximum proportion of thinning, and maximum proportion of external purchase. Up-to-date information is also needed about roadside volumes and location of the harvest teams at the start of the planning period.

The time when a certain harvest area is to be felled is partly determined by its bearing capacity. For many companies, transport bearing capacity is shown as a combination of road and forest bearing capacity and basic conditions and is therefore an appropriate source of information. The time of harvest can also be steered explicitly by the user stating when a certain area is to be harvested. Sites can be prioritised so that they are harvested no later than a certain number of months after purchase.

WHAT THE MODEL CAN OFFER

Which harvest team is allocated which area is determined by several factors. Consideration is primarily taken to the machine type and whether it is permitted on the harvest area in question (for example, a final felling machine may not be permitted in a first thinning).

There are also constraints on how far from the home base a harvest team is permitted to operate. Whether the harvest area lies within the home base area of a harvest team is also considered. For each machine, productivity is stated, which is dependent on mean stem size (harvester), forwarding distance (forwarder) and other factors (e.g. surface conditions, season). In the optimization, the time taken to harvest each area is calculated, and this data is then used to match available capacity for each machine. Productivity of the harvest teams is stated for each felling type (e.g. final felling, thinning, felling of seed trees, standard trees).

One problem of planning is to direct the harvest teams so that they work as much as possible within a limited area, thereby avoiding unnecessary movement costs. This problem is common to many models, as they do not explicitly include decisions, because this would make the models much bigger and more difficult to solve.

The aim of keeping the harvest teams within a limited area sometimes conflicts with finding the best possible harvest areas for each team in relation to their productivity. In this model, a compression factor is used to balance these aims against each other. The compression factor is used in two phases in the second stage of the solution method (described below).

In the first phase, the solution from the model is used to determine a centre point in the harvest areas linked to each team. In the second phase, in which we solve the same problem again, a cost can be included for allocating areas that lie further away from the centre points of the different teams' home areas. This cost is proportional to the distance from the centre point to the harvest areas and can be changed by the user. The method is described in Bredström et al. (2010) and has been modified so that this model applies a greater weight to the harvest area in which each team is located at the start of the planning period. This is to ensure that the centre point is placed close to this.

The model works in three stages, although the user does not notice more than one because they are integrated in an overall methodology. The different stages are described in more detail in the section on solution method.

Movement costs can be expressed in various ways, either as a fixed cost per move, or a variable cost according to the distance. The number of movements per year for a harvest team can also be constrained; if the number is exceeded, a penalty cost is added.

An extra cost can also be added to each area (e.g. clearing supplement for the transporter).

A specific harvest team can be forced to harvest a certain area, for example on special request from the landowner.

In the optimization, revenue, transport cost, logging cost and movement cost can be weighted according to the objective of the organisation. In normal cases, all factors are weighted the same (1), i.e. all factors are equally important.

Optimization also considers other felling objectives, particularly volume percentage in thinning in relation to final felling, and the volume percentage in owned rather than purchased forest.

The results of the optimization mean:

- Scheduling of all machines for the first 30 days (or other period).
- Description of the volumes to be delivered to which recipients.
- Compilation of costs (logging, movement, transport, and miscellaneous).
- Description of wood flows.
- Conclusion on fulfilment of demand with the solution chosen.

SOLUTION METHOD

The model cannot solve practical problems within a reasonable planning time. The model, quite simply, is too big, so a solution method comprising three stages has been developed.

The solution methodology involves a sequence of aggregations and separations, where the individual problems are much simpler to solve than the overall problem. The method, or algorithm, can be described in the following three stages.

Step 1. Solve aggregated model
Only two planning periods are used for optimization. All business periods are aggregated into one period, and all anticipation periods are aggregated into the other. The aim of the model is to include aggregated demand and allocate all areas to either the aggregated business periods or the aggregated anticipation periods when they are to be harvested. This allows a balance between both capacity and demand. Since the optimization problem only has two periods, it becomes much smaller and relatively ease to solve.

Step 2. Solve model using only business periods

In the solution, the areas that are to be harvested in the business periods from Step 1 are stated. Here, all business periods are used, and comprehensive planning is only carried out in the business periods (i.e. the first month). This optimization problem is relatively difficult, but can be solved within a practical planning time, because the model already knows which areas are to be harvested during the planning period and because no anticipation periods are included.

Step 3. Solve model with fixed harvest planning in business periods

Given the comprehensive solution from the business periods, the model solves the problem again with the anticipation periods. In the business periods, the scheduling is fixed but not the flows and stocks, which considerably simplifies the process and gives a reasonable solution time.

There is no guarantee that this method will identify an optimal solution, but the model does find solutions of very high quality. Furthermore, the third step does not need to be solved again if only a detailed description of the next month is needed, because the necessary balancing between business and anticipation periods takes place via the first step.

CASE STUDIES

In the project, the optimization model was used to generate scheduling plans on five different occasions, three at Holmen Skog and two at BillerudKorsnäs. On all occasions, data was collected approximately a week before the end of the month, and the production managers were able to access the optimization proposals a few days later. After another few days, a follow-up meeting was held to discuss what benefits the proposed plan could have in the actual planning. Information about available harvest areas, current roadside stocks, and transport plans were delivered as Excel files that were then adapted to the optimization model.

The harvest teams' home base areas were drawn manually by the production managers and then digitalised. GIS tools could then be used to calculate the distance from each harvest area to all the home base boundaries of the harvest teams. The production managers also supplied information on where (i.e. in which area) each harvest team was expected to be at the start of the planning period.

The studies at Holmen Skog were carried out on a large area (Figure 1) and involved 21 harvest teams, while those at BillerudKorsnäs involved eight harvest teams and a smaller geographical area in eastern Uppland (Figure 2).

Table 1 summarises the most important optimization considerations for each company, including industrial demand. For both companies, the harvest alternatives were limited to final felling and thinning. The companies did not regard seed tree felling, felling for roadside line, and other smaller felling alternatives as important to include in the optimization, as manual planning is simpler and preferable for these.

Table 1. Examples of optimization conditions for each company.

Parameter	Holmen Sko	BillerudKorsnäs
Number of harvest teams	21	8
Number of industries	13	12
Total demand (m^3sub)	134 000/768 000	81 000/477 000
Number of harvest areas/delivery timber items	850	300
Available volume (m^3sub)	760 000	480 000
Number of assortments (according to SDC SSTE code)	12	41
Number of assortment groups	6	5
Number of business periods	45	62
Number of anticipation periods	4	3
Total planning period (months)	5.5	5

All distances (from harvest area to industry, terminal, other areas and home bases, and from terminal to industry) were calculated using data from NVDB/SNVDB and Calibrated Route Finder 3.0.

On all planning occasions, several different optimizations were carried out, with variations in how the model was run, particularly with regard to the harvest team's production target and movement compression factor.

In all optimizations, functions developed by Skogforsk were used to describe machine productivity. Different functions were used for different machine sizes. Machine costs (SEK per hour and machine) were defined by each company.

Both BillerudKorsnäs and Holmen use a forestry operative planning system called VSOP. The system contains databases with information about available harvest areas and delivery wood items. The IT company CGI manages and runs VSOP on behalf of forestry companies, so CGI provided data for the project. In the optimizations, only the harvest areas described as 'planned' or 'plannable' were used. For Holmen Skog, the concept 'tangible' was used to determine whether a plannable site could be included in the scheduling or not.

Transport costs were defined by the respective company.

For Holmen Skog, optimizations were carried out on three planning occasions during spring and summer 2016; ahead of April, May, and restart after the summer break (July/August).

Figures 1 and 2 show the geographical distribution of the optimization data for the two companies.

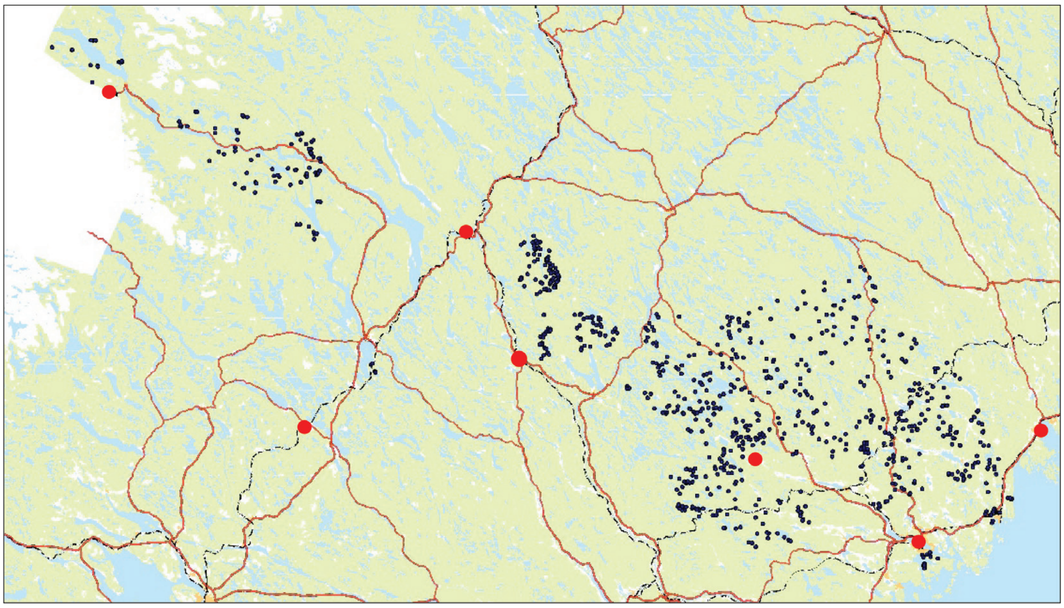


Figure 1. Geographical location of the study based at Holmen Skog, with Örnsköldsvik in the bottom right corner. Dots correspond to harvest areas or locations for delivery wood, and red circles correspond to recipient points.

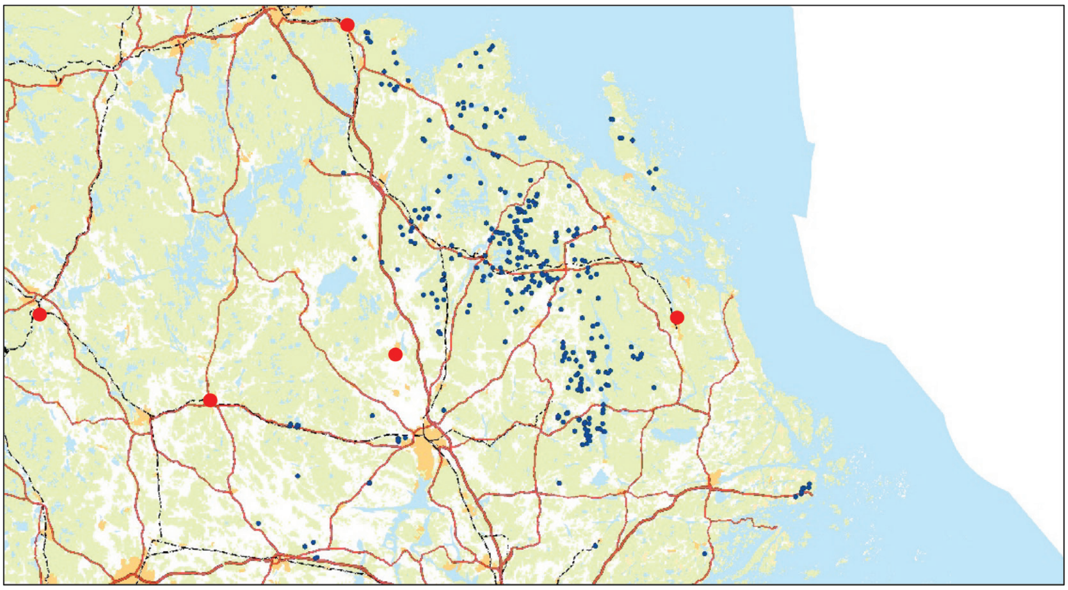


Figure 2. Geographical location of studies based at BillerudKorsnäs in eastern Uppland. Dots correspond to harvest areas or locations for delivery wood, and red circles correspond to recipient points.

After completion of the case studies, the benefits of using the model for scheduling were assessed and prioritised. Skogforsk formulated proposals of benefits that were supplemented and prioritised by the participating production managers.

Results

HOLMEN SKOG

Optimization results

For Holmen Skog, optimizations were carried out both with and without requirements for the model to fulfil the harvest teams' agreed target volumes every month. The optimizations without such a requirement seemed to give better solutions; they would probably be simpler to apply in practice due to more reasonable movement sequences. Since the harvest teams' target volumes matched the production rate, the deviation was not significant in practice. Demand was fulfilled with a certain surplus to meet the demand in subsequent periods when bearing capacity would be lower, thereby reducing available volume.

Table 2 shows the results from one of the optimizations, divided into business periods and total (business + anticipation).

Table 2. Results from one of the optimizations at Holmen Skog, southern Västerbotten.

Parameter	Business	Total
Harvested volume, thinning (m^3sub)	10 797	109 432
Harvesting cost, thinning (SEK/m^3sub)	194	192
Harvested volume, final felling (m^3sub)	110 832	586 754
Harvesting cost, final felling (SEK/m^3sub)	88	96
Produced volume (m^3sub)	121 616	695 696
Transported volume (m^3sub)	152 803	767 595
Travel costs (SEK/m^3sub)	1.2	1.7
Movement cost, proportion of total cost (%)	2	3
Harvesting cost per produced m^3 (business)	97	111
Movement cost (SEK/m^3sub)	3.4	6
Transport cost (SEK/delivered m^3sub)	57	58
Total cost (SEK/produced and delivered m^3sub)	158	175
Harvest and movement (SEK/m^3sub)	101	117

The table shows, for example, that the transport cost per delivered m^3 is SEK 57 in the business periods and SEK 58 for all periods. The table also shows harvested volumes, movement costs, mean stem size, etc, and comprises an important part of the results compilation. The figures are first used to assess the feasibility of the results, and then to compare with results from optimizations where other conditions apply. The difference between produced volume and transported volume is due to existing roadside stocks that were used by the model.

The results in table form are supplemented by detailed descriptions of scheduling for each harvest team. The proposal generated by the model for scheduling three of the harvest teams is illustrated in Figures 3-5. Red dots represent the harvest team's home base and blue dots represent the areas proposed by the model in the business period.

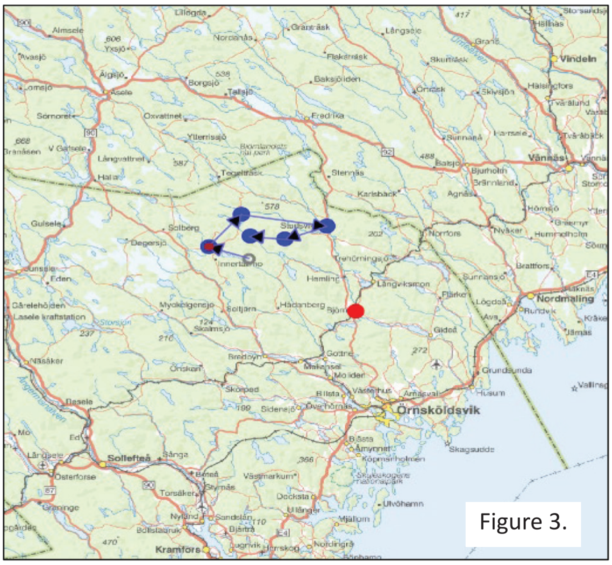


Figure 3.

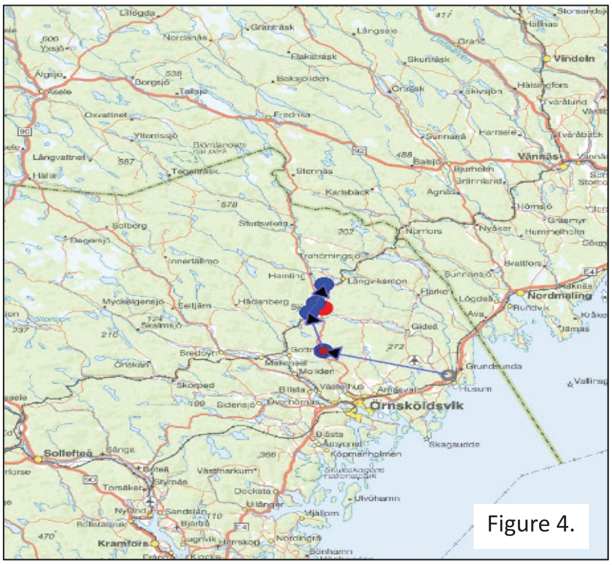


Figure 4.

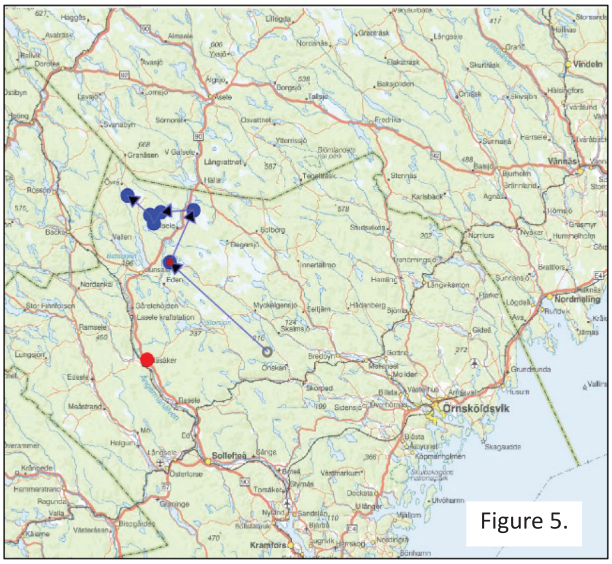


Figure 5.

Figures 3, 4 and 5. Scheduling proposal generated by the model for three different harvest teams, Holmen Skog.

Comments from production managers

The optimization result was compiled in table form and supplemented with the opportunity to review the scheduling proposal on maps as in the figures above. This enabled the production managers to assess how useful the proposals were in practice. The most important comments from the production managers were:

- The scheduling proposals are credible, making implementation of the model interesting.
- Approximately 50 percent of the sites in the proposal were used, but the proposed harvest team was not always used.
- The proposals are the same as would have been made manually, with feasible routes for teams moving between sites.
- Using the home base areas and limiting movement distances with the compression factor gives good results.
- The model includes some smaller areas that would perhaps be excluded in manual planning.
- In relation to transport, the harvest areas for the autumn were clearly not sufficient, which perhaps would not have been observed at that point in the planning process.
- The greatest value of the proposal is to form a basis for planning, a rough plan that can be modified.

When the actual planning needed adjustment in relation to the proposals generated by the optimization, this could be the result of new purchasing sites, newly-planned sites in forests the company owned, and because in practice there is a focus on specific products, such as densely forested sites at start-up after the summer break.

The results above describe the latest optimizations carried out in a period with relatively good conditions in terms of, for example, bearing capacity. In earlier optimizations during the spring, where bearing capacity was significant in choice of harvest areas, it transpired that wrongly registered areas and/or transport bearing capacity and incorrect bearing capacity calendar (periods in the year when an area with a certain bearing capacity can be harvested) can have a major influence on how useful the optimization results are in practice.

Some areas were deemed unsuitable for inclusion in the scheduling proposal. Of these, an estimated 20 percent were caused by registration errors, 20 percent on incorrect bearing capacity calendar, and 10 percent on unknown factors. The remaining 50 percent were caused by requirements and controls in the model, something that could be adjusted in the later optimizations.

BILLERUDKORSNÄS

Optimization results

For BillerudKorsnäs in eastern Uppland, optimizations were carried out ahead of periods with relatively good bearing capacity. The model again chose areas that were not suitable, but in this case the inverse of the optimizations at Holmen Skog in the spring. In the autumn, bearing capacity was greater than normal and, in practice, decisions were made to harvest areas that could not normally be harvested because of bearing capacity problems. If the model had been provided with correct information on bearing capacities, the proposals would have been better. In the final optimization, the bearing capacity was reflected correctly, and the results corresponded well with reality.

The defined demand could not be attained because the available machine capacity was insufficient; instead, the model prioritised generating good route proposals for the harvest teams. The produced volume could probably have been increased, but this would have been at the cost of the harvest teams' routes (more and/or longer movements). This shows clearly the importance of fine-tuning the optimization settings to allow the model to generate satisfactory results. In this case, the requirement to fulfil industrial demand must be balanced against the requirement to generate feasible movement sequences for the harvest teams.

The optimization problems were relatively small because of the small number of harvest areas and teams, so the optimization only took a minute or so. In the first optimizations, several shortcomings were identified in home base areas, productivity functions and bearing capacity calendars, but these were adjusted and fine-tuned for the later optimizations.

Table 3 shows the parameter values from the final optimization.

Table 3. Results from one of the optimizations at BillerudKorsnäs, northern Västerbotten..

Parameter	Business	Total
Harvested volume, thinning (m^3sub)	14 075	62 652
Harvesting cost, thinning (SEK/m^3sub)	197	193
Harvested volume, final felling (m^3sub)	50 856	395 948
Harvesting cost, final felling (SEK/m^3sub)	76	76
Produced volume (m^3sub)	64 931	458 601
Transported volume (m^3sub)	58 367	477 066
Travel costs (SEK/m^3sub)	1.4	1.0
Movement cost, proportion of total cost (%)	1.4	1.7
Harvesting cost per produced m^3 (business)	102.3	92.1
Movement cost (SEK/m^3sub)	2.3	2.8
Transport cost (SEK/delivered m^3sub)	64.2	65.3
Total cost (SEK/produced and delivered m^3sub)	168.9	160.2
Harvest and movement (SEK/m^3sub)	104.6	94.9

The table summarises the most important results from the optimization. Extended and more detailed information is shown in other result files generated by the optimization. However, the compilation is important to allow rapid review of the optimization results and comparison with, for example, results from another optimization.

The proposal generated by the model for scheduling three of the harvest teams is illustrated in Figures 6-8. Red dots represent the harvest team's home base and blue dots represent the sites proposed by the model in the business period. Other dots are areas allocated to the harvest team in other time periods. The model clearly avoids long movements, and attempts, as far as possible, to generate sequences that are feasible from a movement perspective. In one case, Figure 7, the team started outside its defined home base area, and the model chose to quickly move the team into its home area in the next movement.

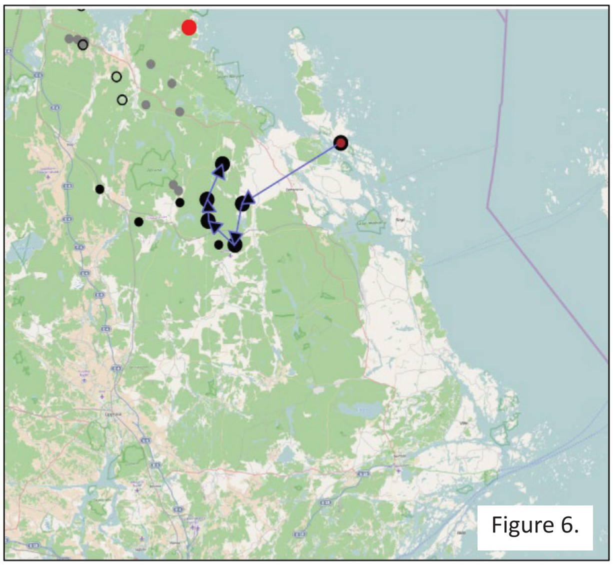


Figure 6.

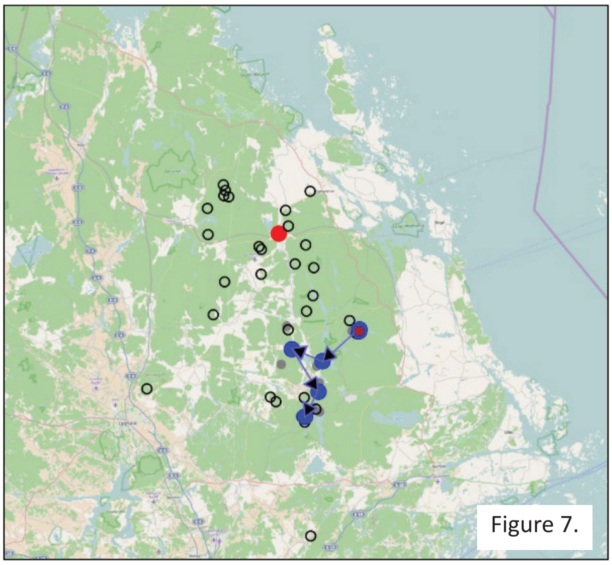


Figure 7.

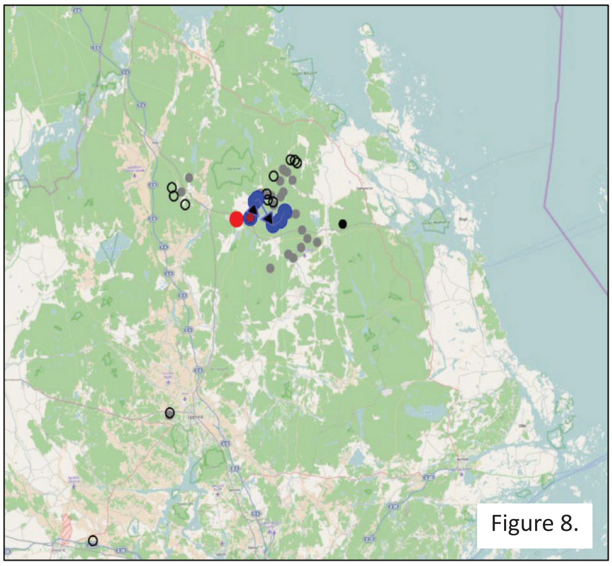


Figure 8.

Figures 6, 7 and 8. Proposal generated by the model for scheduling three different harvest teams, BillerudKorsnäs, eastern Uppland.

Comments from production managers

As for Holmen Skog, the model's proposals are presented in table form, supplemented with maps showing the scheduling proposals. For the final optimization, where home base area, bearing capacity calendar and compression factor had been fine-tuned, the results were very good:

- The proposals were very suitable for the teams and could be implemented with no adjustments.
- Prevailing weather has a major influence on choice of harvest area, so seasonal, local settings should be incorporated in the model.

IDENTIFIED AND PRIORITISED BENEFITS

After demonstrations, several benefits were identified for the user of the decision-support tool. For a cost-benefit analysis, the companies must review their individual circumstances and evaluate the proposed improvements.

1. **Faster scheduling**
   The proposal provides a good base that reduces the time needed for the actual scheduling. If at least 50 percent of the proposed harvest areas are used, this reduces the time needed for production planning. In one of the cases in 2016, nearly 100 sites would be chosen from the 850 available. If 50 sites were proposed, this would reduce the time taken to choose the remaining areas. Unsuitable areas could be excluded, and the optimization could then be rerun without those sites. The new method of working can reduce the total time allocated to production planning, and the opportunities for revised planning are improved as the process is fast. Sudden changes, such as higher or lower bearing capacity, can be more rapidly incorporated in a revised plan.

2. **Higher quality in scheduling**
   The model considers more variables than a production manager could manage, and it is easier to consider a longer time horizon and incorporate suitable sites. The overall view is improved because of the many variables considered by the model.

3. **Planning proposal is a better match to industrial demand**
   The model considers industrial demand, both immediately and within the forthcoming months, making it easier to match demand from industry to the timber stocks. This is much harder with manual planning.

4. **More structured process for production managers**
   A clearer process facilitates the work of both new and more experienced production managers. A greater number of similar processes enables development of the planning process and improves the efficiency of the work. New production managers are given good support, which facilitates their work.

5. **Feedback and improved quality of input data**
   Poor-quality input data will be identified when running the model and in the subsequent harvest. Focus can be placed on quality improvements and allowing better analysis in the future. This can apply to, for example, assessed bearing capacity, mean stem volume, or other variables in the input data that may be of poor quality.

6. **Can reduce logging costs**
   If improved productivity functions or improved stand information linked to the companies' payment systems could be included in the model, this could reduce the costs of logging. This area requires further development compared with the current model, but different scenarios can already be used to evaluate various cost items (see benefit 8).

7. **Model shows consequences over time**
   The model makes it possible to show consequences over time, for example the number of available harvest areas, shortage of sites at times of thaw, etc. This information is currently lacking. Scheduling enables scenario analyses in a completely different way than is currently the case.

8. **Different scenarios can be generated and evaluated against each other using performance indicators**
   Various scenarios can be easily tested after minor adjustments to the settings. This makes it possible to compare various parameters that are changed, e.g. home base area, movement distance, bearing capacity or target volumes/harvest team. One variation tested in the project was to use target volumes per harvest team or a target volume total.

After the optimizations, the participating production managers were asked to evaluate the various benefits (Table 4). Assessment was carried out by one production manager per company, and the result need not reflect the entire company's priorities. However, the results gave an idea of which benefits are regarded as most valuable.

Both companies emphasised the benefits of faster scheduling and the improved match between supply and industrial demand. Apart from these benefits, assessments varied slightly, which can depend on the specific situation within each company. It is noteworthy that all identified benefits were prioritised by one or other of the companies. The table can be used for further analyses and more detailed evaluations of benefits within both participating companies or companies that have yet to test the model.

Table 4. Prioritisation of benefits by the participating production managers.

Benefit/priority (1=lowest priority, 5=highest)	BKS	Holmen
Faster scheduling	5	5
Higher-quality scheduling		3
Planning proposal gives better match between supply and industrial demand	4	4
More structured process for production managers	2	
Feedback and improved quality of input data		2
Reduced logging costs possible		1
Model shows consequences over time	1	
Different scenarios can be generated and evaluated against each other using performance indicators	3	

Discussion

INPUT DATA

Input data must be accurate if the results generated by an optimization are to be credible and applicable. Different types of input data have different effects on the result. If, for example, the bearing capacity of a harvest area has been entered incorrectly, this can result in the model proposing harvest at a time that is not possible in practice, which naturally has a major effect on the feasibility of the plan proposal. If the productivity of a harvest team is ten percent higher than that stated in the input data, this has a certain effect on when timber is available but has little effect on scheduling.

There are several reasons why the model generates scheduling that cannot be fully implemented in practice. Table 5 shows the most important sources of error identified, and their consequences for the optimization model and its results.

Table 5. Possible sources of error and their consequences.

Source of error	Consequence
Error in bearing capacity calendar[2].	Wrong choice of harvest area Problems fulfilling industrial demand
Incorrect bearing capacity on harvest site or roads	Wrong choice of harvest area
Unreliable harvest yield	Incorrect matching of demand Wrong choice of harvest area
Machine productivity	Incorrect time taken for harvest Problem of fulfilling industrial demand

Unreliable input data for bearing capacity is very significant for the model's capability to generate scheduling plans that can be implemented in practice. Input data relating to bearing capacity is also the most common cause of the model proposing scheduling that is impossible. Consequently, correct bearing capacity data must be given high priority when planning the harvest in the field. In addition, the bearing capacity calendar must be adapted to prevailing conditions when the optimization is carried out.

According to the companies, incorrectly calculated harvest yield (both assortment and volume) is common, and this has consequences for how the actual demand can be fulfilled in practice. The effect of this error on scheduling is that the model proposes harvest of different areas to those that would have been proposed had the correct information been available. With better stand data and new methods for yield calculation, this error can be considerably reduced.

Information about the harvest teams' productivity is important for the model's calculation of how long it takes to harvest different sites and the size of the timber yield during a given period. When the stated productivity does not correspond with reality, this makes it difficult to fulfil industrial demand in practice or results in too much timber being produced in relation to the demand. This can also lead to problems of unpermitted solutions if the defined production targets do not match available machine time. However, for the model's scheduling proposal, productivity errors were not significant to the feasibility of a plan.

[2] Bearing capacity calendar concerns input data showing times in the year when harvest can take place on areas with various bearing capacities.

Other factors, such as occurrence of undergrowth, are significant for the time taken for harvest. However, information about undergrowth is lacking in the stand register, and so cannot be included as a parameter in the optimization.

Defining the home base area for the harvest teams proved to be important for the model to choose sites in the correct location for each team. Simply using the home base and allowing harvest within a certain distance is often wrong, because the home base is rarely at the centre of a harvest team's home base area.

The mean stem volume shown in the stand register is important for productivity, and thereby length of harvest time. Incorrect mean stem volume can also affect the choice of harvest team, because productivity between different machine sizes varies with mean stem volume. However, the case studies showed no incorrectly registered mean stem volumes.

Information about industrial demand is assessed as the input data where the risk of error is least. In the case studies, demand was described at assortment group level (e.g. spruce timber and pine timber), but in the future the demand may be defined in more detail, such as volume in different dimension classes. However, such a development would require the capability for better yield calculations.

WEIGHTING OF PARAMETERS AND MODEL REQUIREMENTS

The optimization model uses a large quantity of data, all of which has some effect on the optimization result. Linked to the model's conditions are penalty costs, which are used to attain desired effects in the optimization. Examples are penalties for not fulfilling an industrial demand or for harvesting an area that is outside a home base area. However, problems may arise when different conditions have conflicting effects on the result. In the project, attention has been drawn to several such problems when the results were reviewed in detail. For example, there may be a clear conflict in fulfilling demand while minimising the harvest teams' movement costs. If the requirement for fulfilling high demand is strong, the model can generate scheduling proposals that allow this, but may also generate proposals that are impossible in practice.

Instead, if the requirement for demand is lowered, and a certain deviation allowed, the model may be able to generate better movement sequences. The same applies to fulfilment of target volume for the harvest teams. Is it more important to fulfil the target volume every month than to generate a good movement sequence? Where is the limit for deviation from the target volume to generate an even better movement sequence?

The home base areas of the harvest teams, requirement for harvest type for each harvest team, requirements for outward roadside stocks, compression factor, etc, are other parameters that can have a strong (undesirable) effect on the optimization result. It is therefore important that all parameters and requirements are tested thoroughly in a number of analyses using authentic data, so that correct values and penalty costs can be fine-tuned before the model is used in practical operation.

EVALUATION

The results shown in Table 2 and Table 3 summarise, for example, costs and volumes for both the forthcoming month and the total period considered by the model. It is tempting to compare these figures with the actual outcome, but this is associated with several difficulties. For example, general productivity functions and time costs are used to calculate length of harvest time and logging costs. With correct information, they would adequately reflect the actual cost and produced volume, but the outcome would not exactly match reality. Furthermore, the plan is based on conditions that applied at one specific time. In practice, these conditions rarely apply for the entire planning period because new circumstances are constantly occurring, such as new harvest areas, changed machine availability, changes in prioritisations of assortments and volumes, or harvest team routes.

Earlier studies attempted to simulate actual conditions to make the optimization model find the same solution and then compare it with an optimal solution, but this proved impossible for these reasons.

BENEFITS

The benefits identified are based on results from case studies at two companies. Because conditions relating to input data and method of working can be expected to be the same in other forestry companies, the benefits should apply to most companies. However, they may differ somewhat depending on how companies evaluate the various benefits. There may also be benefits, not described in this report, that involve a focus on the practical use of the tool for production managers engaged in harvest planning.

Overall benefits discussed in earlier studies on scheduling:

- By allocating the machine resources to suitable areas as far as possible (in terms of mean stem and forwarding distance), the biggest cost items in logging are reduced, such as energy consumption per harvested cubic metre.
- Inclusion of onward transport of the timber from the landing to the recipient enables good transport planning, and results in lower transport costs and fuel consumption.
- The model also has the potential to manage more alternative estimates of assortment yield depending on which price list is used. This enables inclusion of more dimensions in the planning work to strengthen the forest value chains.

Even if this report does not quantify the benefits, the model could clearly be a useful tool in practical scheduling.

PRACTICAL USE OF THE MODEL

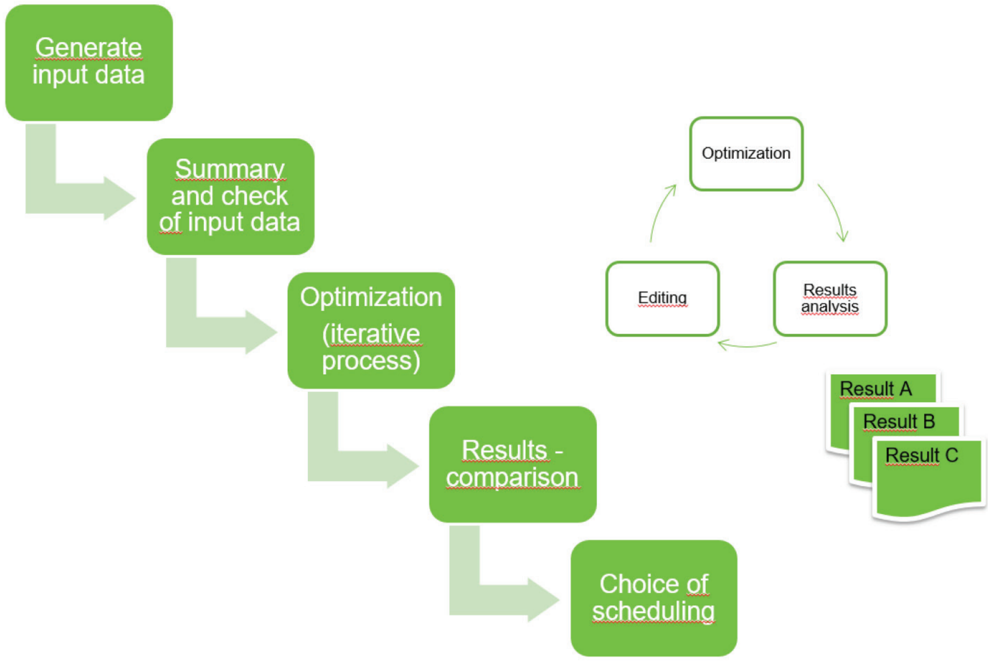


Figure 9. Proposal for work process for scheduling.

The model is intended to be integrated in decision support for scheduling. However, the model is only a small part of an entire production chain that requires several important elements where the user sets limits and analyses result before decisions are made on scheduling. A proposal for a work process is shown in Figure 9. The optimization is assumed to be part of an iterative process where several different optimizations are carried out before a final decision is made on scheduling.

The process requires the following components of a possible decision support tool:

- Generation of data, including determination of distance.
- Summary and visualization of data and editing.
- Entering of optimization results.
- Visualisation of results (map, schedule, tables, etc).
- Adjustment/locking.
- Comparison between different optimization results.

Distance determination involves distances between harvest areas, between areas and industry, and between areas and the home base area of the harvest teams.

Several factors are regarded as very important for successful implementation of the model, such as capability to edit input data, particularly data relating to bearing capacity, adjustment of certain optimization parameters, and the possibility to analyse many scenarios where results can be compared.

TOWARDS IMPLEMENTATION

The stages regarded as central for practical implementation of the scheduling model are:

- Demonstration and adaptation to the company's information flows.
  This does not apply to the forest companies that participated in the development project but does apply for other companies interested in using the model.
- Pilot studies on how the model can be integrated in existing production tools, IT systems, and a description for users in how the results from the model can be used in practical operations.
- Implementation and testing in practical situations. This element includes correct error management and reducing the number of manual elements.
- Updating of process description for production planners.

FURTHER DEVELOPMENT

The scheduling model has been developed and tested in several aspects. The test results show that it generates realistic plans that can be used for decision support in scheduling. However, some aspects have been identified that could be the subject of further testing:

- Test different price lists to steer production in harvest areas.
- Carry out more tests to avoid the creaming effect when the number of harvest areas and their volume exceed industrial demand.
- Use more and improved production functions.
- Improved yield forecasts, that provide better links between forest products and industrial demand.

Conclusions

Optimization results can be generated within a reasonable time (1-5 minutes), which is very important for practical use of the model.

- The developed method generates interesting and realistic plans for harvest, including scheduling of teams and transport of timber.
- The model is also an efficient tool for quickly identifying problems relating to fulfilling demand.
- The model can form the basis for detailed planning, which is necessary for practical implementation.
- Using data generated from VSOP (BillerudKorsnäs/Holmen), it has been shown that data is available for planning using the optimization model.
- We have observed it is difficult to balance machine use, which is important for how well an optimization proposal can be used in practice.
- Many machines are comparable, as they have the same costs and productivity function if they are the same size. It would be interesting to include differences in efficiency among teams, even when they use the same machine sizes.
- The model is a good tool for analysing effects when steering towards certain targets. In addition to minimising costs, examples are ensuring certain teams' work calendars are full and only using certain teams to fulfil demand (these are only occasionally allocated harvest sites). Another target could be to only minimise the total cost, regardless of how much or how little different teams work. Teams can be kept around their home base to minimise travel costs or focus more on reducing harvest cost.
- If demand is great in relation to available machine time and all teams must work full-time, there will be longer movements and increased travel costs because it becomes more important to place teams in the areas they harvest fastest.
- The model makes it possible to balance resource use over a longer period and thereby avoid a creaming effect (e.g. if there is a surplus of harvest areas, simply choose the cheapest). The problem is solved by including more planning periods, increasing demand in the final planning period, and/or limiting harvest cost and estimated transport work for the areas that are not harvested.
- It is important to have an accurate description of length of harvest time and forwarding time via productivity functions. This is something that may need to be revised/developed for different companies, since not all have detailed information about this.

References

Bredström, D., Jonson, P. & Rönnqvist, M. 2010. Annual planning of harvesting resources in the forest industry, International Transactions in Operations Research, Vol. 17, No. 2, 155-177, 2010.

Flexwood, 2012. Summary of WP 5000 – Novel Harvesting and Logistic Concepts for Integration of Forestry with Industry. Deliverable 5.4 – Novel Logistic model – Optimisation model for tactical and operational planning of the logging- and transport operations including data management. FP7 Grant agreement No. 245136.

Frisk, M., Flisberg, P. Rönnqvist, M. & Andersson, G. 2016. Detailed scheduling of harvest teams and robust use of harvest and transportation resources, Scandinavian Journal of Forest Research, 31:7, 681-690, DOI: 10.1080/02827581.2016.1206144

Lundgren, J., Rönnqvist, M. & Värbrand, P. 2010. Optimeringslära, Studentlitteratur, Sweden, 537 pages, 2010, ISBN: 9789144053141.

Troncoso, J., 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, Canadian Journal of Forest Research 45: 937-949.