FlexWood

Flexible Wood Supply Chain

Del. no.	5.3
WP no.	5000
Date	29/09/2010
Version	1.0
Revision	
Confidentiality	CO

Optimization model for scheduling of harvest resources

Responsible Partner: Skogforsk

Authors: Gert Anderson (SkogForsk), Mikael Frisk (Skogforsk), Patrik Flisberg (Skogforsk), Mikael Rönnqvist (Skogforsk)

Project Coordinator: University of Freiburg FeLis (ALU-FR)

SEVENTH FRAMEWORK PROGRAMME

The FlexWood project is funded by the European Commission within the Seventh Framework Programme (FP7). The Collaborative Project (small or medium sized focused research project) contributes to "Meeting industrial requirements on wood raw-materials quality and quantity" activities.

FP7 GRANT AGREEMENT No. 245136

Coordination:

FeLis – Department of Remote Sensing and Landscape Information Systems
University of Freiburg
Tennenbacherstr. 4, D-79106 Freiburg, Germany
www.felis.uni-freiburg.de
Contact:
Prof. Dr. Barbara Koch: barbara.koch@felis.uni-freiburg.de
Alicia Unrau: alicia.unrau@felis.uni-freiburg.de

Partners:

Albert Ludwigs Universität Freiburg	ALU-FR	Germany
Stiftelsen Skogsbrukets Forskningsinstitute	Skogforsk	Sweden
FCBA Institut Technologique	FCBA	France
University of Eastern Finland	UEF	Finland
Technical Research Centre of Finland	VTT	Finland
University College Cork	UCC	Ireland
TreeMetrics Ltd	TreeMetrics	Ireland
Forest Research Institute of Baden-Württemberg	FVA	Germany
Norwegian University of Life Sciences	UMB	Norway
University of Natural Resources and Applied Life Sciences	BOKU	Austria
Polish Research Institute	IBL	Poland
Logica Ltd	Logica	Sweden
Foran Ltd	FORAN RS	Sweden
University of Laval	UL	Canada

Website: www.flexwood-eu.org

Table of Contents

Abstract

In this paper, we describe the background of the harvesting and scheduling problem together with the solution approach. This approach includes the different models used.

1. Background

Within FlexWood work package 5500 we have developed a solution approach and models aimed to schedule harvesting resources (i.e. harvester, forwarder and harwarder) in combination with the selection of stands to be harvested under restriction of fulfilling demand from industry and minimizing the overall logistic cost. The purpose is to create a operational plan on which stands are to be harvested when in time and by which harvesting machine team. The logistic cost includes costs for harvesting, transportation of round wood from forest to mill and moving machines between stands. The outcome of the harvested stands (volume per assortment) will be matched with the demand from pulp-mills, sawmills and CHP-plants.
In order to get the right outcome from the stands the solution approach must suggest which apt file that should be used for each stand.

The plan or schedule is supposed to be detailed (daily) for about one month. However, this short term plan needs to be balanced against the long term use of the resources. Otherwise, we may get stuck in a bad situation with very high cost. A simple example is if we harvest the closest (to mills) harvest areas first (as this has the lowest cost for the transportation). As we get closer to the end of the year, we have a very difficult situation with stands far away and not enough transport capacity and/or long equipment moving. It is possible to formulate the overall problem into one model. However, this model would be too large and not possible to solve in reasonable time. Instead we apply a decomposition scheme where a sequence of models are solved based on a hierarchical structure. With this final solution, we have a detailed schedule for the operational planning. This can then be resolved in a rolling horizon type approach i.e. resolved as things are changed. The result, in the form of a scheduled harvesting plan, is to be presented both as a Gantt chart and in a map. The results will also be shown in tables and diagrams (costs for harvest and transportation, harvested volumes, etc.).

The models and solution approach will be implemented and used in VSOP, an application for operational harvest planning created by Logica and used by several Swedish forest companies. The implementation of the model in VSOP will be conducted and tested within FlexWood 8100 - The Swedish use case. The models need information about the outcome per stand, which can be generated at an earlier stage by the VSOP system. Data for each stand consists of one or more outcomes depending on how many different apt-files that are used. The model in this stage is developed and tested within a Nordic context with cut to length systems with harvester and forwarders as logging devices. It is important to point out that the model is general and usable for any logging- and transportation systems.

The model is working on both a short and long term horizon. The short term is based on short time periods, say 30 one day periods, and the remaining long term on longer timer period, say 11 one-month periods. This provides a detailed planning of the first month and a coarser planning for the remaining 11 months. The first time period is linked to a specific date in order to have control over current operations and inventories, when in time various areas are available and when different machine teams can work (holidays, planned maintenance stops, etc.). In addition, there must be a calendar that determines when different accessibility periods occur as well as an availability calendar for all machine resources.

Demand is described as a target volume of all specified assortments in a given time period (calendar week) for a particular recipient. Also, it should be possible to require a balanced distribution of deliveries between the days of the week (5, 6 or 7 days). Deviation from the target volume is allowed by a specific percentage (both up and down) per week and per month. Tolerance of weekly level is typically greater than the permissible deviation of a monthly level. Demand is complemented with price information, that is, the price the recipient pays for the respective assortment. The model can also maximize the impact by choosing the most convenient apt-file and decide which mill the volume is aimed for. The company's delivery requirements based on agreements must be met. The exception is if there is insufficient amount of volume of a specific assortment. In such case, the model is able to purchase these volumes from an external source with a given cost.

Which machine team that will be assigned to which stand is determined by several factors. Consideration should be given first and foremost to the machine type and whether it is allowed in the current stand (a machine for final felling is not allowed e.g. small thinning). In addition, there are restrictions on how far from home base a machine is allowed to operate. For each machine, a performance which is dependent on the average log (harvesters), forwarding distance (forwarder) together with other factors (e.g. season) is used a s a basis to compute harvest times. The performance of the machine code is also used for different cutting types (clear cutting, thinning and harvesting seed trees). The decision of when a particular area is to be harvested is determined partly by its bearing capacity. In VSOP the bearing capacity is defined as a combination of road and terrain accessibility together with ground conditions. The time of logging can also be controlled explicitly by the user to specify when a specific stand should be harvested. In addition, stands can be forced to become a priority so that they are harvested within a fixed set of months after the purchase (in the case when Korsnäs purchase harvesting rights from Bergvik).

The solution approach is implemented in a web service and should work fully automatically. It is called from the FlexWood platform, see Figure 1. The web service, which is allocated to a server at Skogforsk, consists of a function to receive input files and a model that optimizes the harvesting resources and match assets with demand. The result is sent back to the FlexWood platform to be illustrated graphically together with reports to the user.

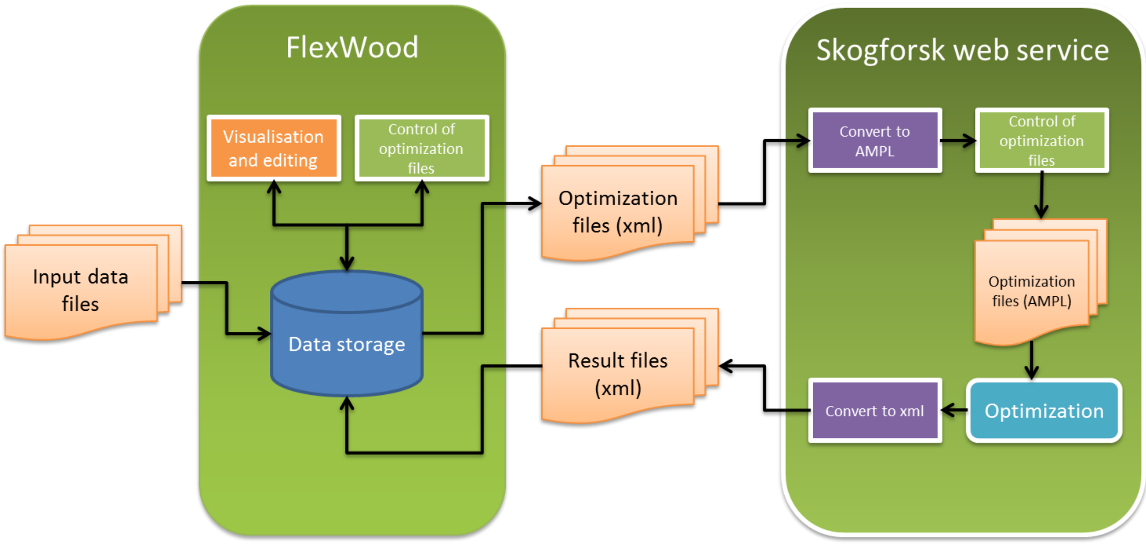

Figure 1. Illustration of the connection between FlexWood and the Skogforsk web service.

2. Solution approach

The solution approach works in several main steps, even if the user does not notice of more than one. These steps are describe in detail in Section 5. Moving costs can be specified directly even if, as in this case, Korsnäs has this cost embodied in the cubic meters price to the contractor. However, it is possible to limit the number of moves per year for a machine.
If this number is exceeded, a penalty fee will fall out. It is also possible to add an additional cost that fall out for each stand (e.g. cleanup compensation to the hauler). If multiple areas can be clustered only one cost for the entire cluster is applied. It is also possible to force a particular harvesting team to harvest a specific stand, for example, if there are special requests from the landowner.

The model is scalable, i.e. it will allow optimization with a smaller data set if all data are available. The optimization provides possibilities for having various factors weighted depending on the organization objectives. Factors that can be weighted are revenue, transportation cost, harvesting cost and moving costs. By default all the factors will be given the weight one, i.e. all the factors are equally important. The optimization also takes into account other harvesting objectives, in particular the percentage volume in thinning versus clear cutting and the also the proportion of volumes harvested in own forests versus purchase from private forest owners.

The overall information flow process is described in Figure 2. First the data files are converted into a standard optimization format. In our case we use the modelling language AMPL and hence the files are converted into a AMPL format. With this data we perform a number of controls to make sure that the data satisfy some basic rules. In case any error is detected, this generate an error output. We then apply a solution approach by solving a number of models. The models are described in detail in A, B and C. The models are solved using the commercial solver CPLEX. Once the solutions are generated they are produced in AMPL format. This needs to be converted back into a general XML format and then sent back to the user.

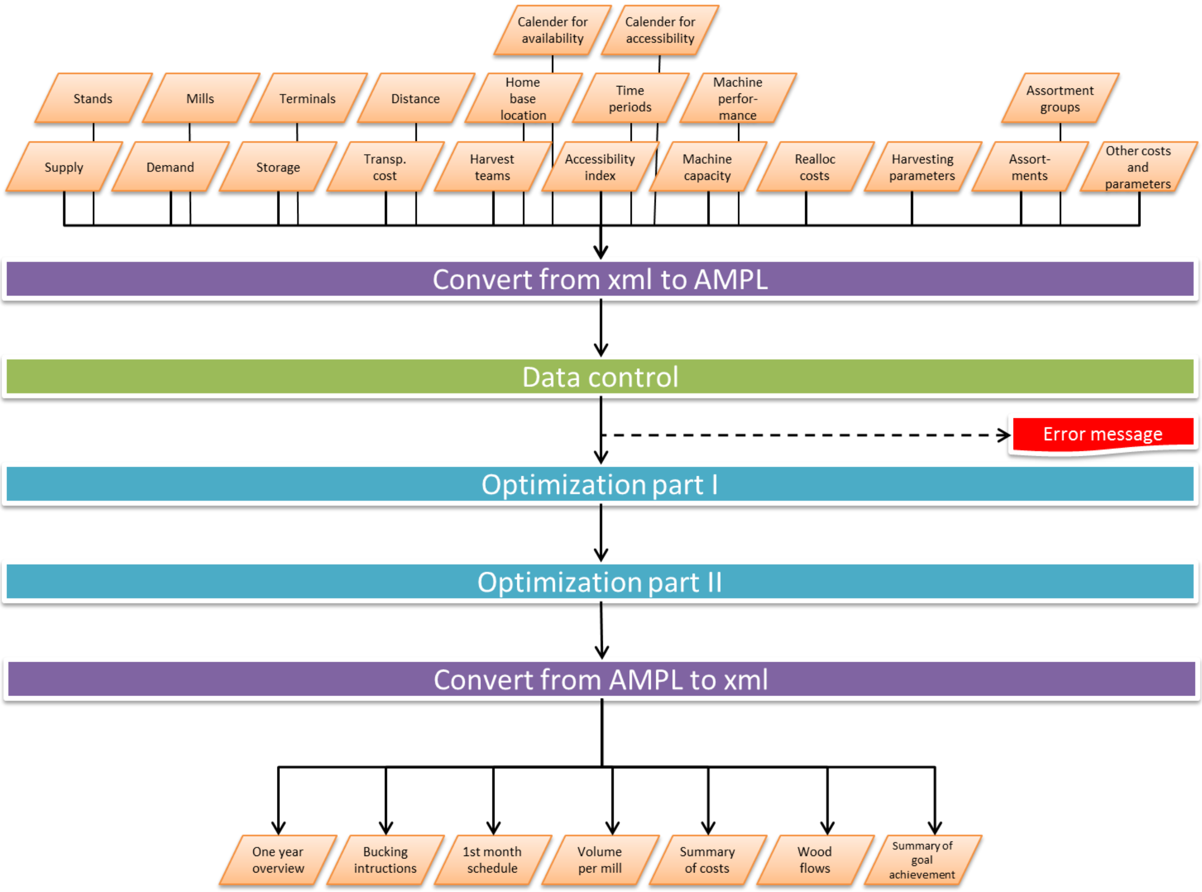

Figure 2. Overall description of the process with data, solution approach, and result handling.

The result of the optimization includes:

- a scheduling of all machines of the first 30 days,
- a note about what apt-file to be used in each stand,
- a description of the volumes that will be allocated to which recipients,
- a summary of the costs (harvesting, moving, transport and other),
- flows and
- summaries of how well the demand is achieved with the current solution.

The results are integrated into VSOP and can be visualized in different reports. One important output is a Gantt schedule, see an example in Figure 3. The harvesting sequence for the teams can be illustrated with maps. Figure 4 illustrate a harvest sequence where stands are represented with different colors. In this example, the colors represent the dominant tree species. The figure represents the harvesting sequence for the first ten stands. In addition there will be tables with costs and other summaries.

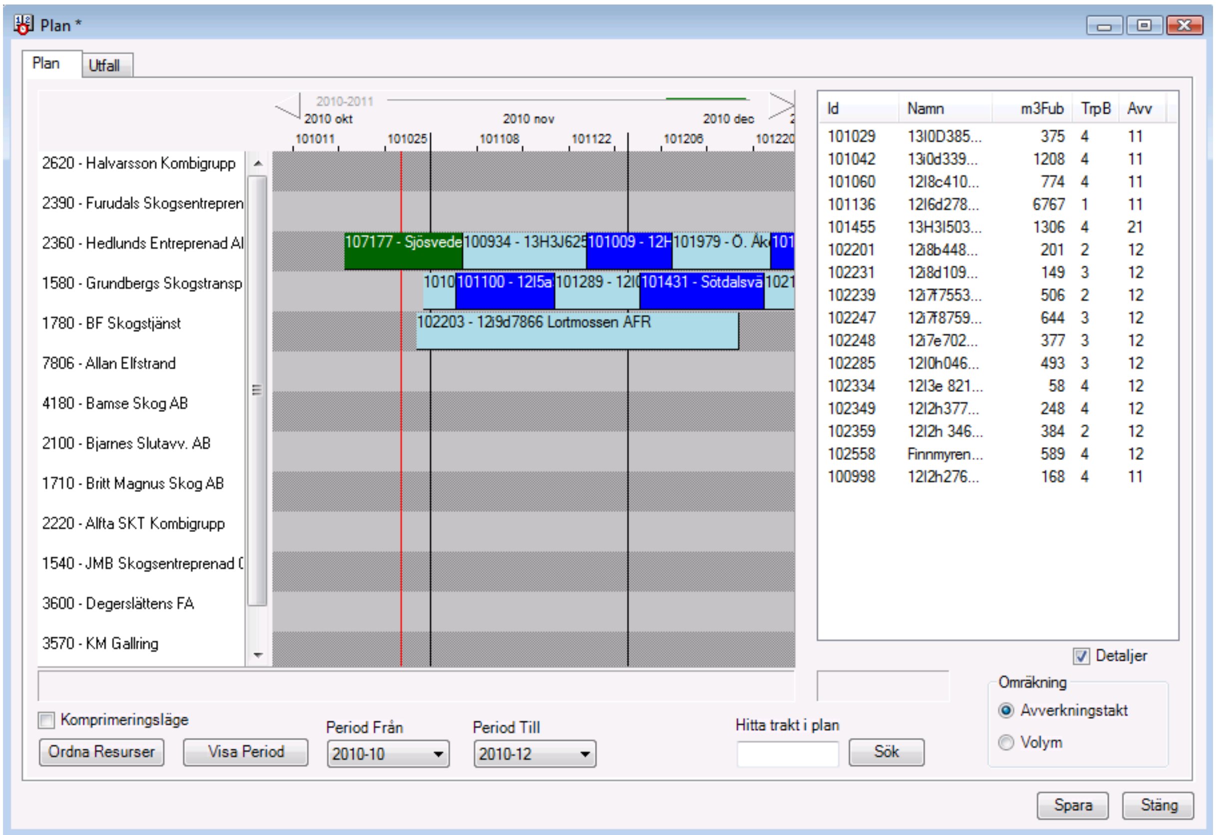

Figure 3. An example with a Gantt scheme.

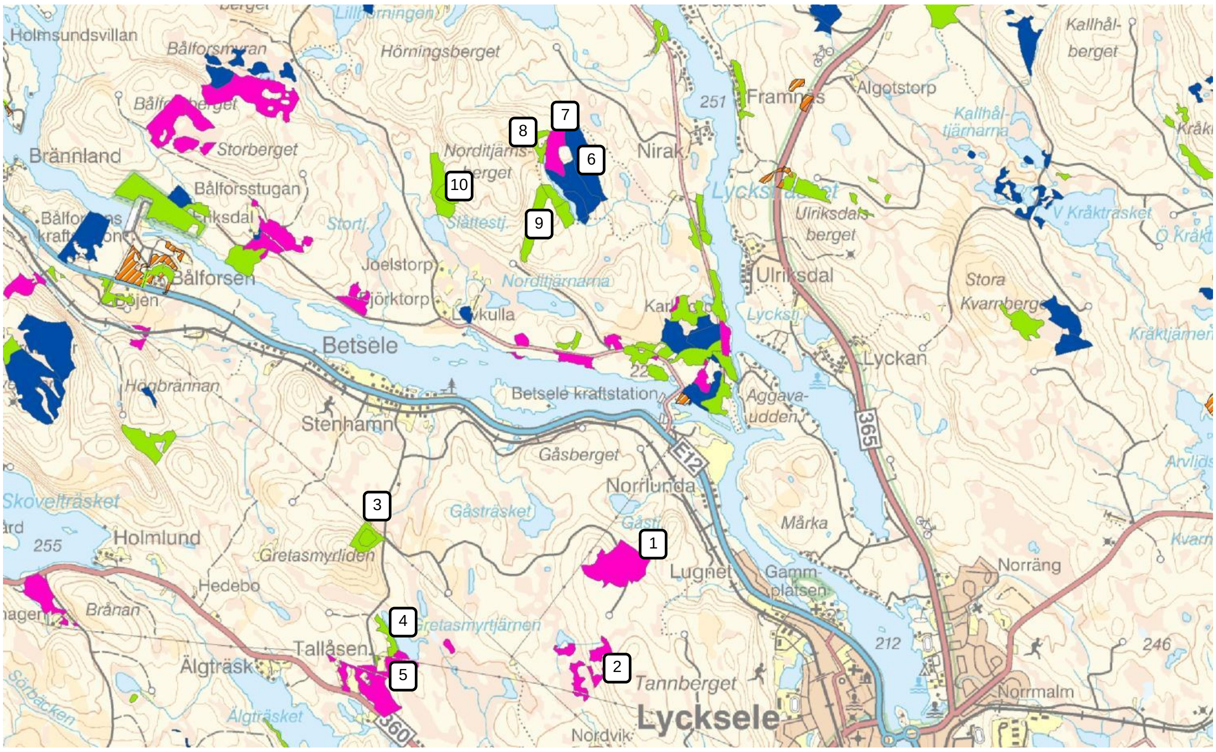

Figure 4. An example with a map describing which areas to harvest and when.

3. Input data

A separate document describes the input data files in xml format and its contents. This section will only describe the data in a comprehensive way. The optimization models require input in the form of asset description (volume and value of the outcomes of all stands), stand description (average stem, forwarding distance, bearing capacity, etc.), the demand description (delivery requirements to various reception sites) and description of machine and machine teams. In addition, it requires distances between all the stands, between stands and the home base for the harvest teams and between stands and recipient sites. Input is retrieved from various system/subsystem but is defined in the same way before it is sent to the optimization.

3.1 Assets

The forest assets for all stands available in the bank of stands is described with one or more sets of volume outcomes per assortment depending on the used apt-file (price list). Assets are described with an id number for the stand, names of apt-file and volume per assortment. This can be described in one file, or in multiple files (one file per apt-file).

3.2 Stands

For each stand it is required (except for the volume and value outcome) information about the properties that are relevant for the selection of harvesting machine, time of harvesting and choice of harvesting point of time. These properties are total volume, average log, forwarding distance, bearing capacity, felling form (clear cutting, thinning, seed tree felling), any performance reduction and bearing capacity area. Furthermore, the coordinates of the stand as well as information about if it is own forest or purchase from private forest owner.

3.3 Demand

The demand is described for each mill with volume per assortment and time period. Volume per week will probably be the most common. The mills must also be described individually by name, id and coordinates.

3.4 Machines

The described of harvesting machines is associated with the description of harvesting teams. Each machine is described with the id, which team the machine belongs to, machine type (harvesters, forwarders or harwarder), size (large, medium, small), available capacity per time period and the cost per hour.

3.5 Harvesting teams

The teams are described with id, type (own or contractor), home base, radius of action (max allowed distance between home base and stand), the minimum and maximum time that the team can work each time period and possibly the minimum working time if there is any. For each home base, name and coordinates are required.

3.6 Additional information

Additional information necessary for the optimization is distance information (between all stands, between the home base and stand and between stand and mills), transport costs (timber transport and passenger transport), road maintenance costs (such as snow removal), moving costs for machinery , the accessibility of the bearing capacity areas, the minimum distance to move machines to apply the moving cost, time to move between stands, the maximum share of thinning and the maximum percentage of purchase from private forest owners. We might also add an adjustment of the performance functions that depends on the season.

4. Solution method

In this section, we outline the proposed solution approach. This approach together with the models are developed from a number or earlier contributions and developments at Skogforsk. A general description of problems in the forest industry is found in D'Amours *et al*. (2008). Annual harvest planning has been studied by Bredström *et al*. (2010) and Karlsson *et al*. (2004). More short term scheduling of teams is given in Karlsson *et al*. (2003). Integration of harvest planning and road investment over several years is studied in Henningsson *et al*. (2007) and Frisk *et al*. (2006). Transportation planning can be done with the Decision Support System (DSS) FlowOpt, see Forsberg *et al*. (2005) and Carlsson and Rönnqvist (2007). Detailed routing and related models can be found in Andersson *et al*. (2008). An application where harvesting is integrated with logistic planning using an extension of FlowOpt is described in Broman *et al*. (2009). The issue to integrate long term and short term planning models is studied in Troncoso *et al*. (2011).

The solution approach is based on solving one *Master* problem. This Master problem includes the main decision variables for allocating teams to stands, time to harvest stands, flows between stands and industries, inventories and apt instructions. The main interest is to decide an operational short term plan but include long term planning to balance capacities and supplies. To include this, we divide the planning horizon into *business* periods (detailed short term) and *anticipation* periods (aggregated long term). Examples are daily periods for the first month and monthly periods for the remaining part of the year. It is important to note that the business decisions provide the operational decisions and the anticipation decisions provide possible plans in the future. This Master problem will be extremely large in our application and it is not possible to solve directly. Instead, we need to apply some decomposition and aggregation techniques to stepwise solve the full Master problem. The overall solution approach is described below.

Algorithm 1 Overall solution approach

Phase 1:
Assumptions: All periods (business and anticipation) are aggregated into one single period.
Solve Problem P1 (Simplified allocation problem)
Output: Initial allocation of stands to teams.

Phase 2:
Assumptions: Teams aggregated into one final felling team and one thinning team, all business periods aggregated into one, original anticipation periods
Solve Problem P2 (aggregated Master problem)
Output: Allocation of stands to aggregated business period

Phase 3:
Assumptions: Selected stands to business periods.
Solve Problem P3 (Master problem with business periods only)

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

Phase 4:
Assumptions: Generation of many detailed schedules based on initial stand-team allocation
Solve Problem P4 (Detailed scheduling)
Output: Detailed schedule in business periods

Phase 5:
Assumptions: Detailed schedule in business periods
Solve Problem P5 (Full Master problem fixed schedule (not flows and inventories) in business periods)
Output: Full plan in business periods and anticipation periods including all flows and inventories.

Below follow some comments for each of the problems.

Problem P1

The objective with problem P1 is to allocate harvest areas to teams. There is only one time period. The purpose is to support problem P2 to make sure that the spread of areas to home bases is balanced i.e. we need to set some restrictions on P2. There are no flows included in this problem.

Problem P2

We use two aggregated teams to make sure that the proportion of final felling and thinning stands are balanced. We use all anticipation periods together with one aggregated business period. Based on the solution from P1, we make sure that there is balance of harvest areas close to the home bases (and the related teams). The purpose of problem P2 is to allocate areas to the aggregated business period. In this model we include inventory and flows between stands and industry.

Problem P3

From P2, we know which stands that will be harvested in the business periods. Note that now we have a quality balance between business and anticipation periods. This coordination is done by solving P1 and P2. We now want to solve the full model but only for the business periods. The purpose is to allocate areas to teams and an initial sequence in how they will be harvested. The sequencing part is an approximation as we allow only one area to be harvested in each business period. In this model we include inventory and flows between areas and industry.

Problem P4

Given that we know which areas that are allocated to each team and an initial approximate sequence the first month we generate many detailed schedules. These detailed schedules include exact costs for moving equipment and how much is produced in each business period. The next problem is a set partitioning type problem where each team is to select one detailed schedule while all together satisfies demand restrictions and minimize logistic costs. A schedule may also include a detailed description of apt instruction for each area. In this model we include inventory and flows between areas and industry.

Problem P5

Given the detailed schedule for the business periods, we can solve the remaining full problem to allocate areas to teams for the anticipation periods. In this model we include inventory and flows between areas and industry. This will provide the final solution to be presented.

Problem P1 is an approximation and will be described in detail in Appendix B. Problem P2 is a special case of the full Master problem (with aggregated teams and aggregated business periods) and here we can use the full model as a basis. The Master model will be described in detail in Appendix A. Problem P3 is one part of the master problem as we consider only the business periods but no anticipation periods. Problem P4 is a detailed formulation using sequences as variables. This model will be described in detail in Appendix C. Problem P5 is one part of the full model. In this problem, the sequences are fixed but harvesting decisions in the anticipation periods must be taken. Also, all flows over all periods are to be decided. The latter also include flows in the business periods.

5. References

Andersson, G., Flisberg, P., Liden, B., and Rönnqvist, M. 2008. RuttOpt - A decision support system for routing of logging trucks. Canadian Journal of Forest Research **38**: 1784–1796.

Bredström, D., Jönsson, J., and Rönnqvist, M. 2010. Annual planning of harvesting resources in the forest industry. International Transactions in Operations Research **17**(2): 155–177.

Broman, H., Frisk, M., and 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. Canadian Journal of Forest Research **37**: 2612–2623.

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

Frisk, M., Karlsson, J., and Rönnqvist, M. 2006. RoadOpt - A decision support system for road upgrading in forestry. Scandinavian Journal of Forest Research **21**(7): 5–15.

Forsberg, M., Frisk, M., and Rönnqvist, M. 2005. FlowOpt - a decision support tool for strategic and tactical transportation planning in forestry. International Journal of Forest Engineering **16**(2): 101–114.

Henningsson, M., Karlsson, J., and Rönnqvist, M. 2007. Optimization models for forest road upgrade planning. Journal of Mathematical Modelling and Algorithms **6**(1): 3-23.

Karlsson, J., Rönnqvist, M., and Bergström, J. 2003. Short-term harvest planning including scheduling of harvest crews. International Transactions of Operations Research **10**: 413-431.

Karlsson, J., Rönnqvist, M., and Bergström, J. 2004. An optimization model for annual harvest planning. Canadian Journal of Forest Research **34**(8): 1747–1754.

Troncoso, J., D'Amours, S., Flisberg, P., Rönnqvist, M., and Weintraub, A. 2011. A mixed integer programming mo del to evaluate integrating strategies in the forest value chain - A case study in the Chilean forest industry. submitted to Annals of OR.

Appendix A

Model formulation - Master problem

This is the Master problem and is the basis for the problems P2, P3 and P5.

Sets and input data

The sets and input data are described below.

Notation	Description
I	set of harvest areas
C	set of bucking price lists
Q	set of harvest operations
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 $T = T_B \cup T_A$
M	set of machines (machine groups)
	Supporting sets
I_q^Q	set of harvest areas for harvest operation $q \in Q$
I_m	set of potential harvest areas for machine $m \in M$
M_i	set of machines that can harvest area $i \in I$
J	set of industries
O_j	set of orders at industry j
H	set of assortments
G	set of group assortments
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.
L	set of terminals
n_{mit}^B	all periods that team m can start harvesting area i and still be busy harvesting it 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.
F^B	set of harvest areas i that have to be harvested by team m using bucking price list c.

Comments:

- The possible harvest operations are final felling and thinning.
- The supporting sets are used to clarify the model.

Notation	Description
t^i_{mi}	operation time for machine m in harvest area i
t^B_{mit}	operating time used for machine m in harvest areas i when starting in business period t until the last business period
c^p_{mi}	operation cost for machine m in harvest area i
t^t_{mt}	available time for machine m in period t
t^{max}_{mt}	longest time that can be left to operate a harvest area with machine m if it has been operating on it the whole period t
n^A_{mt}	maximal number of harvest areas that can be started in period t by machine m
c^g_{mij}	cost to move machine m between harvest area i and harvest area j
c^h_{mi}	cost for machine m to travel from home base to harvest area i and back
a_{mq}	minimum level (proportion) of harvest operation q for machine m
s^A_{hic}	volume of assortment h in harvest area i when using bucking price list c
s^B_{hmicn}	volume of assortment h in harvest area i when using bucking price list c in n business periods after it started when using machine m
s^{AB}_i	volume at harvest area i
p_{it}	percent availability at harvest area i in period t
c^f_{hij}	transportation cost for assortment h from harvest area i to demand point j
c^i_{hit}	inventory cost for assortment h at harvest area i at the end of period t
c^l_{hit}	inventory cost for assortment h at terminal l at the end of period t
c^j_{hjt}	inventory cost for assortment h at demand point j at the end of period t
b^m_t	maximum number of harvest areas that can be operated in period t
d_{gjot}	accumulated goal value for demand of group assortment g at demand point j of order o in period t
$\underline{\delta}_{gjot}$	maximum deviation below accumulated demand level of group assortment g at demand point j of order o in period t
$\overline{\delta}_{gjot}$	maximum deviation above accumulated demand level of group assortment g at demand point j of order o in period t
$\underline{d}^h_{hgjot}$	accumulated lower demand level of assortment h in group assortment g at demand point j of order o in period t
$\overline{d}^h_{hgjot}$	accumulated upper demand level of assortment h in group assortment g at demand point j of order o in period t
$c^{\underline{d}_{gjot}}$	cost to supply below goal value of demand for group assortment g at demand point j of order o in period t
$c^{\bar{d}_{gjot}}$	cost to exceed goal value of demand for group assortment g at demand point j of order o in period t
c^c_{mit}	cost to move machine m to harvest area i from its centre area in period t
n^m_m	maximum number of allowed moves for machine m
c^m_m	cost for each move exceeding the maximum allowed number of moves for machine m
v_i	NVP if harvest area i is not harvested during the planning horizon
n_m	number of units of team m

Comments:

- A harwarder has both a harvesting and a forwarding time. A harvester has the value 0 for forwarding and a forwarder, a value 0 for harvesting.
- The travel cost h_{mi} includes the cost of all back and forward journeys needed for that specific harvest area.
- The moving cost include both fixed cost and the cost related to the distance between areas.

Decision variables

The main decisions are to assign machines to harvest areas and to schedule machines between harvest areas. We also need to decide any overlap between the periods and whether a harvest area is in the pool or not. The definition of the variables are as follows.

$$y_{mit} = \begin{cases} 1, & \text{if machine } m \text{ starts in harvest area } i \text{ at period } t \\ 0, & \text{otherwise} \end{cases}$$

$$y^c_{mict} = \begin{cases} 1, & \text{if machine } m \text{ starts in harvest area } i \text{ applying bucking price list c} \\ & \text{at period } t \\ 0, & \text{otherwise} \end{cases}$$

$$o_{mit} = \begin{cases} 1, & \text{if machine } m \text{ starts at harvest area } i \text{ in period } t \\ & \text{but continues to the next period (i.e. does not finish it in time)} \\ 0, & \text{otherwise} \end{cases}$$

$$z_{mt} = \begin{cases} 1, & \text{if machine } m \text{ cannot start at any new harvest area in period } t \\ & \text{because the job started in last period will last during the whole} \\ & \text{of this one as well} \\ 0, & \text{otherwise} \end{cases}$$

$$x^m_{mij} = \begin{cases} 1, & \text{if machine } m \text{ is moved from harvest area } i \text{ to harvest area } j \\ 0, & \text{otherwise} \end{cases}$$

v_{mit} = time needed in periods after period t for machine m to finish harvesting area i

v^c_{mit} = 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 areas i to demand point j in period t

s^l_{gjot} = volume below accumulated goal value of demand of group assortment g at demand point j of order o in period t

s^u_{gjot} = volume above accumulated goal value of demand of group assortment g at demand point j of order o in period t

l^i_{hit} = inventory of assortment h at harvest area i at the end of period t

l^l_{hit} = inventory of assortment h at terminal i at the end of period t

l^j_{hjt} = inventory of assortment h at demand point j 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

Objective function

We have eight cost components and one value component in the objective. The first three are associated with real costs, whereas the fourth is a penalty cost for the harvest areas put in the pool.

$$
\begin{aligned}
z_{production} &= \sum_{m\in M}\sum_{i\in I_m}\sum_{t\in T} c^{p}_{mi} y_{mit} \\
z_{eridingMoves} &= \sum_{m\in M} c^{m}_{m} s^{m}_{m} \\
z_{compression} &= \sum_{m\in M}\sum_{i\in I_m}\sum_{t\in T} c^{c}_{mit} y_{mit} \\
z_{demanPenalty} &= \sum_{g\in G}\sum_{j\in J}\sum_{o\in O_j}\sum_{t\in T} (c^{\underline{d}}_{gjot} s^{l}_{gjot} + c^{\bar{d}}_{gjot} s^{u}_{gjot}) \\
z_{traveling} &= \sum_{m\in M}\sum_{i\in I_m}\sum_{t\in T} c^{h}_{mi} y_{mit} \\
z_{transport} &= \sum_{h\in H}\sum_{i\in I\cup L}\sum_{j\in L\cup J}\sum_{t\in T} c^{f}_{hij} x_{hijt} \\
z_{inventory} &= \sum_{h\in H}\sum_{t\in T}(\sum_{i\in I} c^{i}_{hit} l^{i}_{hit} + \sum_{i\in L} c^{l}_{hit} l^{l}_{hit} + \sum_{j\in J} c^{j}_{hjt} l^{j}_{hjt}) \\
v_{NPV} &= \sum_{i\in I} v_i (1 - \sum_{m\in M_i}\sum_{t\in T} y_{mit})
\end{aligned}
$$

Model

The model can be stated as follows.

$$\min \quad z = z_{production} + z_{exceedingMoves} + z_{compression} + z_{demandPenalty} + z_{traveling} + z_{moving} + z_{transport} + z_{inventory} - v_{NPV}$$

mboxs.t.

$$\begin{aligned}
\sum_{m \in M_t} \sum_{t \in T} y_{mit} &\leq 1, && i \in I && (A1)\\
\sum_{m \in M_t} \sum_{i \in I_M} \sum_{t \in T_B : p_{it} < 100} 1/p_{it} s_i^{AB} y_{mit} - {}&&&&\\
1/100 \sum_{m \in M} \sum_{i \in I_M} \sum_{t \in T_B} s_i^{AB} y_{mit} &\leq 0, &&&& (A2)\\
\sum_{m \in M_t} \sum_{i \in I_M : p_{it} < 100} 1/p_{it} s_i^{AB} y_{mit} - {}&&&&\\
1/100 \sum_{m \in M} \sum_{i \in I_M} s_i^{AB} y_{mit} &\leq 0, && t \in T_A && (A3)\\
\sum_{m \in M} \sum_{i \in I_M : p_{it} = 0} y_{mit} &= 0, && t \in T && (A4)\\
\sum_{i \in I_M} \sum_{t' \in n_{mit}^B} y_{mit'} &\leq n_m, && m \in M, t \in T_B && (A5)\\
\sum_{i \in I_m} \sum_{t \in T_B} t_{mi}^i y_{mit} - \sum_{i \in I_m} v_{mi\bar{t}B)} - \sum_{t \in T_B} t_{mt}^t n_m &\leq 0, && m \in M && (A6)\\
\sum_{i \in I_m} \sum_{t \in T} y_{mit} - s_m^m &\leq n_m^m && m \in M && (A7)\\
o_{mi\bar{t}_B)} - \sum_{t' \in n_{mi\bar{t}_B}^B} y_{mit'} &\leq 0, && m \in M, i \in I_m, && (A8)\\
t_{mi}^i - \sum_{t \in n_{mi\bar{t}_B}^B} t_{mit}^B y_{mict}^c - v_{mic\bar{t}_B}^c &\geq 0, && m \in M, i \in I_m, c \in C && (A9)\\
\sum_{i \in I_m} (v_{mi(t-1)} + t_{mi}^i y_{mit} - v_{mit}) &\leq t_{mt}^t n_m, && m \in M, t \in T_A && (A10)\\
o_{mit} - o_{mi(t-1)} - y_{mit} &\leq 0, && m \in M, i \in I_m, t \in T_A && (A11)\\
\sum_{i \in I_m} o_{mit} &\leq n_m, && m \in M, t \in T_A \cup \bar{t}_B && (A12)\\
n_{mt}^A (1 - z_{mt}) - \sum_{i \in I_m} y_{mit} &\geq 0, && m \in M, t \in T_A && (A13)\\
\sum_{c \in C} y_{mict}^c - y_{mit} &= 0, && m \in M, i \in I_m, t \in T && (A14)\\
\sum_{c \in C} v_{mict}^c - v_{mit} &= 0, && m \in M, i \in I_m, t \in T_A \cup \bar{t}_B && (A15)\\
t_{mi}^i y_{mict}^c - v_{mict}^c &\geq 0, && m \in M, i \in I_m, c \in C, t \in T_A \cup \bar{t}_B && (A16)\\
t_{mi}^i \sum_{t \in n_{mi\bar{t}_B}^B} y_{mict}^c - v_{mic\bar{t}_B}^c &\geq 0, && m \in M, i \in I_m, c \in C && (A17)\\
l_{hi(t-1)}^i - l_{hit}^i + {}&&&&\\
\sum_{m \in M_t} \sum_{c \in C} \sum_{t' \in n_{mit}^B} s_{hmictt'}^B y_{mict'}^c - \sum_{j \in J \cup L} x_{hijt} &= 0, && h \in H, i \in I, t \in T_B && (A18)\\
l_{hi(t-1)}^i - l_{hit}^i + \sum_{m \in M_t} \sum_{c \in C} s_{hic}^A y_{mict}^c + {}&&&&\\
\sum_{m \in M_t} \sum_{c \in C} s_{hic}^A / t_{mi}^i v_{mic(t-1)}^c - {}&&&&\\
\sum_{m \in M_t} \sum_{c \in C} s_{hic}^A / t_{mi}^i v_{mict}^c - \sum_{j \in J \cup L} x_{hijt} &= 0, && h \in H, i \in I, t \in T_A && (A19)
\end{aligned}$$

$$
\begin{array}{rcll}
l^l_{hi(t-1)} + \sum_{j \in I} x_{hjit} - \sum_{j \in J} x_{hijt} - l^l_{hit} & = & 0, & h \in H, i \in L, t \in T \quad (A20) \\
l^j_{hj(t-1)} + \sum_{i \in I \cup L} x_{hijt} - l^j_{hjt} - \sum_{g \in G_h} \sum_{o \in O_j} u_{hgjot} & = & 0, & h \in H, j \in J, t \in T \quad (A21) \\
\sum_{h \in H_g} \sum_{t' \in 1..t} u_{hgjot'} + s^l_{gjot} & \geq & d_{gjot}, & g \in G, j \in J, o \in O_j, t \in T \quad (A22) \\
\sum_{h \in H_g} \sum_{t' \in 1..t} u_{hgjot'} - s^u_{gjot} & \leq & d_{gjot}, & g \in G, j \in J, o \in O_j, t \in T \quad (A23) \\
s^l_{gjot} & \leq & \underline{\delta}_{gjot}, & g \in G, j \in J, o \in O_j, t \in T \quad (A24) \\
s^u_{gjot} & \leq & \overline{\delta}_{gjot}, & g \in G, j \in J, o \in O_j, t \in T \quad (A25) \\
\sum_{t' \in 1..t} u_{hgjot'} & \geq & \underline{d}^h_{hgjot}, & h \in H, g \in G, j \in J, o \in O_j, t \in T \quad (A26) \\
\sum_{t' \in 1..t} u_{hgjot'} & \leq & \overline{d}^h_{hgjot}, & h \in H, g \in G, j \in J, o \in O_j, t \in T \quad (A27) \\
\sum_{t \in T} (\sum_{i \in I^Q_q} t^i_{mi} y_{mit} - & & & \\
a_{mq} \sum_{i \in I_m} t^i_{mi} y_{mit}) & \geq & 0, & m \in M, q \in Q \quad (A28) \\
y^c_{mict} & = & 1, & (mict) \in F^T \quad (A29) \\
\sum_{tinT} y^c_{mict} & = & 1, & (mic) \in F^B \quad (A30) \\
y_{mit} & & \in \{0,1\}, & \forall m \in M, i \in I_m, t \in T \quad (A31) \\
y^c_{mict} & & \in \{0,1\}, & \forall m \in M, i \in I_m, c \in C, t \in T \quad (A32) \\
y_{mit} & & = 0, & \forall m \in M, i \notin I_m, t \in T \quad (A33) \\
o_{mit} & & \in \{0,1\}, & \forall m \in M, i \in I_m, t \in T \quad (A34) \\
z_{mt} & & \in \{0,1\}, & \forall m \in M, t \in T \quad (A35) \\
x_{hijt}, v_{mit}, v^c_{mict}, l^i_{hit}, l^l_{hit}, l^j_{hjt} & \geq & 0, & \quad (A36) \\
s^l_{gjot}, s^u_{gjot}, u_{ghjot} & \geq & 0, & \quad (A37)
\end{array}
$$

The description of the constraints are summarized below.

Set	Description
(A1)	each harvest area can only be harvested once
(A2, A3)	limit the harvesting at harvest areas with limited availability
(A4)	not available harvest areas cannot be harvested
(A5)	a machine can only run one operation each business period
(A6)	total time in business periods is limited
(A7)	total number of moves for a machine is limited
(A8)	an operation carrying over from business to anticipation period must run the last business period
(A9)	limit carried over time from business to anticipation period
(A10)	limit on available time for each machine in each period
(A11)	the operation carrying over to the next period must have been started in this period (or started in earlier periods and still running)
(A12)	only one operation can carry over to the next period
(A13)	no operations can start in a period if an operation is carried over both before and after the period. (6a tvingar upp z)
(A14, A15)	only one bucking price list to be used
(A16, A17)	limit overtime and only for the used bucking price list
(A18)	flow balance at harvesting areas for business periods
(A19)	flow balance at harvesting areas for anticipation periods
(A20)	flow balance at terminal points
(A21)	flow balance at demand points
(A22, A23)	fulfill aggregated demand with goal value
(A24, A25)	limits on deviation from the demand goal value
(A26, A27)	assortment requirements on demand
(A28)	minimum proportion on final felling and thinning for each machine
(A29)	some harvest areas have to be harvested by a particular team a specific period
(A30)	some harvest areas that have to be harvested by a particular team
(A31, A32)	binary requirements on the harvesting area assignment decisions
(A33)	removes all infeasible combinations of assignments
(A34)	binary requirements on the operations carrying over between periods.
(A35)	binary requirements on the possibility for a machine to start at a new harvest area
(A36, A37)	non-negative requirements

The model is an integrated assignment and routing problem. One part of the problem is to make an assignment and the second part is to make the routing. The problem is more complicated than a standard vehicle routing problem, which is very hard to solve, even for small instances.

Appendix B

Model formulations - Resource allocation problem

The Resource allocation problem is an approximation of the Master problem. It only includes constraints on available time for each of the teams. The problem is a Generalized Assignment Problem (GAP) and it is solved quickly for the case sizes we work with.

Sets and input data

The sets and input data are.

Notation	Description
I	set of harvest areas
M	set of teams
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_m^l	set of harvest areas that have to be harvested by team m

Notation	Description
c_{mi}^h	cost for all daily travels for team m to and from harvest area i and home base (until harvesting completed)
t_{mi}^i	operation time for team m in harvest area i
q_m	required working factor for team m of total working time for all teams

Decision variables

The main decisions are to assign teams to harvest areas.

$$
\begin{aligned}
w_{mi} &= \begin{cases} 1, & \text{if team } m \text{ is assigned to harvest area } i \\ 0, & \text{otherwise} \end{cases} \\
q^t &= \text{total working time for all teams}
\end{aligned}
$$

Model

The resource allocation model can be stated as follows.

$$\min \quad z = \sum_{m \in M} \sum_{i \in I_m} c^h_{mi} w_{mi}$$

s.t.

$$\begin{array}{rcllr}
\sum_{m \in M_i} w_{mi} & = & 1, & i \in I & (B1) \\
\sum_{m \in M} \sum_{i \in I_m} t^i_{mi} w_{mi} - q^t & = & 0, & & (B2) \\
\sum_{i \in I_m} t^i_{mi} w_{mi} - q_m q^t & \geq & 0, & m \in M & (B3) \\
w_{mi} & = & 1, & m \in M, i \in I^l_m & (B4) \\
w_{mi} & \in & \{0,1\}, & m \in M, i \in I_m & (B5)
\end{array}$$

The objective is to minimize the traveling time for the teams to and from their home bases and the harvest areas. Constraint set (B1) expresses that all harvest areas must be assigned to a team. Constraint sets (B2) and (B3) add requirements on the relative working time for each team. Constraint set (B4) allocates already locked harvest areas (if any) to the correct teams and Constraint set (B5) describes the binary restrictions on the allocation variables.

Appendix C

Model formulation - Scheduling problem

The Scheduling problem is the basis for problem P4. The model is a set partitioning model and is used in many scheduling and routing problems. The approach is to generate a large number of detailed schedules for each team. As the schedules are pre-generated they can be very detailed and moving costs and times can easily be included. In the model, each team must select exactly one schedule while satisfying many other logistic constraints.

Sets and input data

The sets and input data are described below.

Notation	Description
S	set of sequences of harvest areas to harvest
I	set of harvest areas
T	set of periods
M	set of machines (machine groups)
	supporting sets
S_i^I	set of sequences where harvest area i is included
S_m^M	set of sequences which team m can do
M_s^s	set of machines that can harvest sequence s
J	set of industries
O_j	set of orders at industry j
H	set of assortments
G	set of group assortments
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.
L	set of terminals

Comments:

- The possible harvest operations are final felling and thinning.
- The supporting sets are used to clarify the model.

Notation	Description
$c^{\bar{p}}_{sm}$	operation cost for machine m in sequence s
$c^{\bar{g}}_{sm}$	cost to move machine m in sequence s
c^{h}_{sm}	cost for machine m to travel to and from harvest areas and home base for sequence s
s^{s}_{smhit}	volume of assortment h that falls out at harvest area i in period t when team m uses sequence s
p^{s}_{sm}	percent availability at the harvest areas that are in sequence s
c^{f}_{hij}	transportation cost for assortment h from harvest area i to demand point j
c^{i}_{hit}	inventory cost for assortment h at harvest area i at the end of period t
c^{l}_{hit}	inventory cost for assortment h at terminal l at the end of period t
c^{j}_{hjt}	inventory cost for assortment h at demand point j at the end of period t
b^{m}_{t}	maximum number of harvest areas that can be operated in period t
d_{gjot}	accumulated goal value for demand of group assortment g at demand point j of order o in period t
$\underline{\delta}_{gjot}$	maximum deviation below accumulated demand level of group assortment g at demand point j of order o in period t
$\overline{\delta}_{gjot}$	maximum deviation above accumulated demand level of group assortment g at demand point j of order o in period t
$\underline{d}^{h}_{hgjot}$	accumulated lower demand level of assortment h in group assortment g at demand point j of order o in period t
$\bar{d}^{h}_{hgjot}$	accumulated upper demand level of assortment h in group assortment g at demand point j of order o in period t
$c^{\underline{d}_{gjot}}$	cost to supply below goal value of demand for group assortment g at demand point j of order o in period t
$c^{\bar{d}_{gjot}}$	cost to exceed goal value of demand for group assortment g at demand point j of order o in period t
n^{m}_{m}	maximum number of allowed moves for machine m
c^{m}_{m}	cost for each move exceeding the maximum allowed number of moves for machine m

Comments:

- A harwarder has both a harvesting and a forwarding time. A harvester has the value 0 for forwarding and a forwarder, a value 0 for harvesting.
- The travel cost h_{mi} includes the cost of all back and forward journeys needed for that specific harvest area.
- The moving cost include both fixed cost and the cost related to the distance between areas.

Decision variables

The main decisions are to assign machines to harvest areas and to schedule machines between harvest areas. We also need to decide any overlap between the periods and whether a harvest area is in the pool or not. The definition of the variables are as follows.

$$
\begin{aligned}
r_{sm} &= \begin{cases} 1, & \text{if machine } m \text{ uses sequence } s \\ 0, & \text{otherwise} \end{cases} \\
x_{hijt} &= \text{flow of assortment } h \text{ from harvest areas } i \text{ to demand point } j \text{ in period } t \\
s^{l}_{gjot} &= \text{volume below accumulated goal value of demand of group assortment } g \\
& \quad \text{at demand point } j \text{ of order } o \text{ in period } t \\
s^{u}_{gjot} &= \text{volume above accumulated goal value of demand of group assortment } g \\
& \quad \text{at demand point } j \text{ of order } o \text{ in period } t \\
l^{i}_{hit} &= \text{inventory of assortment } h \text{ at harvest area } i \text{ at the end of period } t \\
l^{l}_{hit} &= \text{inventory of assortment } h \text{ at terminal } i \text{ at the end of period } t \\
l^{j}_{hjt} &= \text{inventory of assortment } h \text{ at demand point } j \text{ at the end of period } t \\
u_{hgjot} &= \text{fulfilled demand of group assortment } g \text{ from assortment } h \text{ at demand} \\
& \quad \text{point } j \text{ of order } o \text{ in period } t \\
s^{m}_{m} &= \text{number of moves exceeding allowed number for machine } m
\end{aligned}
$$

Objective function

We have eight cost components in the objective. The components are costs for production, exiding maximum allowed moves for a machine, demand penalties, traveling, moving, transports and inventory.

$$
\begin{aligned}
z_{production} &= \sum_{s \in S} \sum_{m \in M^{s}_{s}} \sum_{t \in T} c^{\bar{p}}_{sm} r_{sm} \\
z_{exidingMoves} &= \sum_{m \in M} c^{m}_{m} s^{m}_{m} \\
z_{demanPenalty} &= \sum_{g \in G} \sum_{j \in J} \sum_{o \in O_j} \sum_{t \in T} (c^{\underline{d}}_{gjot} s^{l}_{gjot} + c^{\bar{d}}_{gjot} s^{u}_{gjot}) \\
z_{traveling} &= \sum_{s \in S} \sum_{m \in M^{s}_{s}} \sum_{t \in T} c^{\bar{h}}_{sm} r_{sm} \\
z_{moving} &= \sum_{s \in S} \sum_{m \in M^{s}_{s}} c^{\bar{g}}_{sm} r_{sm} \\
z_{transport} &= \sum_{h \in H} \sum_{i \in I \cup L} \sum_{j \in L \cup J} \sum_{t \in T} c^{f}_{hij} x_{hijt} \\
z_{inventory} &= \sum_{h \in H} \sum_{t \in T} (\sum_{i \in I} c^{i}_{hit} l^{i}_{hit} + \sum_{i \in L} c^{l}_{hit} l^{l}_{hit} + \sum_{j \in J} c^{j}_{hjt} l^{j}_{hjt})
\end{aligned}
$$

Model

The model can be stated as follows.

$$
\begin{aligned}
\min \quad z = {} & z_{production} + z_{exceedingMoves} + + z_{demandPenalty} + z_{traveling} + z_{moving} + \\
& z_{transport} + z_{inventory}
\end{aligned}
$$

$$
\begin{array}{rcll r}
\text{s.t.} & & & & \\
\displaystyle\sum_{s\in S_i^t}\sum_{m\in M^S s_S} r_{sm} & \leq & 1, & i \in I & (C1) \\
\displaystyle\sum_{s\in S_m^m} r_{sm} & = & 1, & i \in I & (C2) \\
\displaystyle\sum_{s\in S}\sum_{m\in M_s^s} p_{sm}^s r_{sm} & \leq & 0, & & (C3) \\
l_{hi(t-1)}^i - l_{hit}^i + & & & & \\
\displaystyle\sum_{s\in S_i^t}\sum_{m\in M_s^s} s_{smhit}^s r_{sm} - \sum_{j\in J\cup L} x_{hijt} & = & 0, & h \in H, i \in I, t \in T & (C4) \\
\displaystyle l_{hi(t-1)}^l + \sum_{j\in I} x_{hjit} - \sum_{j\in J} x_{hijt} - l_{hit}^l & = & 0, & h \in H, i \in L, t \in T & (C5) \\
\displaystyle l_{hj(t-1)}^j + \sum_{i\in I\cup L} x_{hijt} - l_{hjt}^j - \sum_{g\in G_h}\sum_{o\in O_j} u_{hgjot} & = & 0, & h \in H, j \in J, t \in T & (C6) \\
\displaystyle\sum_{h\in H_g}\sum_{t'\in 1..t} u_{hgjot'} + s_{gjot}^l & \geq & d_{gjot}, & g \in G, j \in J, o \in O_j, t \in T & (C7) \\
\displaystyle\sum_{h\in H_g}\sum_{t'\in 1..t} u_{hgjot'} - s_{gjot}^u & \leq & d_{gjot}, & g \in G, j \in J, o \in O_j, t \in T & (C8) \\
s_{gjot}^l & \leq & \underline{\delta}_{gjot}, & g \in G, j \in J, o \in O_j, t \in T & (C9) \\
s_{gjot}^u & \leq & \overline{\delta}_{gjot}, & g \in G, j \in J, o \in O_j, t \in T & (C10) \\
\displaystyle\sum_{t'\in 1..t} u_{hgjot'} & \geq & \underline{d}_{hgjot}^h, & h \in H, g \in G, j \in J, o \in O_j, t \in T & (C11) \\
\displaystyle\sum_{t'\in 1..t} u_{hgjot'} & \leq & \overline{d}_{hgjot}^h, & h \in H, g \in G, j \in J, o \in O_j, t \in T & (C12) \\
r_{sm} & & \in \{0,1\}, & \forall s \in S, m \in M_s^s & (C13) \\
x_{hijt}, l_{hit}^i, l_{hit}^l, l_{hjt}^j, s_{gjot}^l, s_{gjot}^u, u_{ghjot} & \geq & 0, & & (C14)
\end{array}
$$

The description of the constraints are summarized below.

Constraint set	Description
(C1)	each harvest area can only be harvested once
(C2)	each machine needs to do one sequence
(C3)	limit the harvesting at harvest areas with limited availability
(C4)	flow balance at harvesting areas
(C5)	flow balance at terminal points
(C6)	flow balance at demand points
(C7, C8)	fulfill aggregated demand with goal value
(C9, C10)	limits on deviation from the demand goal value
(C11, C12)	assortment requirements on demand
(C13)	binary requirements on the sequential decisions
(C14)	non-negative requirements

This problem can potentially be very big but we limit the generated sequences to keep the solution time low.