Applications in the Forest Sector

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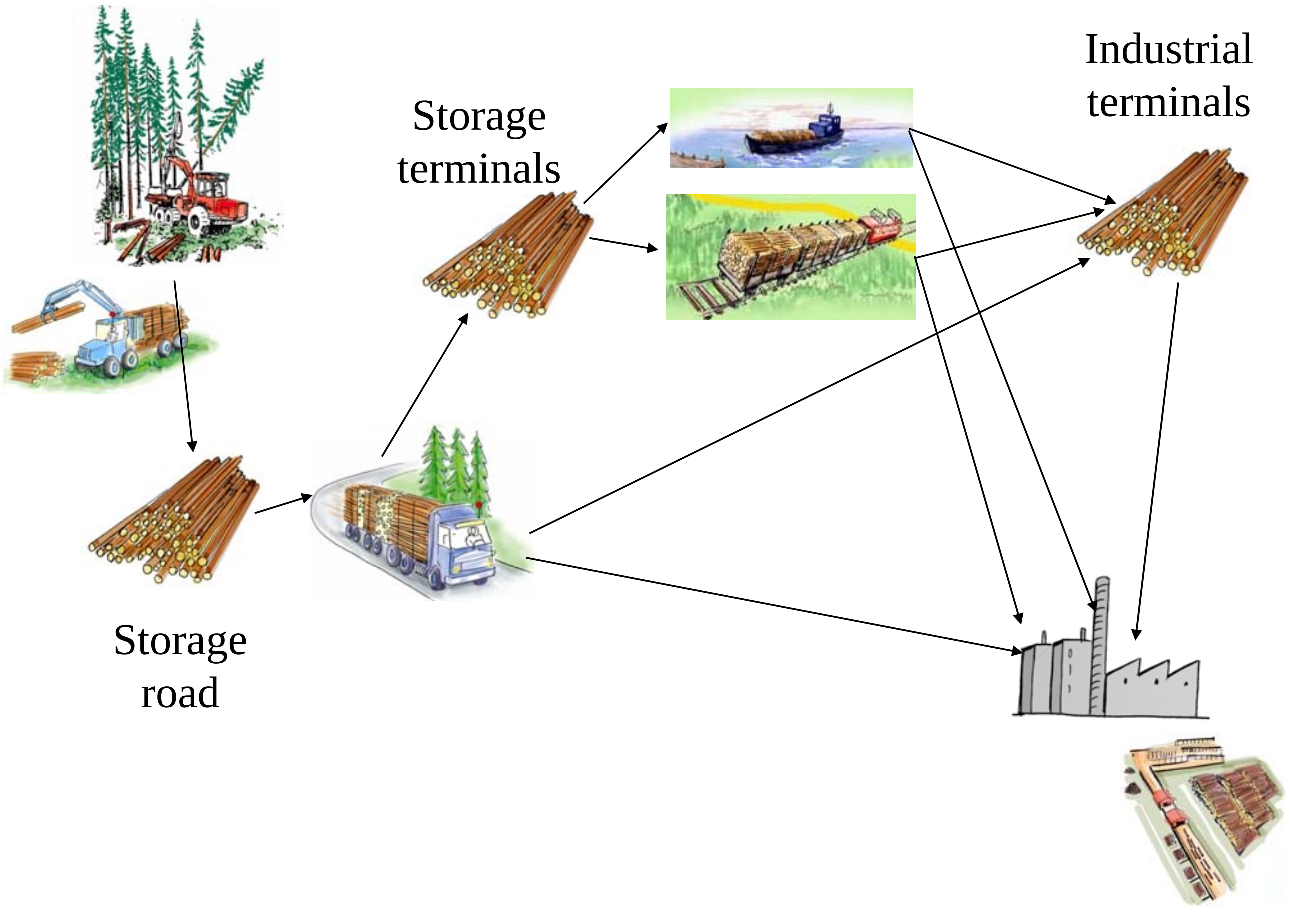
Outline

- Introduction to the forest industry
- Decision support systems
- Applications
  - Online operations: *cutting problem*
  - Operational/ Short term: *routing and production*
  - Tactical/ Medium term: *transportation, harvesting / routing, StormOpt, Forest fuel*
  - Strategic/ Long term: *logistics and supply chain design, terminal structure, train system*
- Concluding remarks

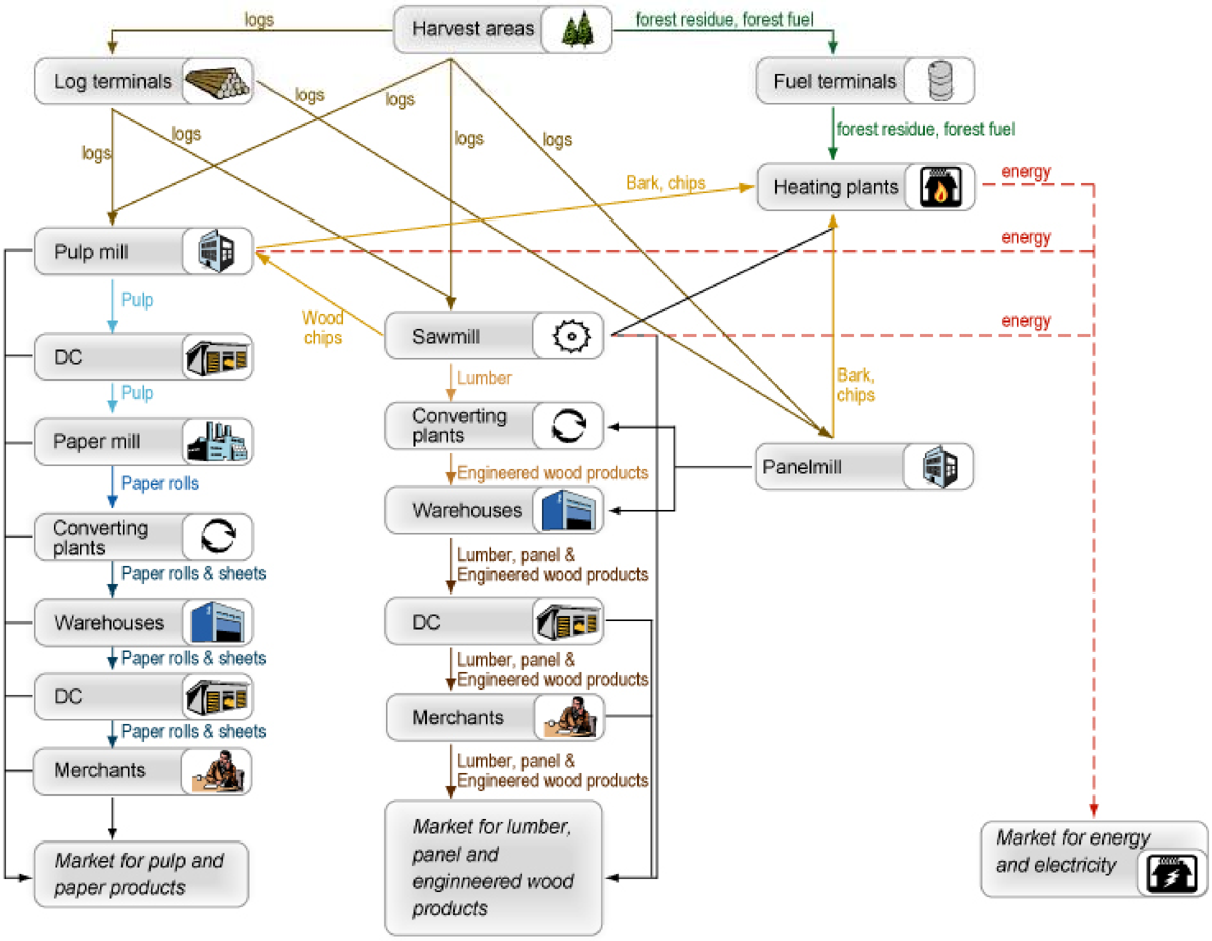
Introduction to forest industry and planning problems



Industrial
terminals

Storage
terminals

Storage
road



Harvest areas

logs

forest residue, forest fuel

Log terminals

Fuel terminals

logs

logs

logs

logs

logs

logs

forest residue, forest fuel

Heating plants

Bark, chips

energy

Pulp mill

energy

Pulp

Wood chips

Sawmill

energy

DC

Pulp

Lumber

Bark, chips

Paper mill

Converting plants

Engineered wood products

Panelmill

Paper rolls

Converting plants

Warehouses

Paper rolls & sheets

Lumber, panel & Engineered wood products

Warehouses

DC

Paper rolls & sheets

Lumber, panel & Engineered wood products

DC

Merchants

Paper rolls & sheets

Merchants

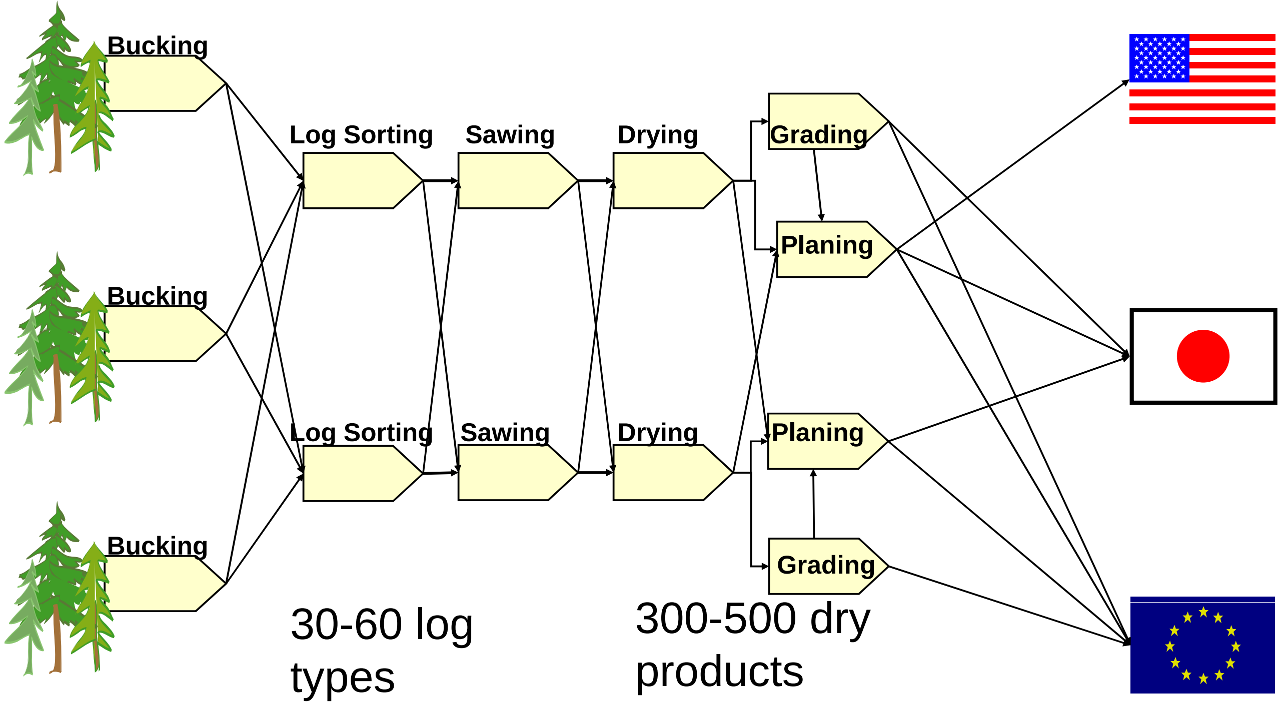
Lumber, panel & Engineered wood products

Market for energy and electricity

Market for pulp and paper products

Market for lumber, panel and enginneered wood products

Divergent flows



Bucking

Bucking

Bucking

Log Sorting

Log Sorting

Sawing

Sawing

Drying

Drying

Grading

Planing

Planing

Grading

30-60 log types

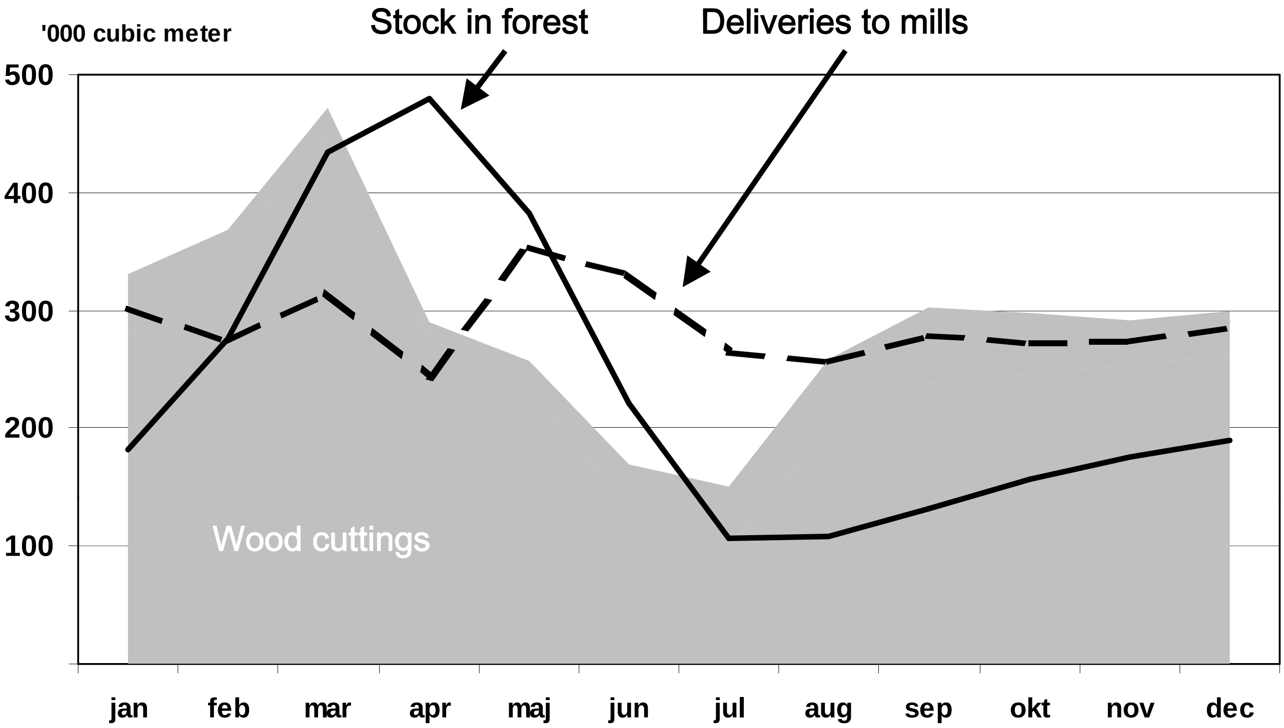
300-500 dry products

5-8 assortments

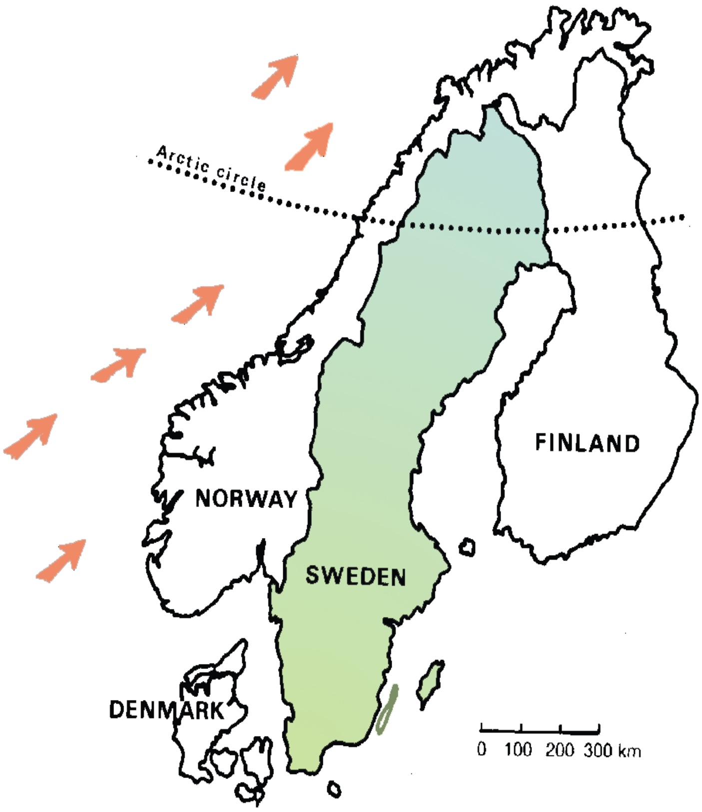
100-200 raw products

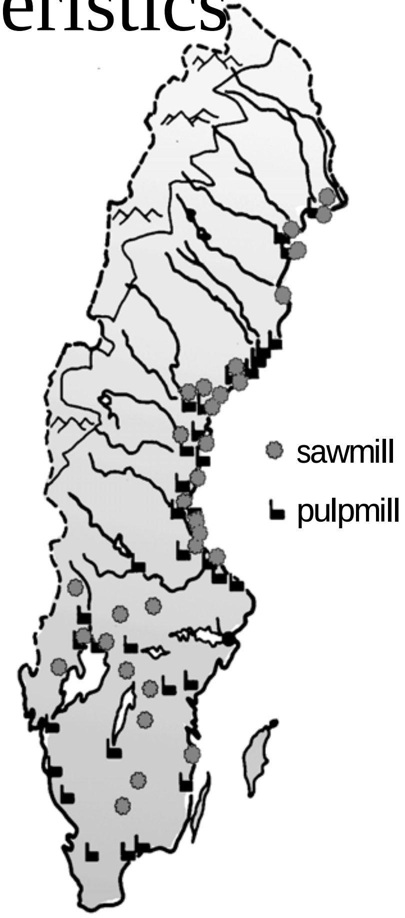
1000-3000 products

Unbalanced annual harvesting



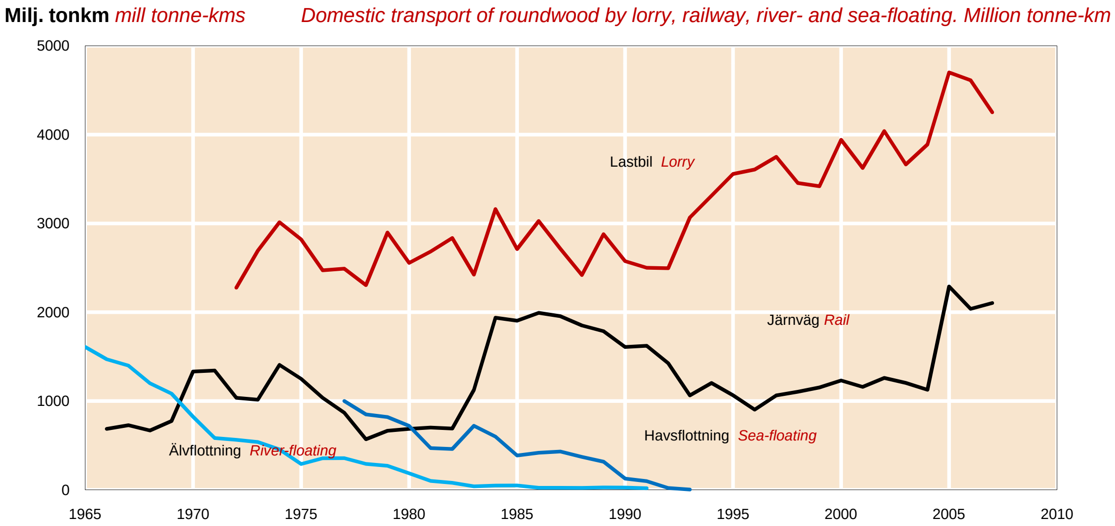
Geographical characteristics





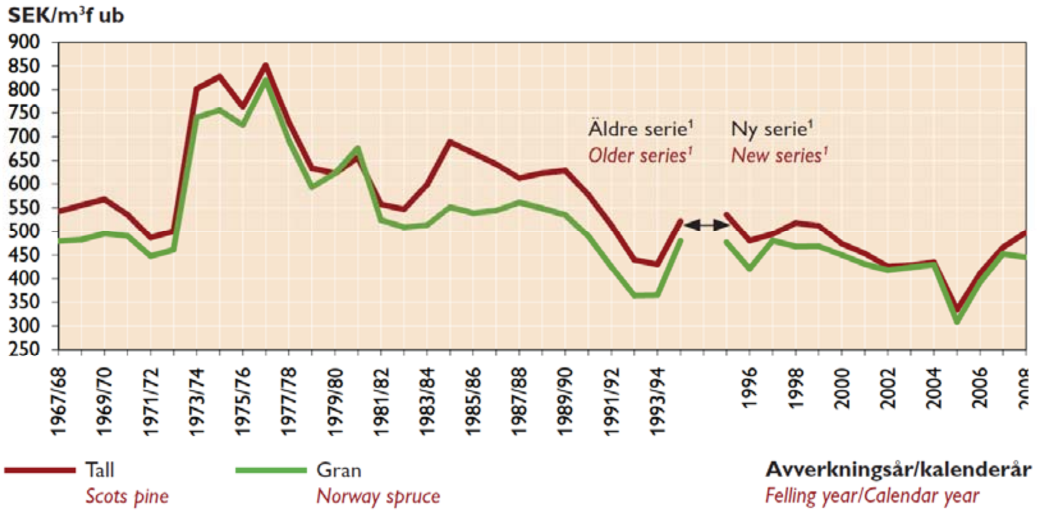
Forest transportation work

Average distances travelled were: 88 kilometres for road, 272 kilometres for rail and 510 km by sea between Swedish ports.



Källa: SCB, SIKA och Skogsstyrelsen
Sources: Statistics Sweden, SIKA, Swedish Forest Agency

Price trends for sawlogs of scots pine and Norway spruce, delivery logs, in the price level of 2008 (deflated with CPI)



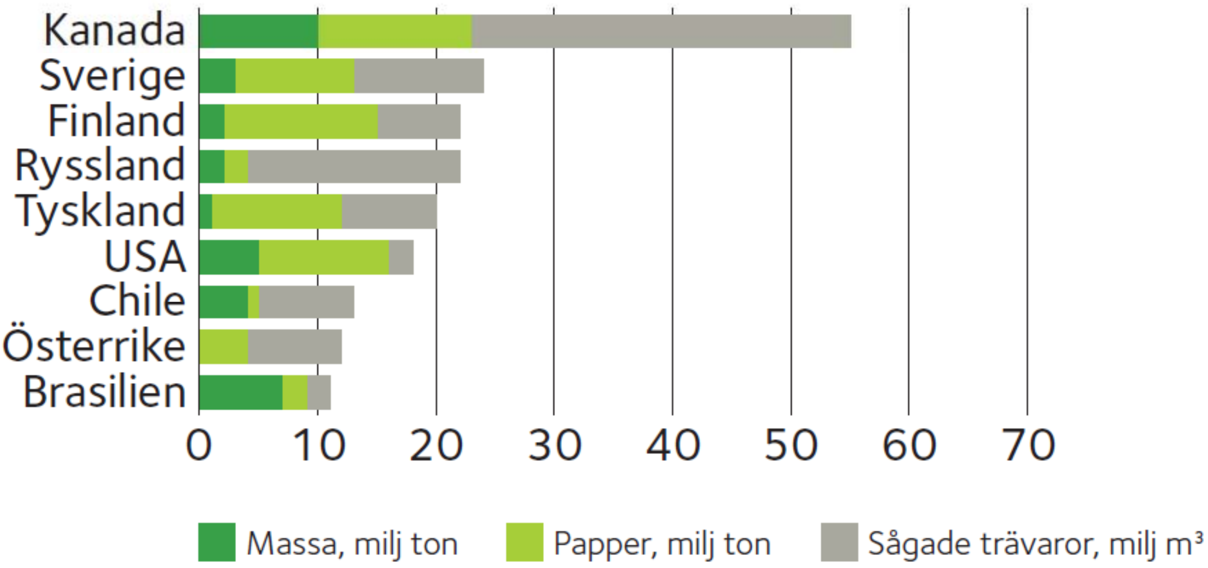
[1] Se kapiteltexten.
See the capter text.

Källa: SDC; Skogsstyrelsen, Analysenheten.
Source: SDC; Swedish Forest Agency, Analysis Division.

Number of assessed units by ownership category and size of forest area held 2005

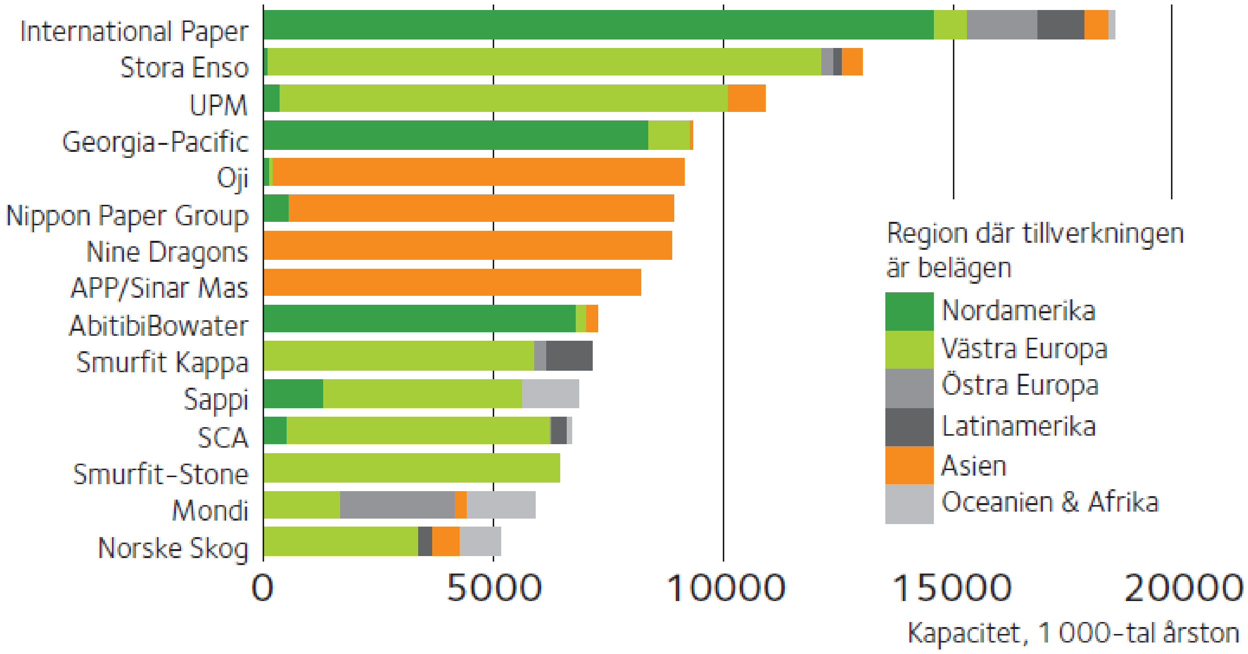
Skogsmark i storleksklasser Size of forest land	Ägargrupp Ownership category								
	Fysisk person Physical person	Dödsbo Estate of a deceased person	Kommuner och landsting Municipalities & county councils	Svenska kyrkan Church	Aktiebolag Company forest	Staten State	Övriga Others	Okänd ägar-kategori Unknown category	Samtliga ägare All owners
ha hectare	Antal taxeringsenheter Number of assessed units								
1-9	82 908	2 080	1 984	102	792	291	1 961	16	90 134
10-19	44 875	966	955	71	357	162	685	16	48 087
20-49	62761	1 172	963	88	383	217	875	23	66 482
50-99	36 829	634	582	53	321	156	730	21	39 326
100-399	24 881	407	552	42	516	158	1 062	57	27 675
400-999	1 450	25	98	7	240	56	323	13	2 212
1000-	176	4	31	7	626	52	196	1	1 093
Summa Total	253 880	5 288	5 165	370	3 235	1 092	5 832	147	275 009
Information from the General Assessment of Real Estates in 2005									
Källa: SCB Source: Statisics Sweden	92,3%	1,9%	1,9%	0,1%	1,2%	0,4%	2,1%	0,1%	100,0%

Leading exporter of pulp, paper and sawn wood



pulp paper Sawn wood

Production (paper) first quarter 2009



Diagrammet visar läget första kvartalet 2009.

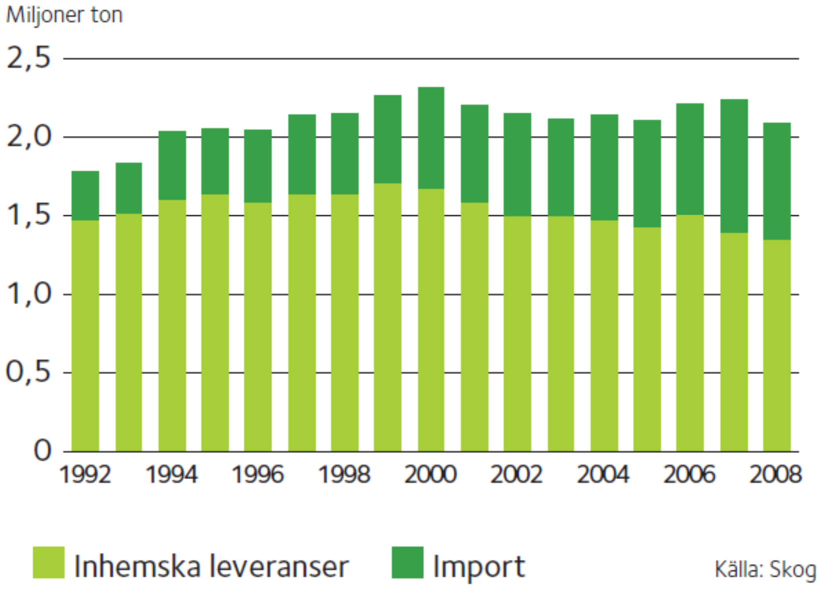
Källa: Pöyry

- International Paper
  - United States
    - 18 pulp, paper and packaging mills
    - 94 converting and packaging plants
    - 5 wood products facilities
    - 250 distribution branches
  - Europe, Asia and South America
    - 8 pulp and paper mills
    - 44 converting and packaging mills

Top 5
International paper (~$22 B)
Weyerhaeuser (~ $20 B)
Georgia Pacific (~ $20 B)
Stora Enso (~ $15 B)
Kimberly Clark (~ $15 B)

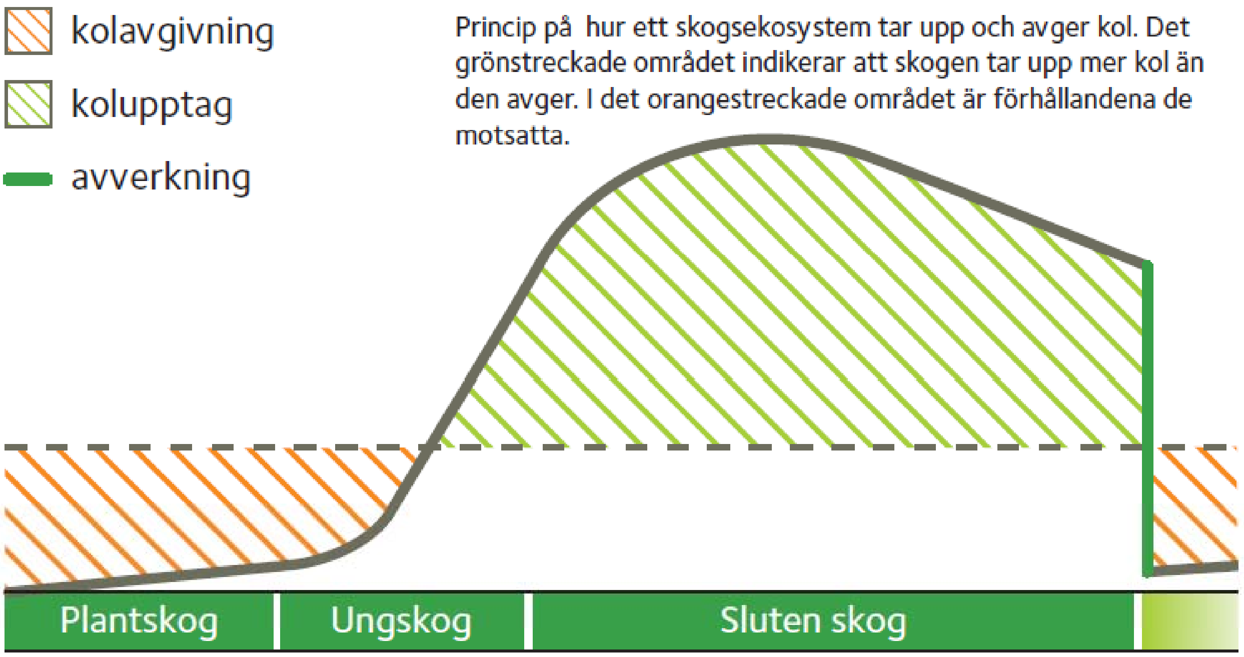
PWC – Global Forest and Paper Industry Survey 2005

Paper consumption, Sweden



Källa: Skogsindustrierna, SCB

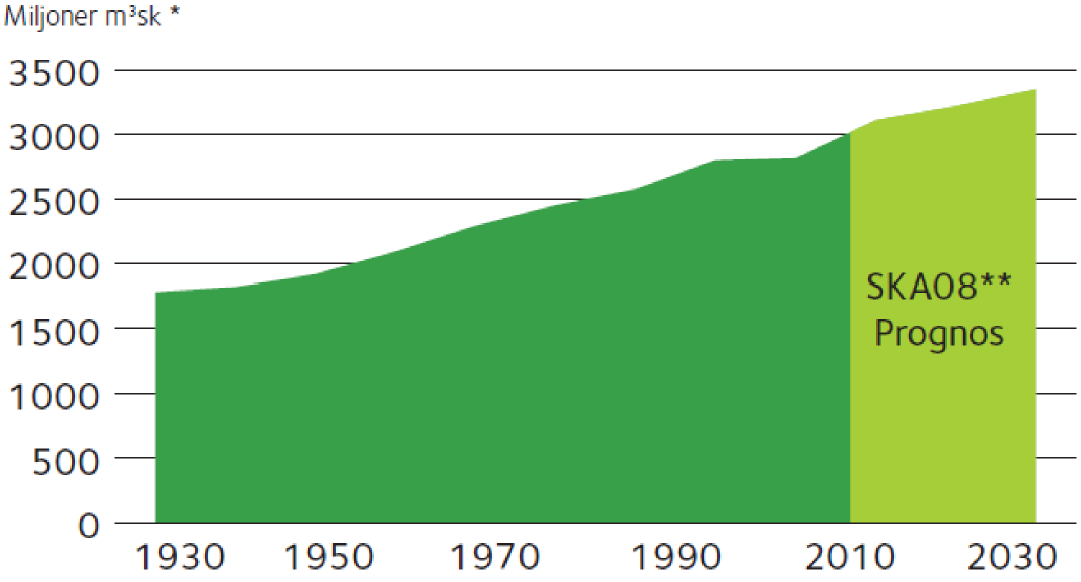
CO2 emissions – over a life cycle



Princip på hur ett skogsekosystem tar upp och avger kol. Det grönstreckade området indikerar att skogen tar upp mer kol än den avger. I det orangestreckade området är förhållandena de motsatta.

Källa: SLU (Sveriges Lantbruks Universitet)

Swedish forest inventory (standing)



* m³sk = skogskubikmeter
** SKA = Skogliga konsekvensanalyser

Källa: Skogsstyrelsen

Decision support systems

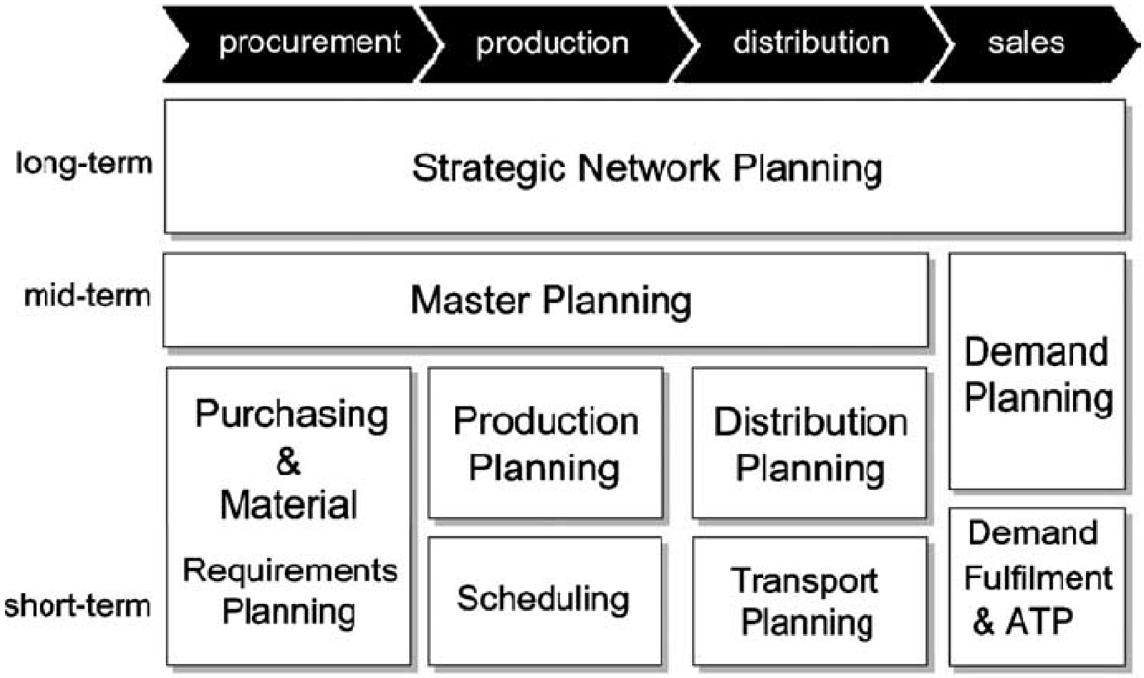


Fig. 2. Software modules covering the SC planning matrix (Meyr et al., 2002, p. 99).

	Procurement	**Production**	**Distribution**	**Sales**
Strategic	• Wood procurement strategy (private vs public land) • Forest land acquisitions and harvesting contracts • Silvicultural regime and regeneration strategies • Harvesting and transportation technology and capacity investment • Transportation and investment strategies (e.g., roads, construction, trucks, wagons, terminals, ships)	• Location decisions • Outsourcing decisions • Technology and capacity investments • Allocation of product families to facilities • Order penetration point strategy • Investments in information technology and planning systems (e.g., advance planning and scheduling technologies, ships)	• Warehouse location • Allocation of markets/customers to warehouses • Logistics resource investments (e.g., warehouses, handling) • Contracts with logistics providers • Investments in information technology and planning systems (e.g., warehouse execution)	• Selection of markets (e.g., location, segment) • Customer segmentation • Product-solution portfolio • Pricing strategy • Service strategy • Contracts • Investments in information technology and planning systems (e.g., On-line tracking systems, CRM)
Tactical	• Sourcing plan (log class planning) • Aggregate harvesting planning • Route definition and transshipment yard location and planning • Allocation of harvesting and transportation equipment to cutting blocks • Allocation of products/ blocks to mills • Yard layout design • Log yard management policies	• Campaign duration • Product sequencing during the campaigns • Lot-sizing • Outsourcing planning • Seasonal inventory target • Parent roll assortment optimization • Temporary mill shutdowns	• Warehouse management policies (e.g., dock management) • Seasonal inventory target at DCs • Routing (Ship, train and truck) • 3PL contracts	• Aggregate demand planning per segment • Customer contracts • Demand forecasting, safety stocks • Available to promise aggregate need and planning • Available to promise allocation rules (including rationing rules and substitution rules) • Allocation of products and customers to mills and DCs
Operational	• Detailed log supply planning • Forest to mill: daily carrier selection and routing	• Daily production plans for pulp mills/paper machines/ winders/sheeters • Mill to converter/DC/ customer: daily carrier selection and routing • Roll-cutting • Process control	• Warehouse/DC inventory management. • DC to customer: daily carrier selection and routing • Vehicle loads	• Available to promise consumption • Rationing • Online ordering • Customer inventory management and replenishment

DSS structure: input database, analytical tool and presentation tool

Reality expressed into an OR model

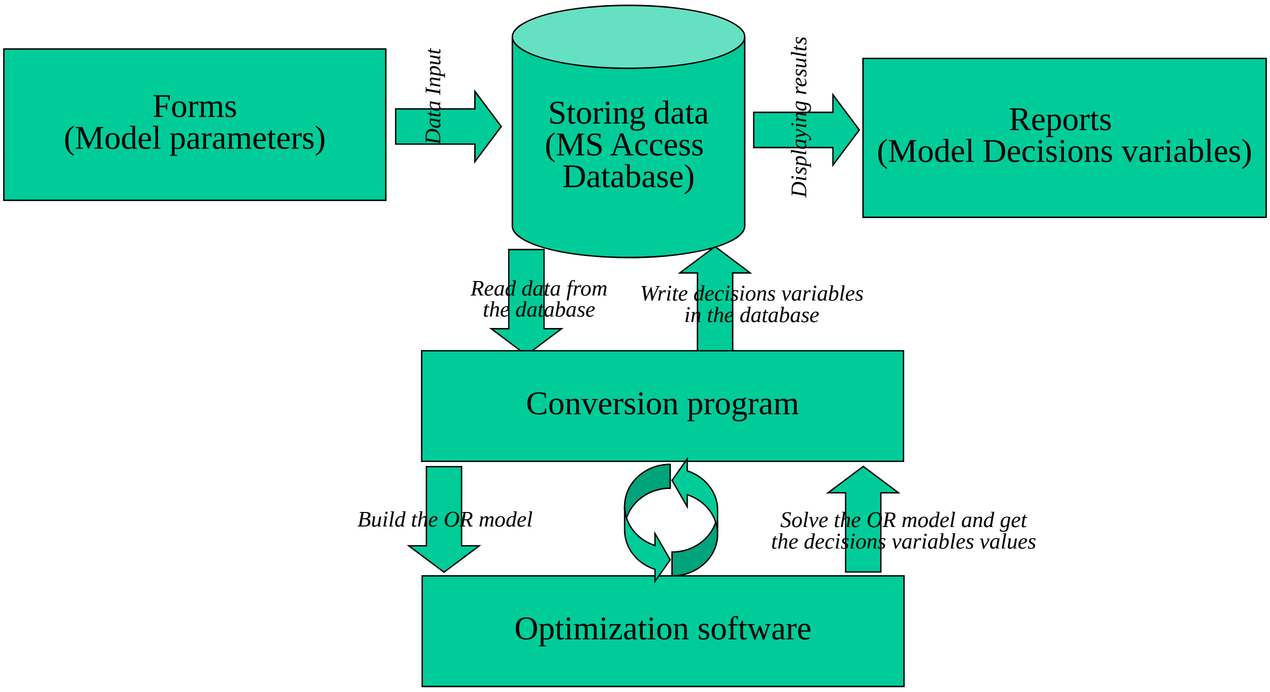
Bucking

Production planning

Transportation-planning

$$\begin{aligned} &\min \quad f(x) \\ &st \quad g(x) \leq b \\ &x \in \mathrm{X} \end{aligned}$$

Structure of analytical tool



Forms
(Model parameters)

Data Input

Storing data
(MS Access
Database)

Displaying results

Reports
(Model Decisions variables)

*Read data from
the database*

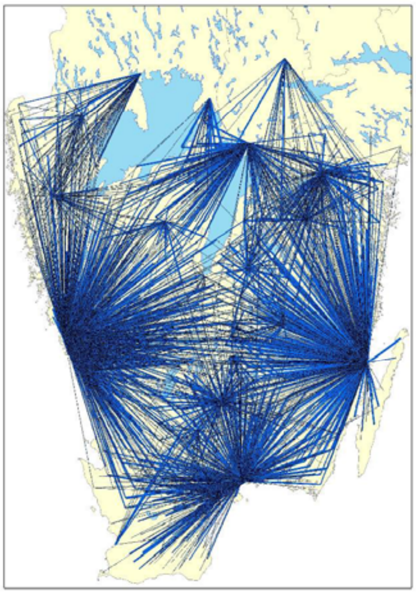
*Write decisions variables
in the database*

Conversion program

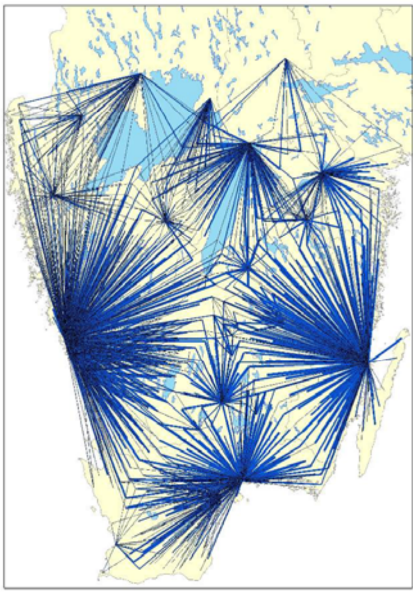
Build the OR model

*Solve the OR model and get
the decisions variables values*

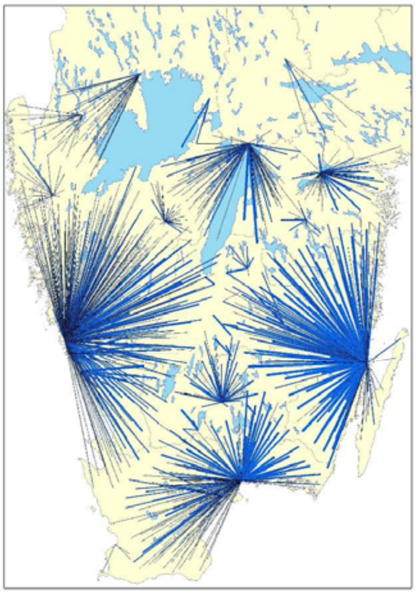
Optimization software



Real

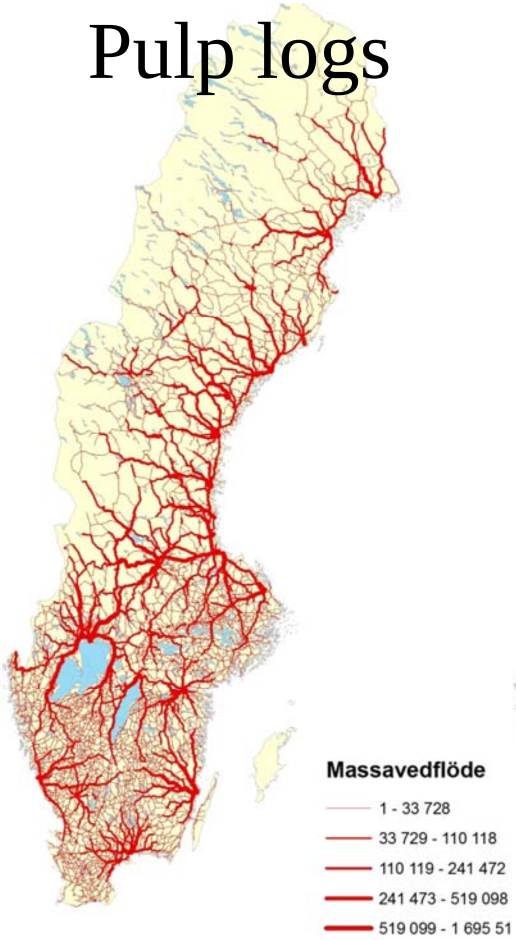


Optimized 12 periods

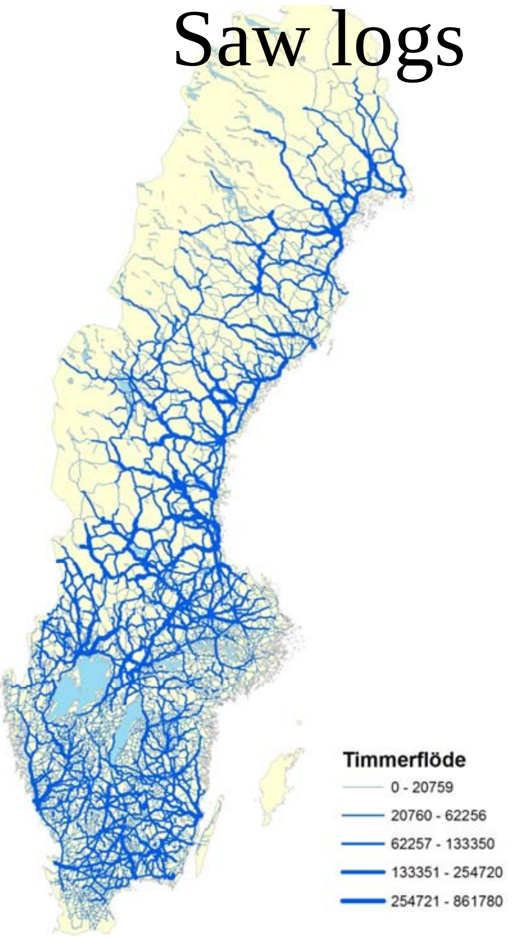


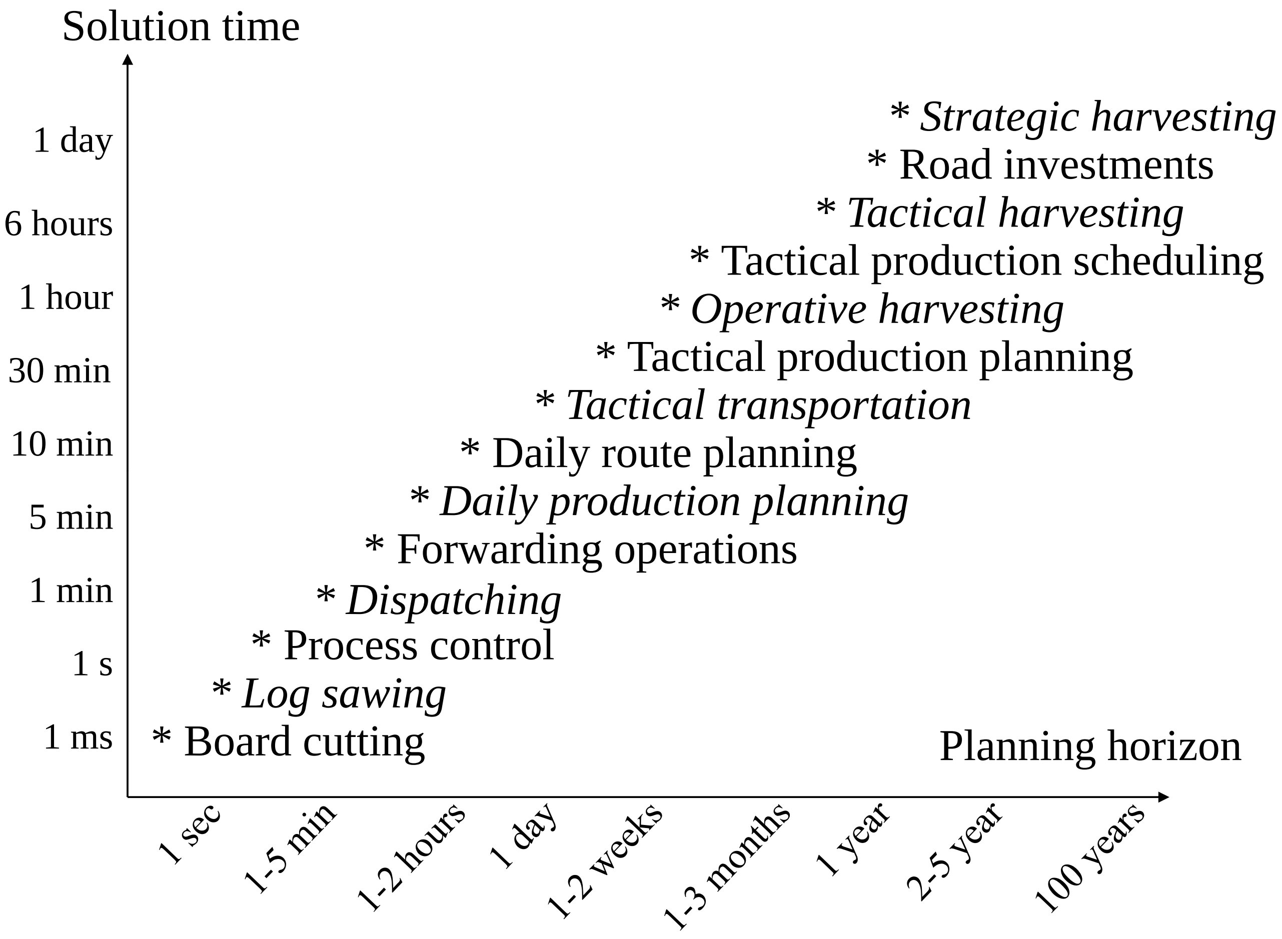
Optimized one period

Pulp logs



Saw logs





Solution time

* *Strategic harvesting*
* Road investments
* *Tactical harvesting*
* Tactical production scheduling
* *Operative harvesting*
* Tactical production planning
* *Tactical transportation*
* Daily route planning
* *Daily production planning*
* Forwarding operations
* *Dispatching*
* Process control
* *Log sawing*
* Board cutting

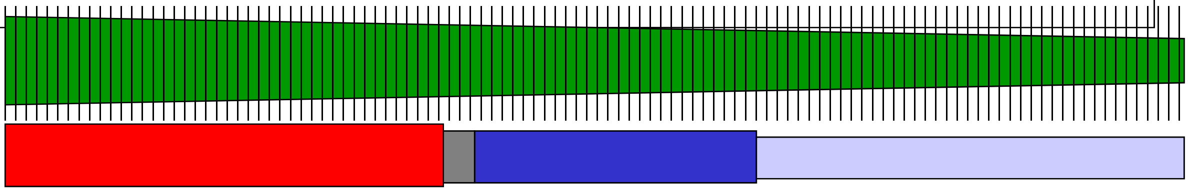
Planning horizon

DSS at Skogforsk (Forest Research Institute of Sweden)

- Planning systems
  - Base: national road database, operations research, company data & collaboration, server solution with GIS
  - FlowOpt (flow & inventory, trucks, trains, ships, terminals, collaboration, *robustness*)
  - RuttOpt (detailed routing, *queuing*)
  - FuelOpt (forest fuel, chipping operations)
  - VägRust (road investments, flows & inventory, *robustness*)
  - Resource planning (harvesting, scheduling)
  - New: ChipOpt (tactical and operational harvest planning)

Online operations – Cutting applictions

Dynamic Programming model

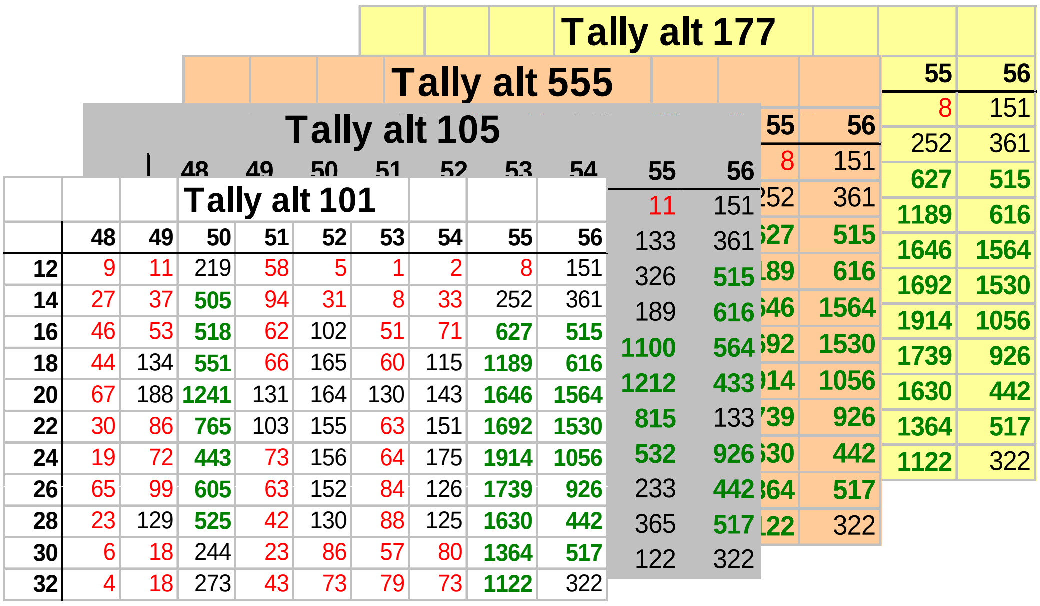


Problem can be solved as a longest path problem.

1. Discretize into elements which forms nodes in a graph.
2. Introduce arcs while checking feasibility where it is possible to cut products.
3. Solve longest path using e.g. Dijkstras algorithm

Use a price list to set relative prices of products

Log tally



Diameter

Tally alt 101

	48	49	50	51	52	53	54	55	56
12	9	11	219	58	5	1	2	8	151
14	27	37	505	94	31	8	33	252	361
16	46	53	518	62	102	51	71	627	515
18	44	134	551	66	165	60	115	1189	616
20	67	188	1241	131	164	130	143	1646	1564
22	30	86	765	103	155	63	151	1692	1530
24	19	72	443	73	156	64	175	1914	1056
26	65	99	605	63	152	84	126	1739	926
28	23	129	525	42	130	88	125	1630	442
30	6	18	244	23	86	57	80	1364	517
32	4	18	273	43	73	79	73	1122	322

Tally alt 105

55	56
11	151
133	361
326	515
189	616
1100	564
1212	433
815	133
532	926
233	442
365	517
122	322

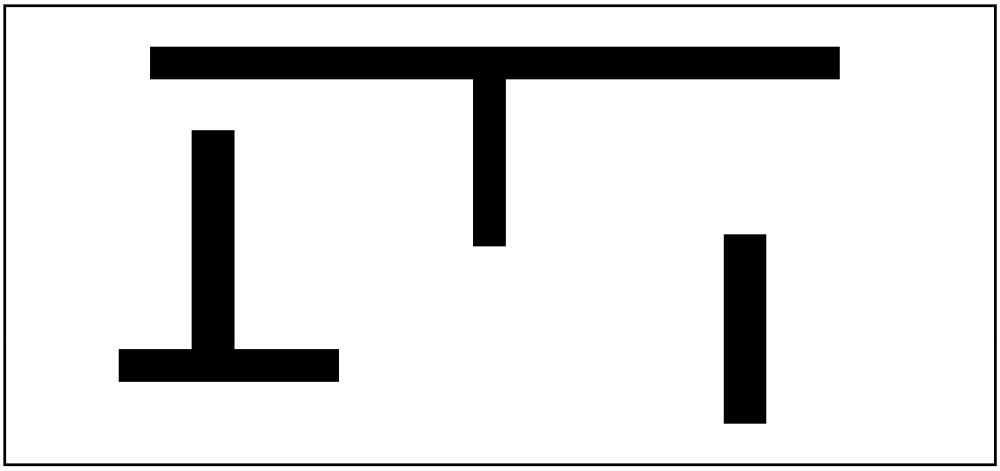
Tally alt 555

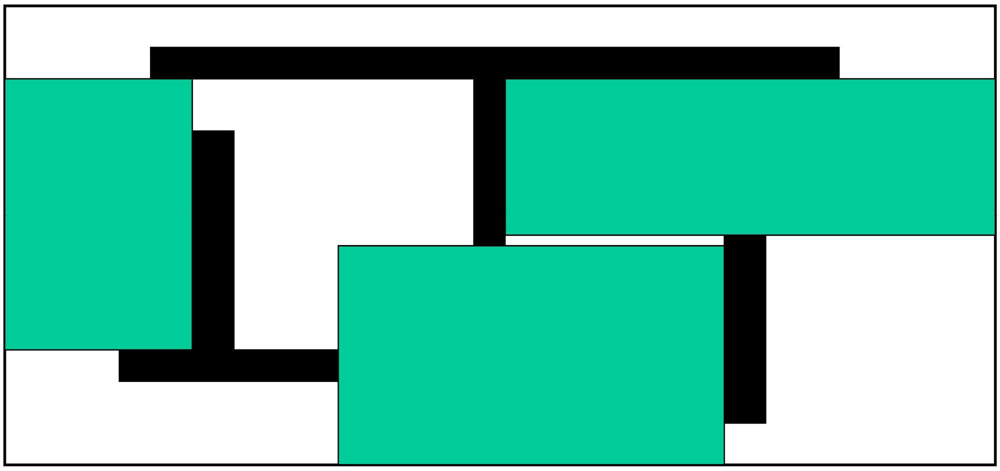
Tally alt 177

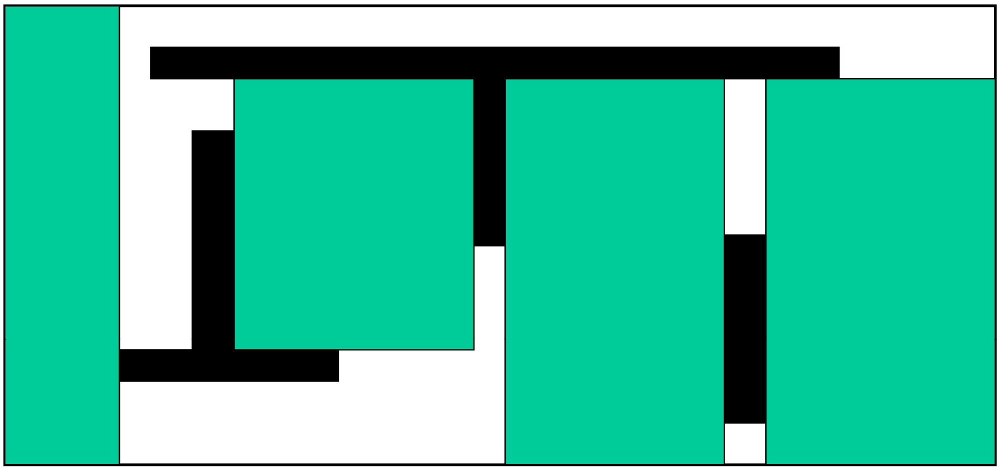
55	56
8	151
252	361
627	515
1189	616
1646	1564
1692	1530
1914	1056
1739	926
1630	442
1364	517
1122	322

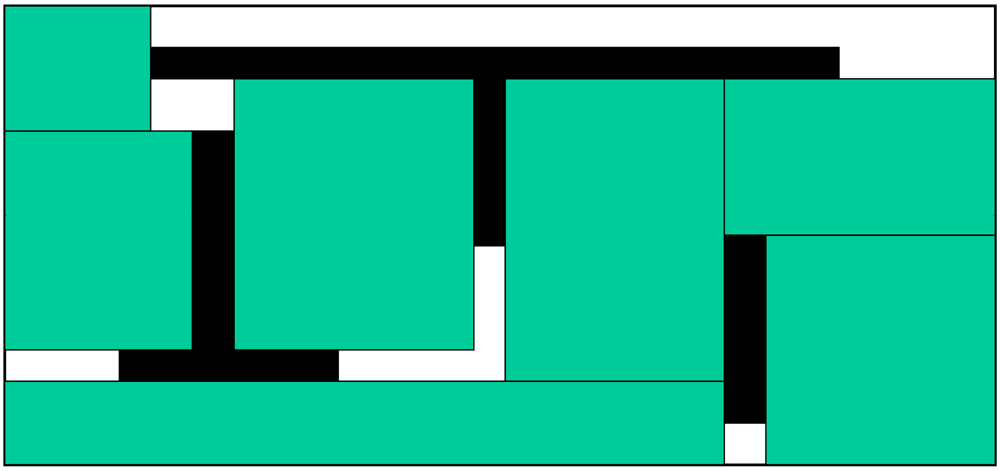
Length

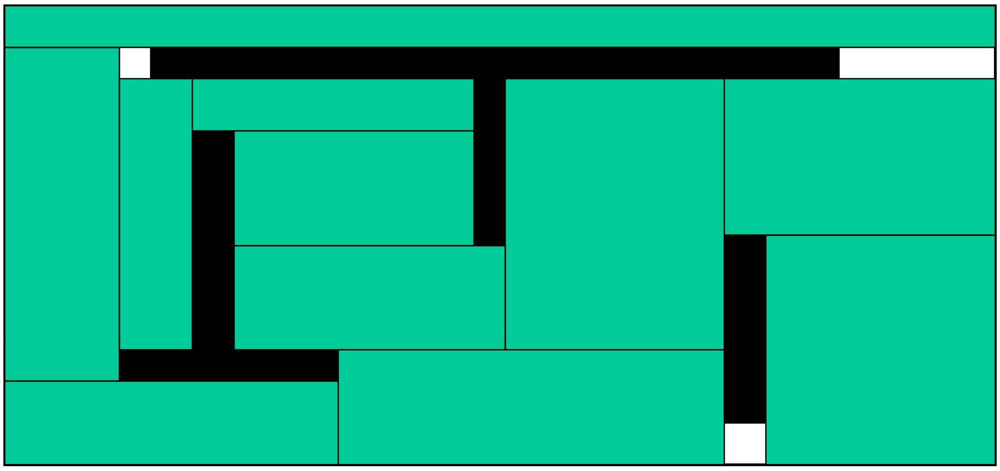
2-dimensional packing at sawmills

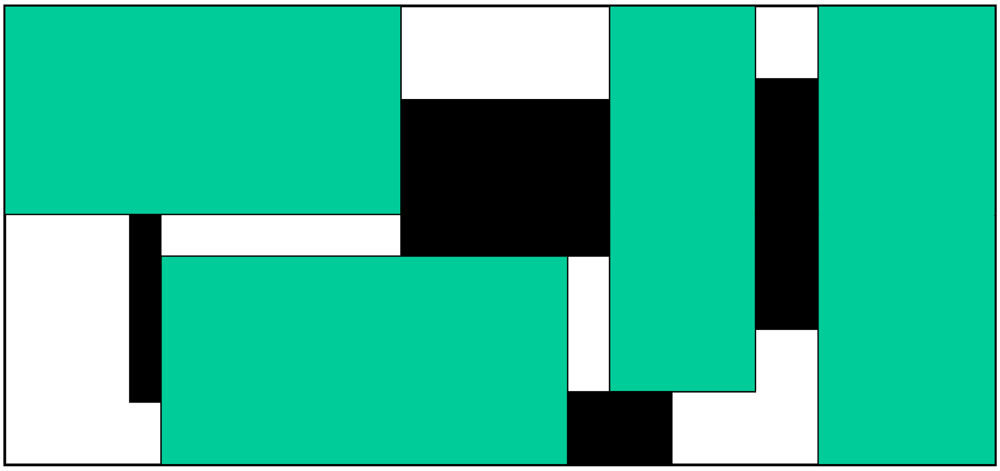


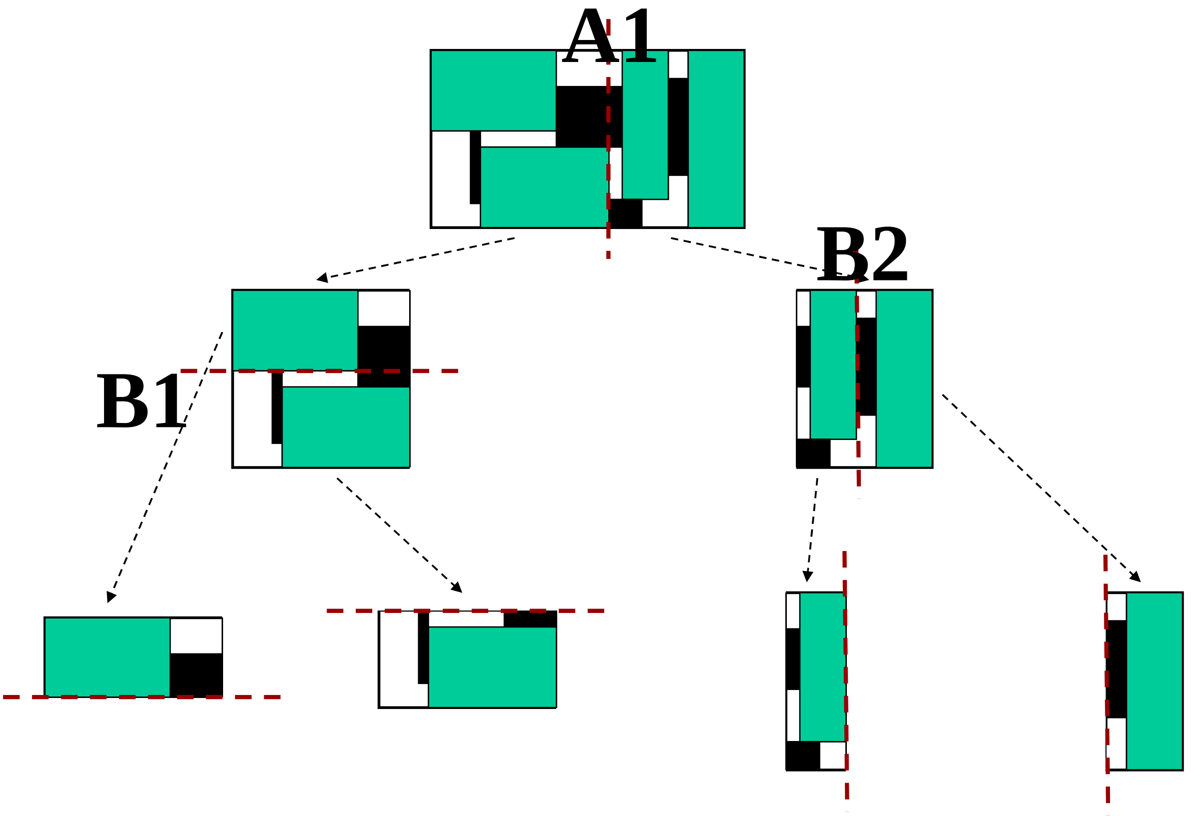


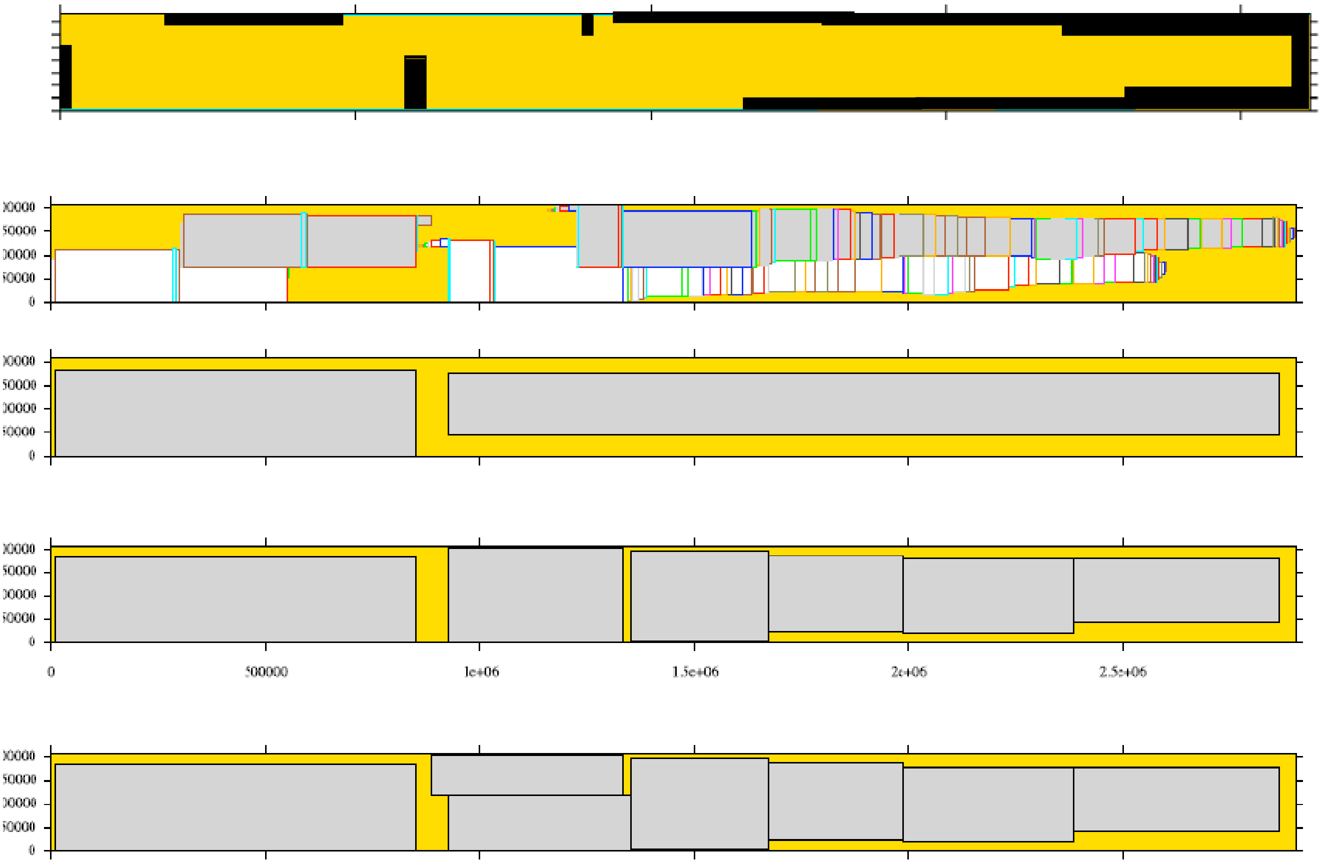




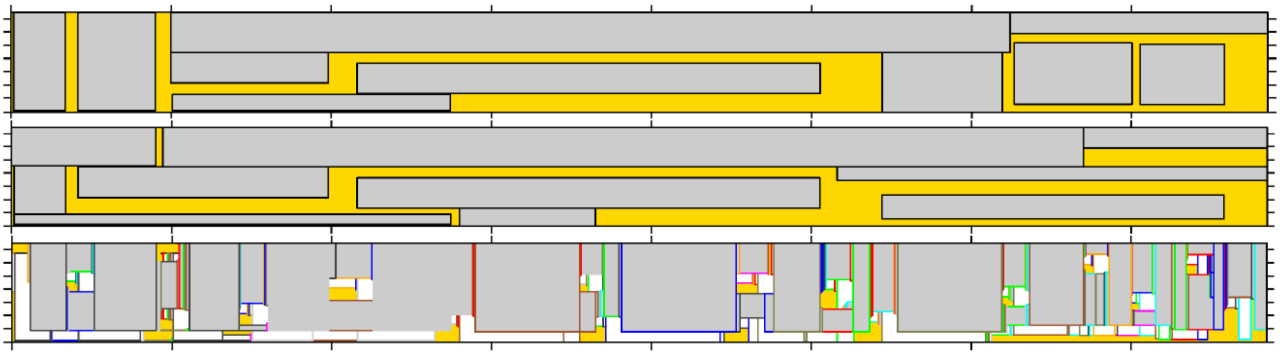




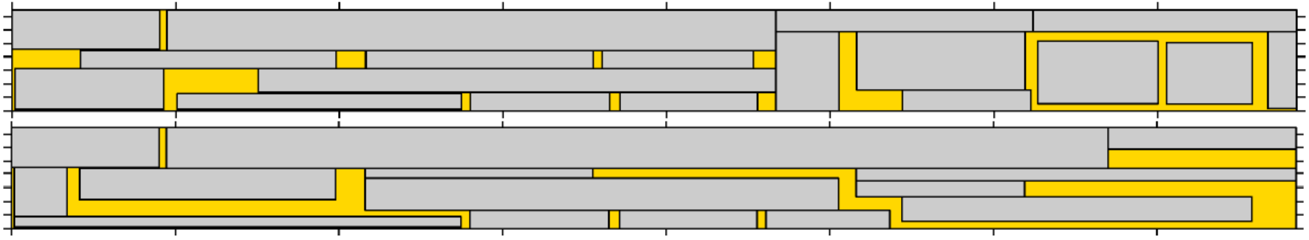

A1
B2
B1



Max 10 products



Max 100 products



Models, methods and challenges

- Cutting applications with guilliotine cuts often includes Dynamic programming models /methods
- Special heuristics for general cutting applications
- Challenges:
  - Collect detailed information online (e.g. image processing)
  - Co-ordinate bucking (i.e. log cutting) to match actual online demand
  - Applications with non-guilliotine cuts

Transportation

Planning levels

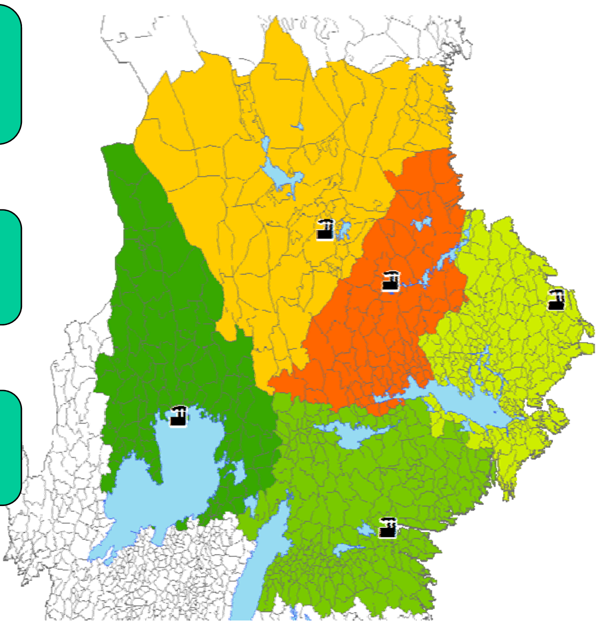
Destination planning:
Decide catchment areas, backhauling and destination of logs

↓

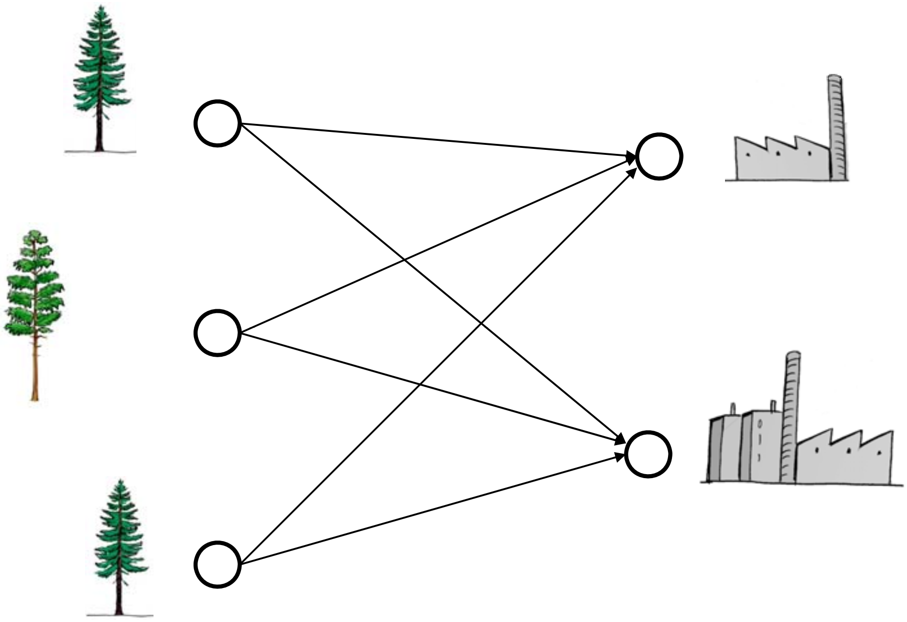
Route planning/ scheduling:
Decide routes for the next 1-7 days

↓

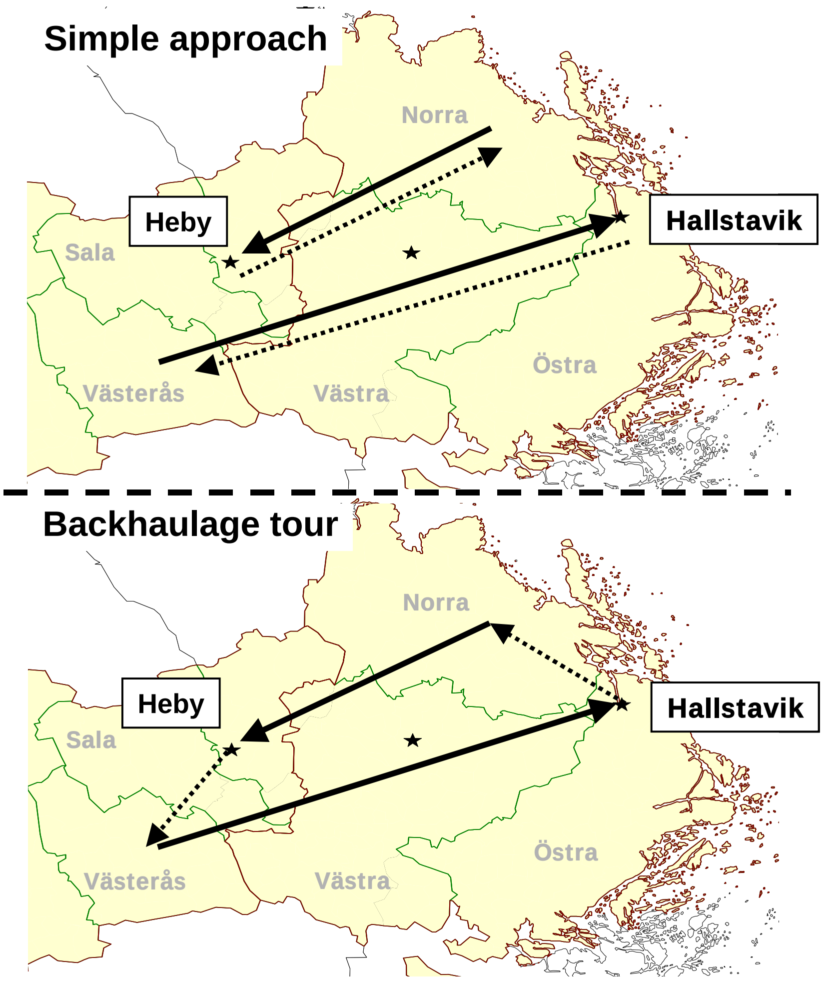
Despatching:
Decide, in real time, the next trip in a daily route



”Classical” transportation problem



x_{ijk} = flow from supply point i to demand point j with assortment k



Mathematical model – backhaulage problem

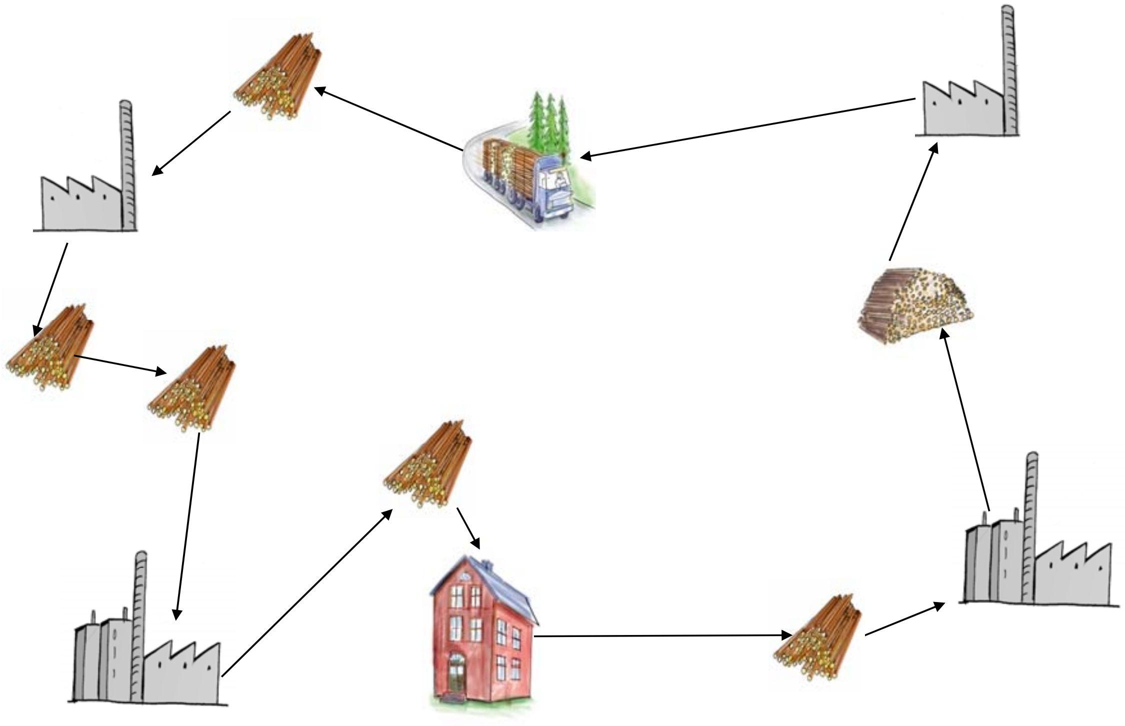
$$\min \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} c_{ijk}x_{ijk} + \boxed{\sum_{l\in L} d_l y_l}$$

$$\sum_{j\in J} x_{ijk} + \boxed{\sum_{l\in L} a_{ikl} y_l} \le s_{ik}, \quad \forall\ i,k \qquad \text{(supply at harvest areas)}$$

$$\sum_{i\in I} x_{ijk} + \boxed{\sum_{l\in L} b_{jkl} y_l} = d_{jk}, \quad \forall\ j,k \qquad \text{(demand at industries)}$$

$$x_{ijk}, y_l \ge 0, \ \forall\ i\in I, j\in J, k\in K, l\in L$$

Forest vehicle routing problem



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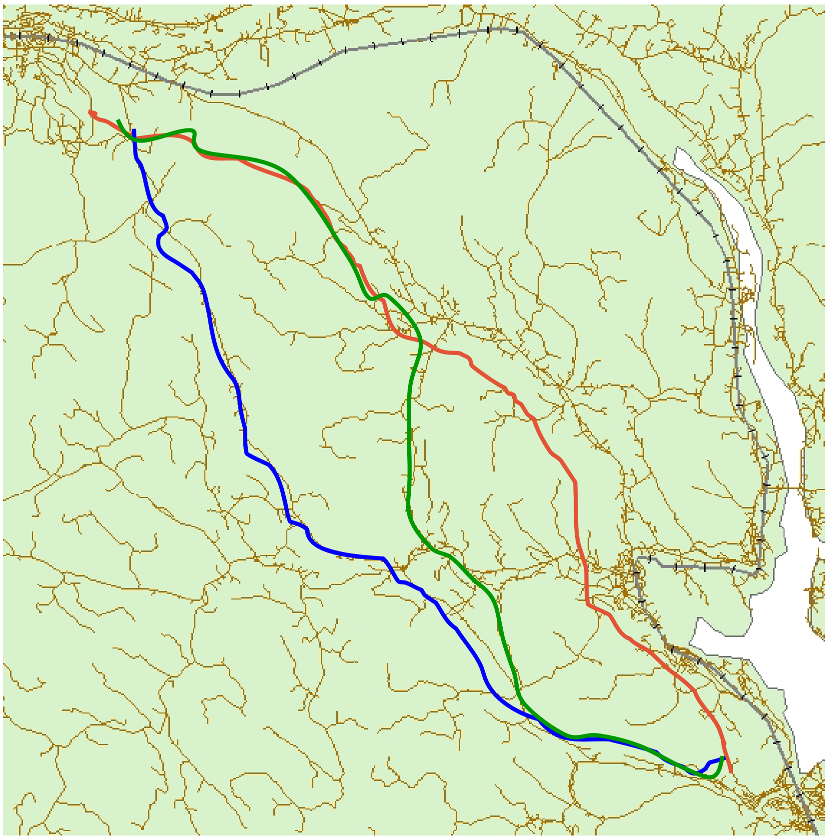
quizz

- Given a truck, starting and ending point, what is the correct transportation cost?

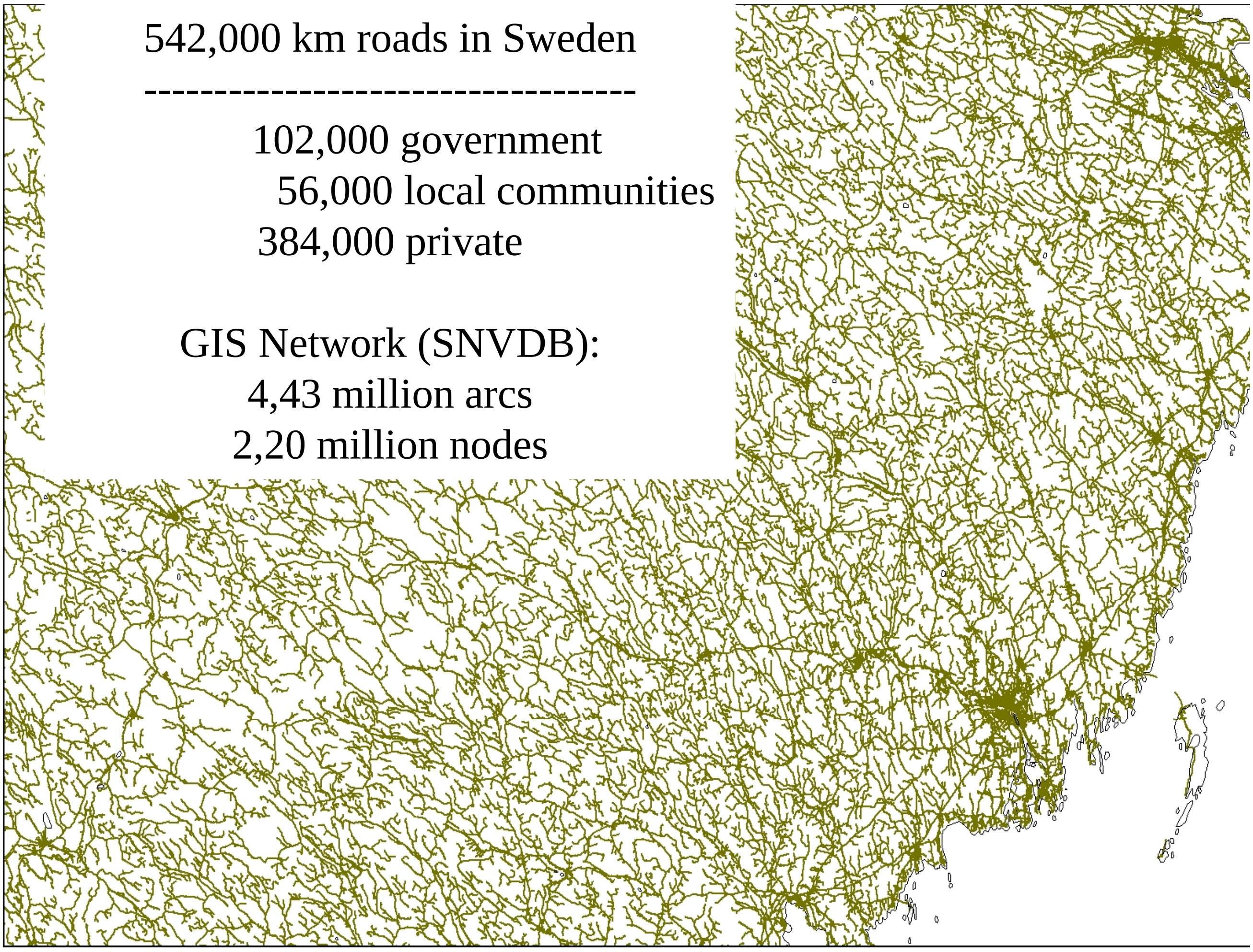
- Answer: it depends ……

Route selection with road database



- Shortest path?
- Quickest path?
- Best road class?
- Driven route is based on weighting of attributes

Road length,
Speed limit,
Road class,
Bearing class,
Terrain class,
Road width,
Ownership,
Special routes/links
(total of 55 weights)

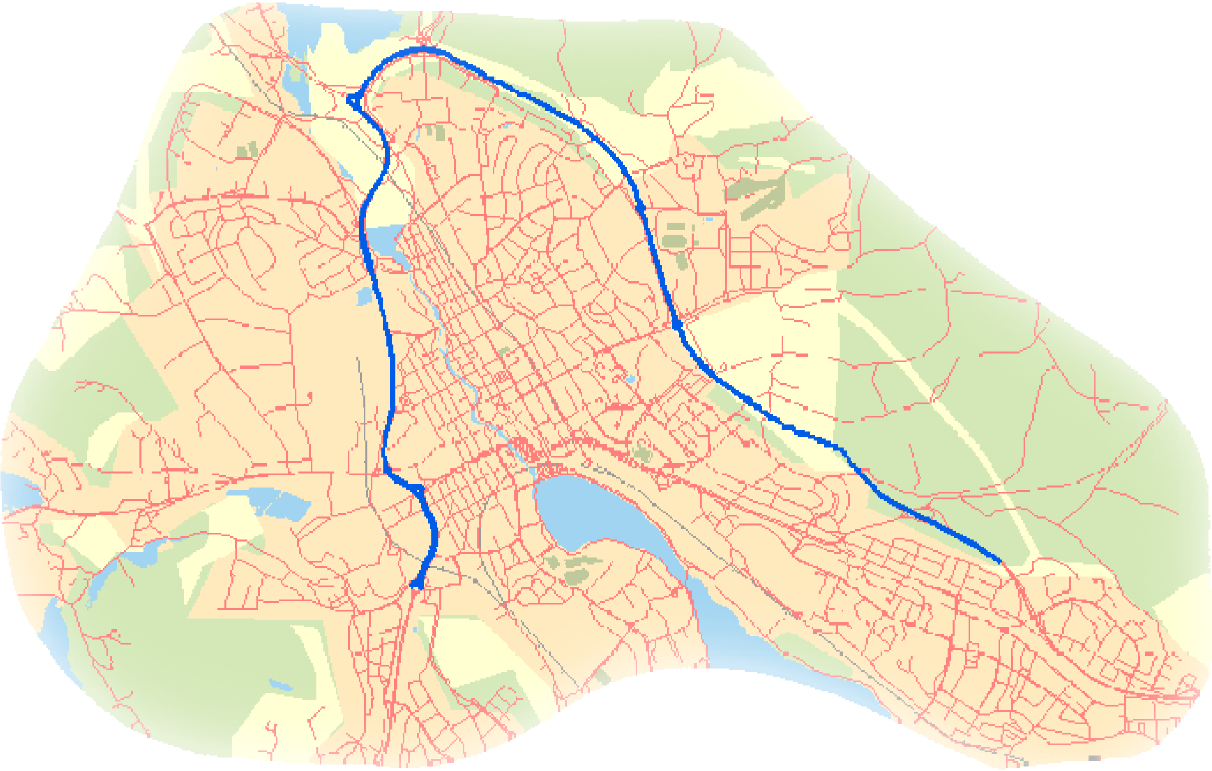


542,000 km roads in Sweden

102,000 government
56,000 local communities
384,000 private

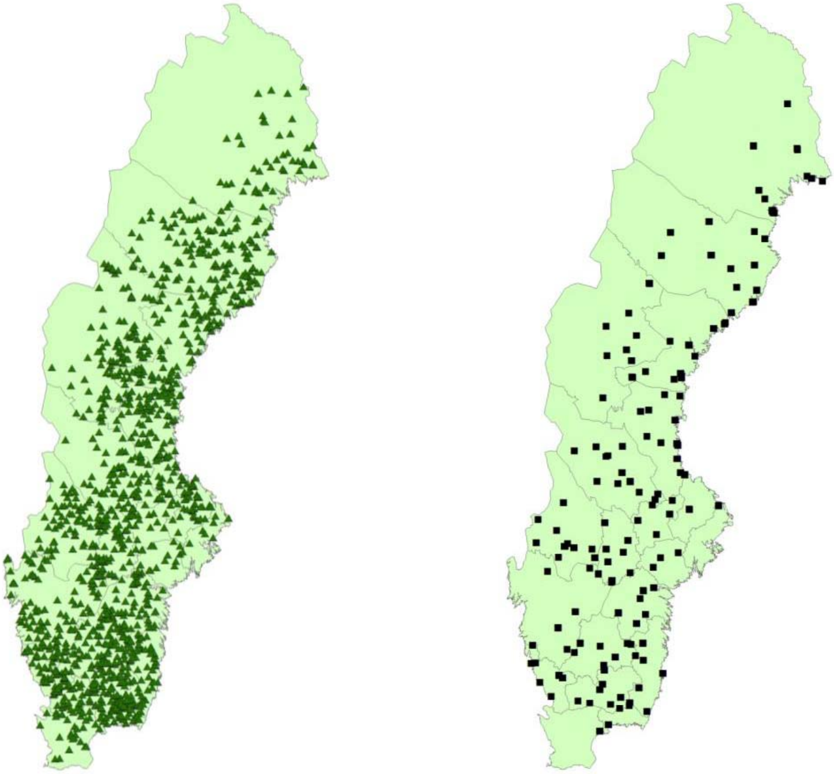
GIS Network (SNVDB):
4,43 million arcs
2,20 million nodes

Passing routes in or around cities

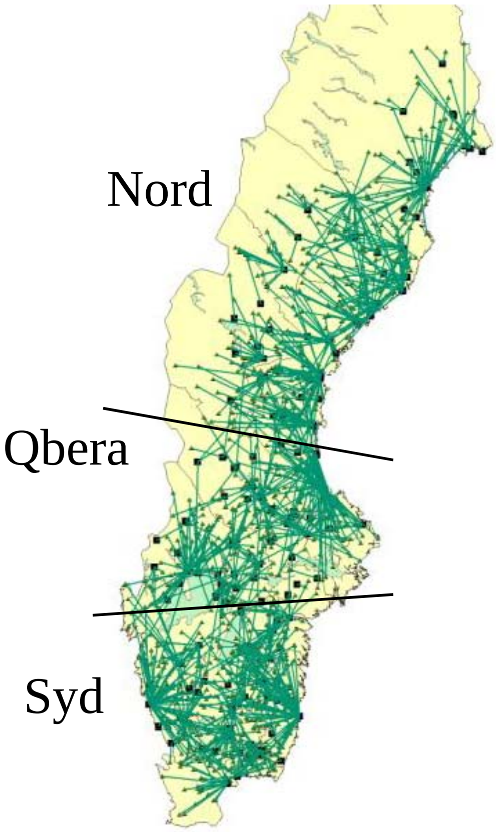


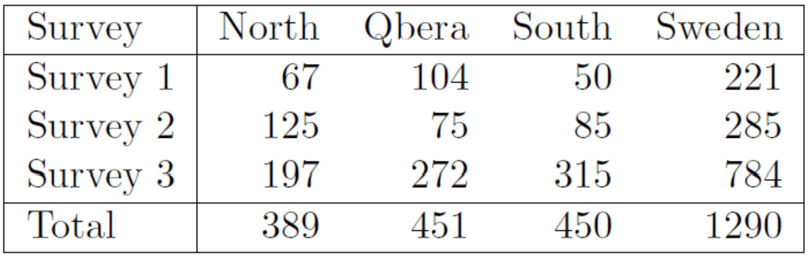
TP routes: routes in cities,
18 industries have TP routes

Key-routes: harvest areas and industries



Key routes: geographical distribution





Survey	North	Qbera	South	Sweden
Survey 1	67	104	50	221
Survey 2	125	75	85	285
Survey 3	197	272	315	784
Total	389	451	450	1290

Inverse shortest path problem

Decision variable	Definition
w_k	weight of parameter k
x_{ij}	1 if shortest path j associated to key route i is best, 0 otherwise
y_i	1 if key route i is best, 0 otherwise

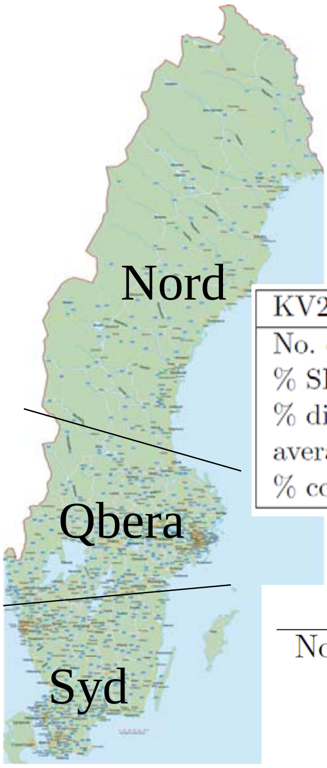
$$
\begin{array}{llllll}
\max & z = \sum_{i \in I} c_i y_i - \sum_{i \in I} \sum_{j \in J_i} \ell_{ij} x_{ij} & & & & \\
\text{s.t.} & \sum_{k \in K} (a_{ik} - b_{ijk}) w_k & \leq & M(1 - y_i) + \sum_{j' \in J_i} M x_{ij'}, & \forall\, i \in I, j \in J_i & (1) \\
& \sum_{k \in K} (b_{ijk} - b_{imk}) w_k & \leq & M(1 - x_{ij}) + M y_i + \sum_{j' \in J_i : j' \neq j} M x_{ij'}, & \forall\, i \in I, j, m \in J_i (j < m) & (2) \\
& y_i + \sum_{j \in J_i} x_{ij} & = & 1, & \forall\, i \in I & (3) \\
& w_k & \leq & w_l, & \forall\, k \in K, l \in L_k & (4) \\
& y_i, x_{ij} & \in & \{0, 1\}, & \forall\, i \in I, j \in J_i &
\end{array}
$$

”*Standard road*” comparison

Standard road		Sweden I	April 08	KV0.2	KV1.0	KV2
Road class	0	100	100	100	100	100
	1	100	100	100	100	100
	2	100	100	100	101	100
	3	110	117	111	111	107
	4	124	139	137	137	135
	5	163	212	171	172	168
	6	231	287	171	163	169
	7	187	424	333	358	358
	8	345	744	540	560	558
	9	527	963	762	805	730
	Timber route	-	-	124	124	133
	Passing route	-	-	-	-	88

BeLi1

Key routes – with one weight setting in three geographical regions

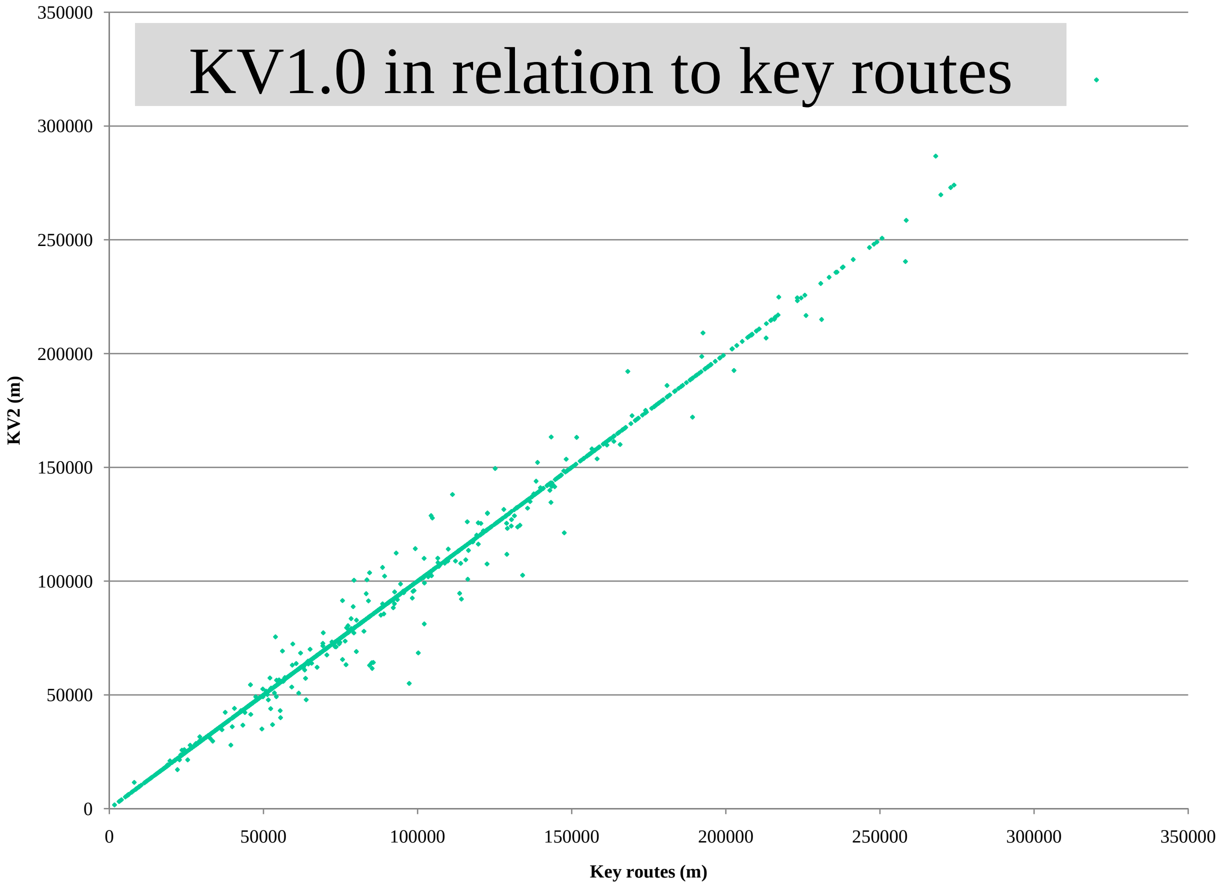


KV2.0	Sweden	Nord	Qbera	Syd
No. of shortest paths (SP) equal with key routes	1050	340	358	352
% SP equal with key routes	81.7	88.5	79.4	78.2
% distance of SP relative key routes	99.9	100.3	99.9	99.6
average absolute deviation of SP %	1.22	0.73	1.19	1.78
% common route, SP and key routes	93.9	94.1	94.2	92.6

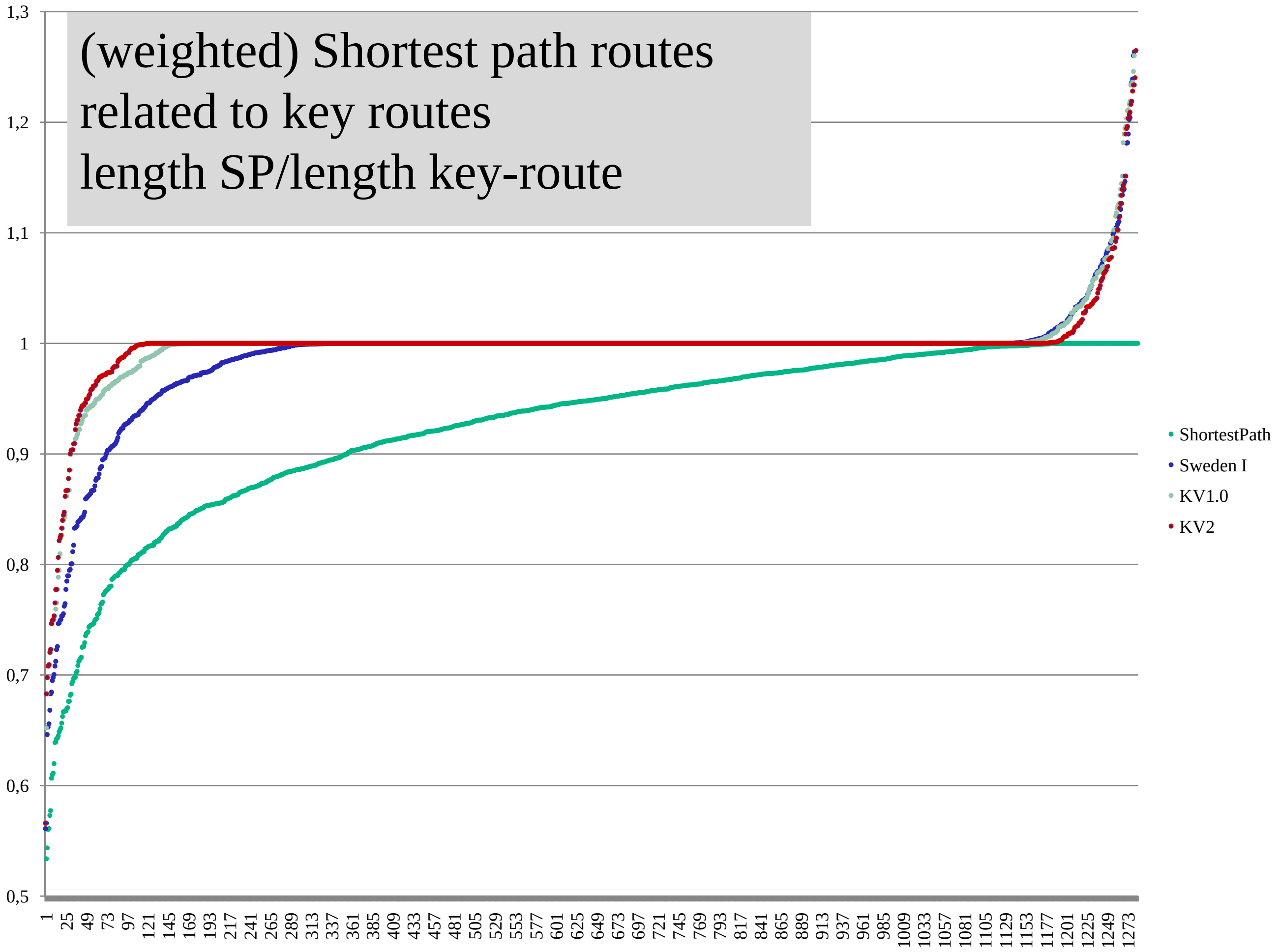
	Sweden I	April 08	KV0.2	KV1.0	KV2.0
No. SP = key routes	794	869	912	966	1050
SP = key routes	61.79	67.63	70.97	75.18	81.71
distance	99.10	101.68	99.48	99.92	99.86
average deviation	2.31	2.92	1.82	1.51	1.22
common route	88.89	89.44	91.00	92.38	93.87

BeLi1 Hela Sverige
bör vara
Sweden i tabellen längst ner!
Bertil Lidén; 2009-06-17

KV1.0 in relation to key routes

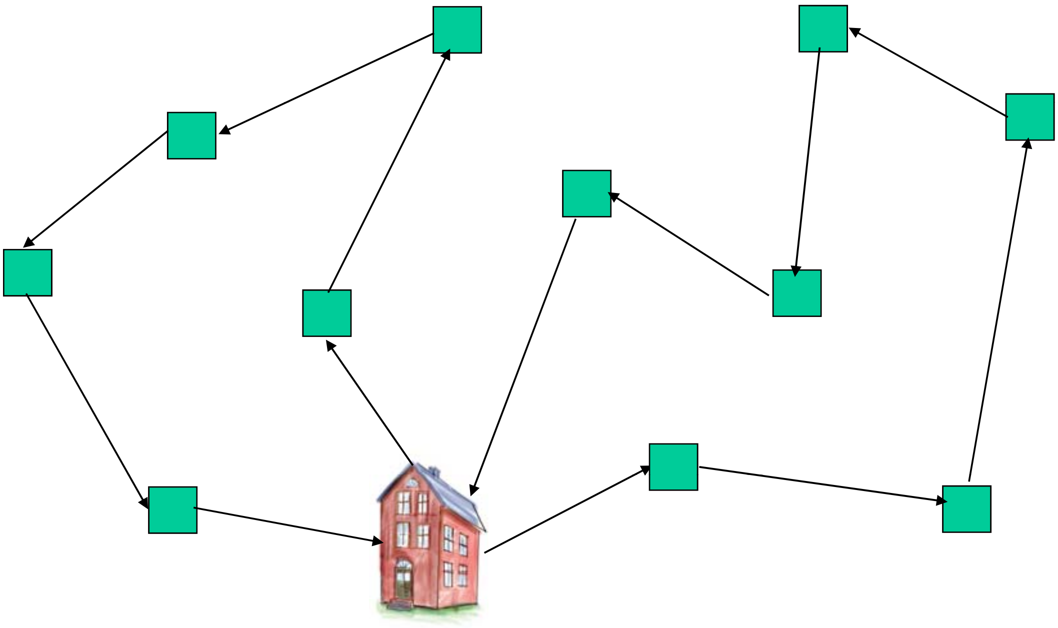


(weighted) Shortest path routes related to key routes length SP/length key-route

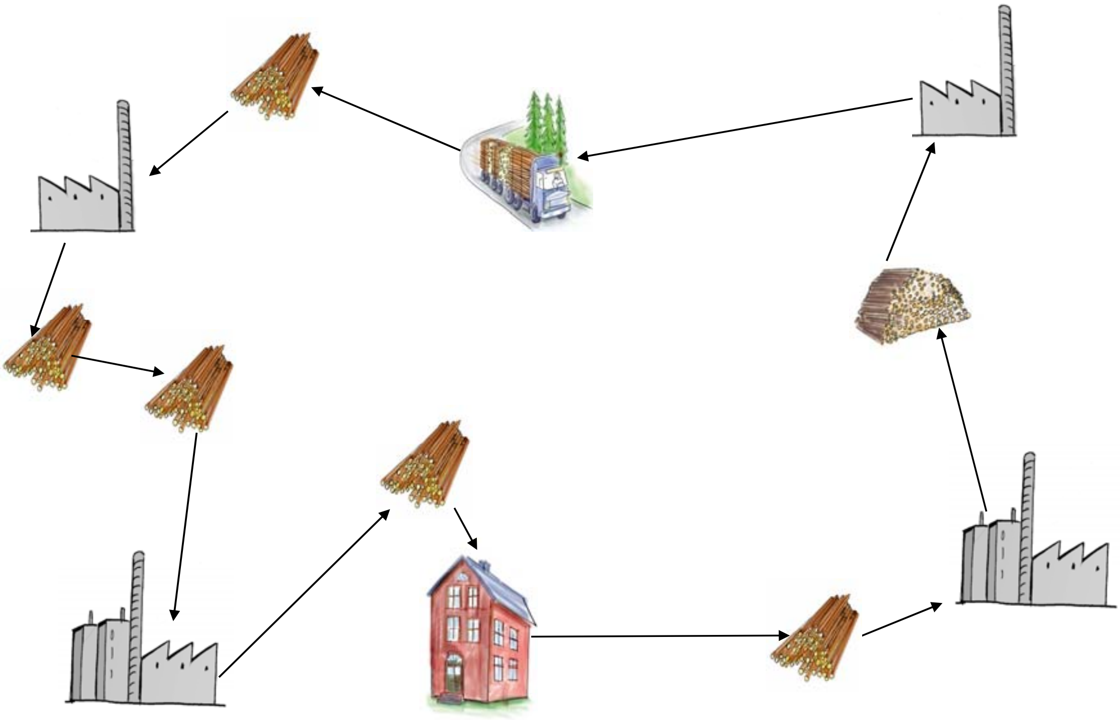


Operational planning – Routing

Standard vehicle routing problem



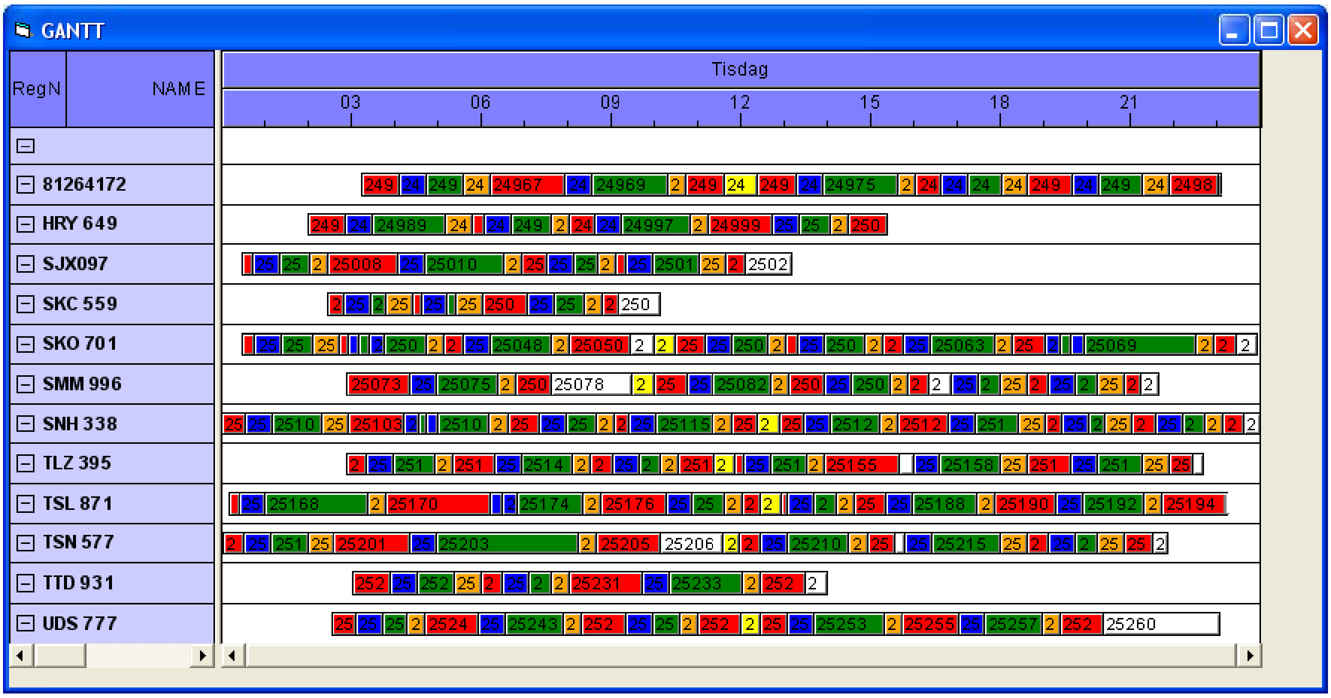
Forest vehicle routing problem



Challenges

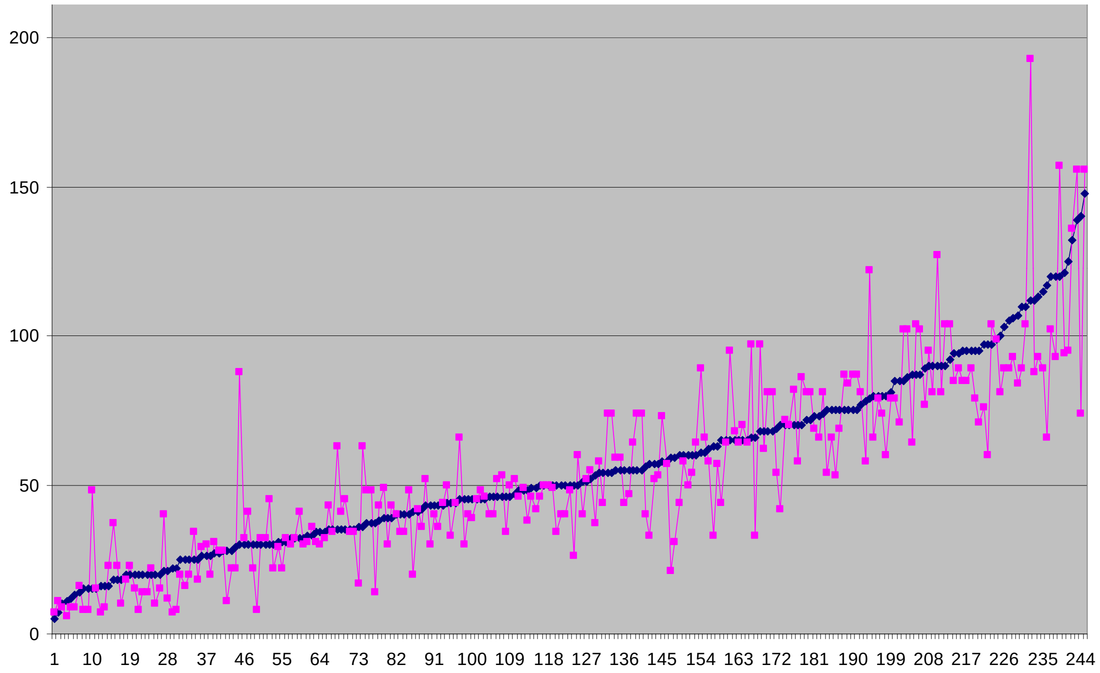
- No balance between supply and demand
- No destination given
- No full loads are available
- Multiple pickups necessary
- Different truck type
- Flexible change of driver
- Time estimates of routes
- Multiple time periods
- Accumulating demands
- Avoid cleaning

Gantt schedule for a day

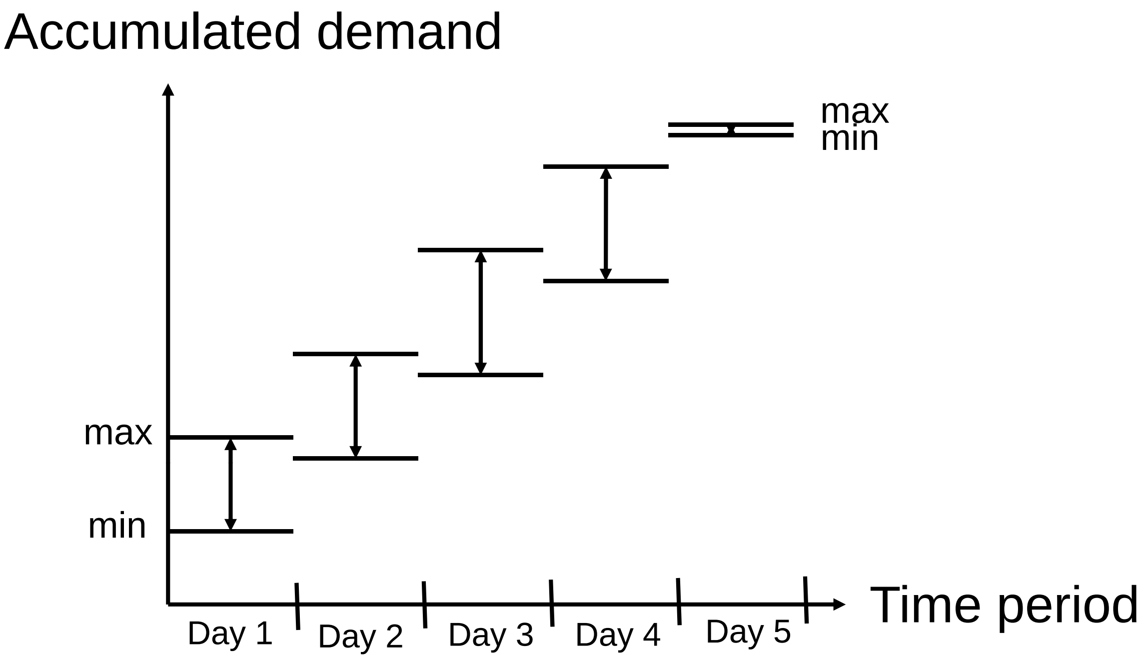


Gantt schedule for three days

Driving times – real and SNVDB



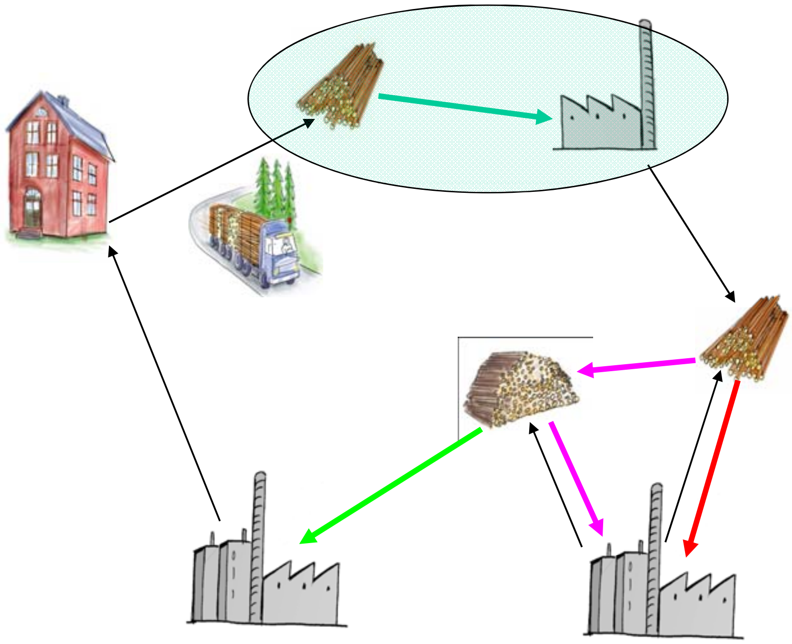
Industrial demand

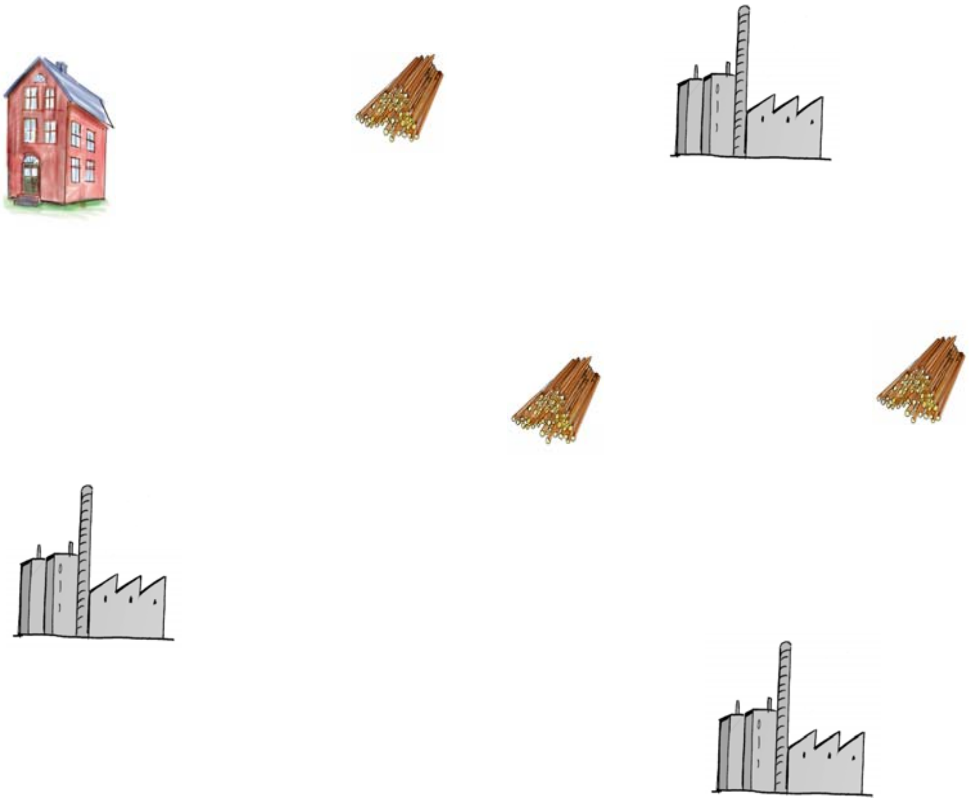


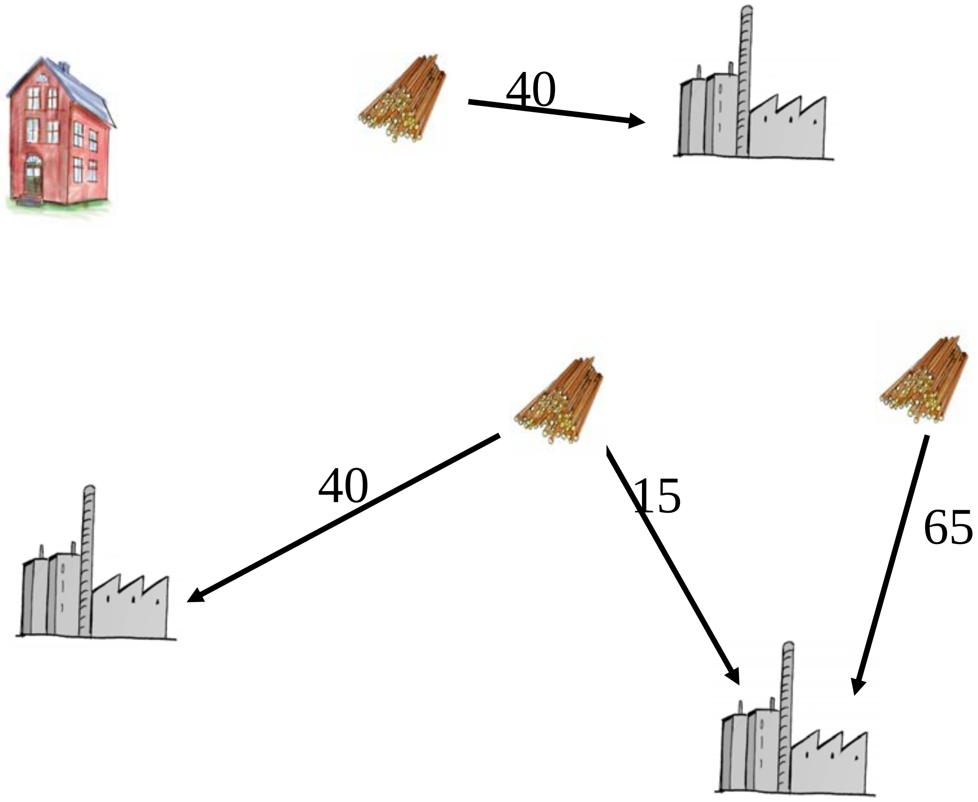
Two – phase method

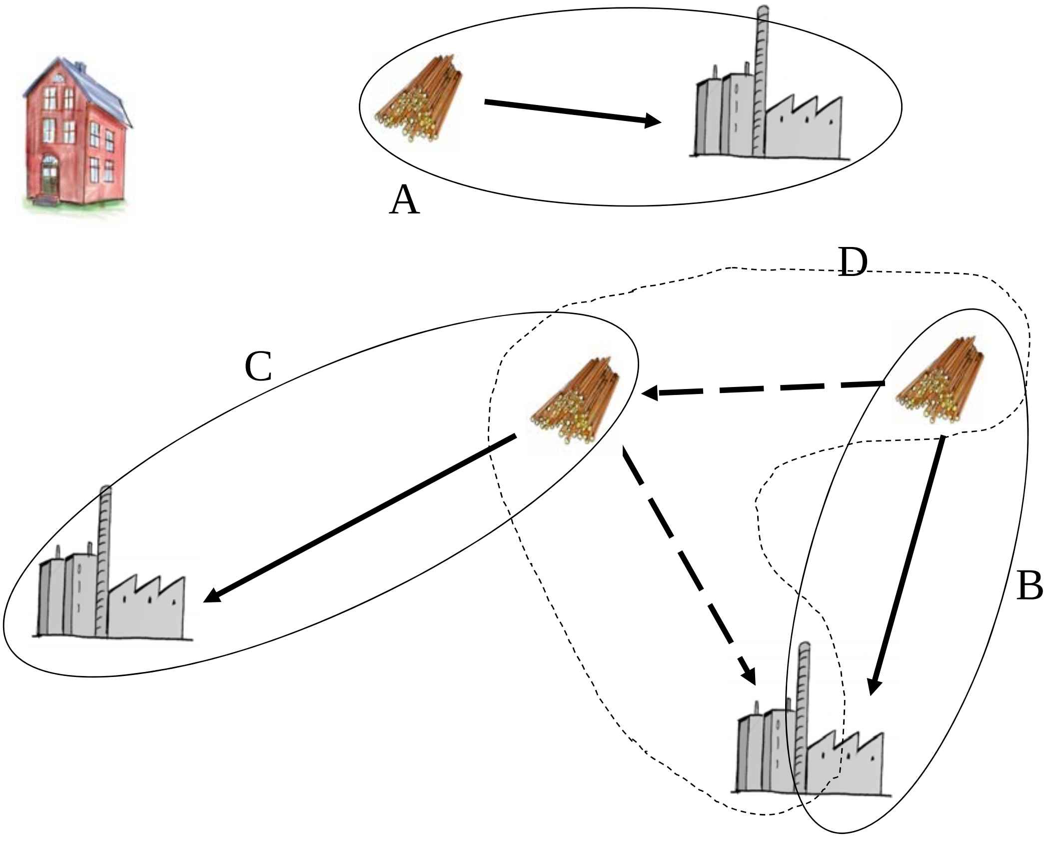
- Idea:
  - Use an efficient tabu search algorithm to form routes
- Phase 1:
  - Construct transport nodes mainly by solving a destination problem (LP) and form loads taken from supply point(s) to demand point
- Phase 2:
  - Use an extended and modified tabu search to construct routes where e.g. time windows and excess supply is taken care of

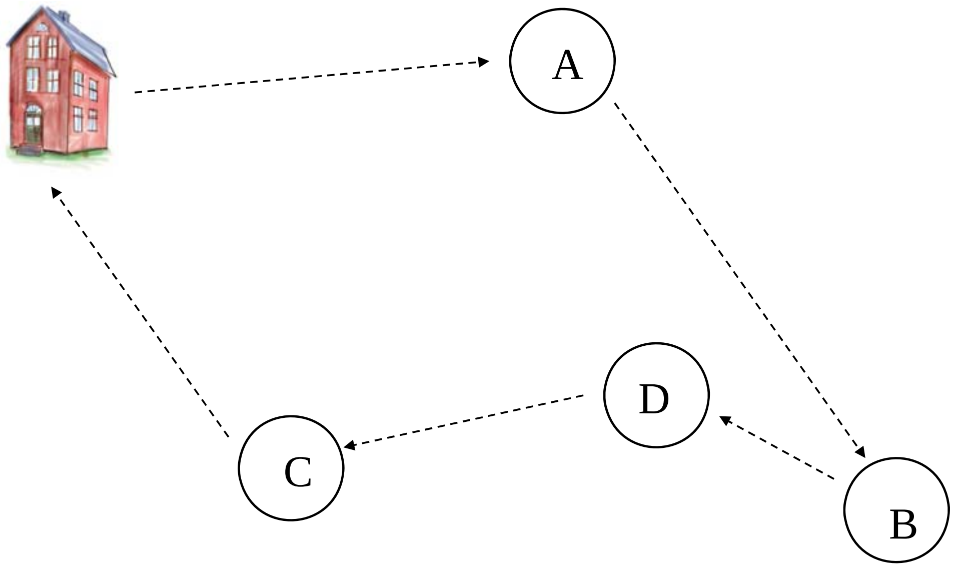
Transport nodes (example)

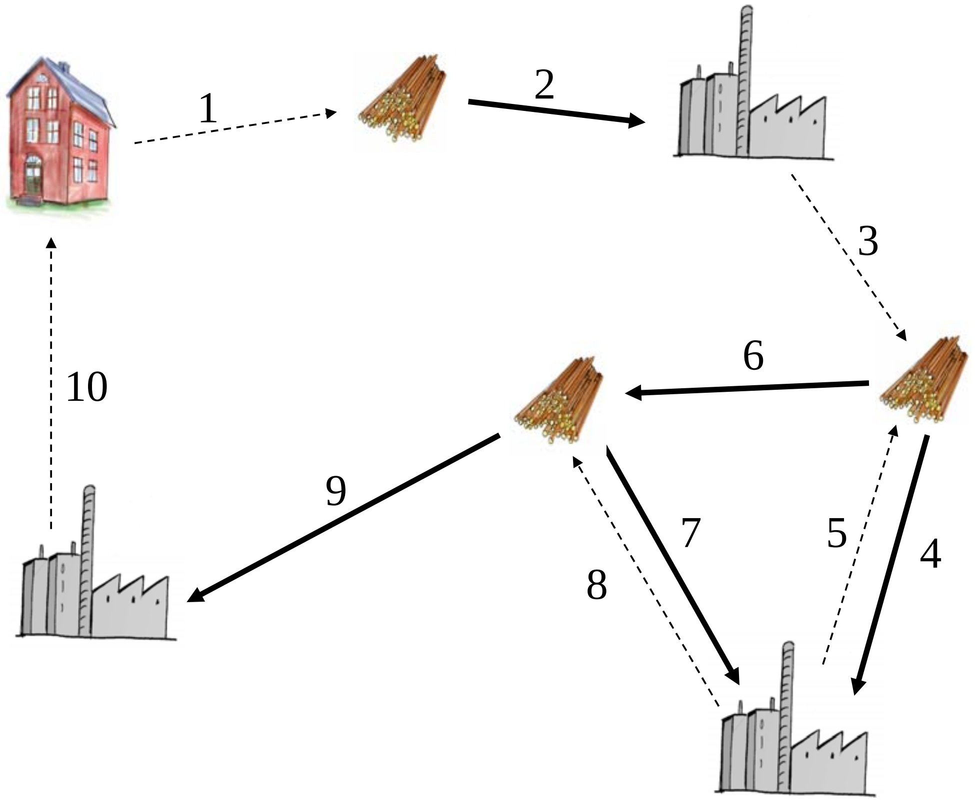





40
40
15
65


A
D
C
B


A
D
C
B


1
2
3
6
10
9
7
5
4
8

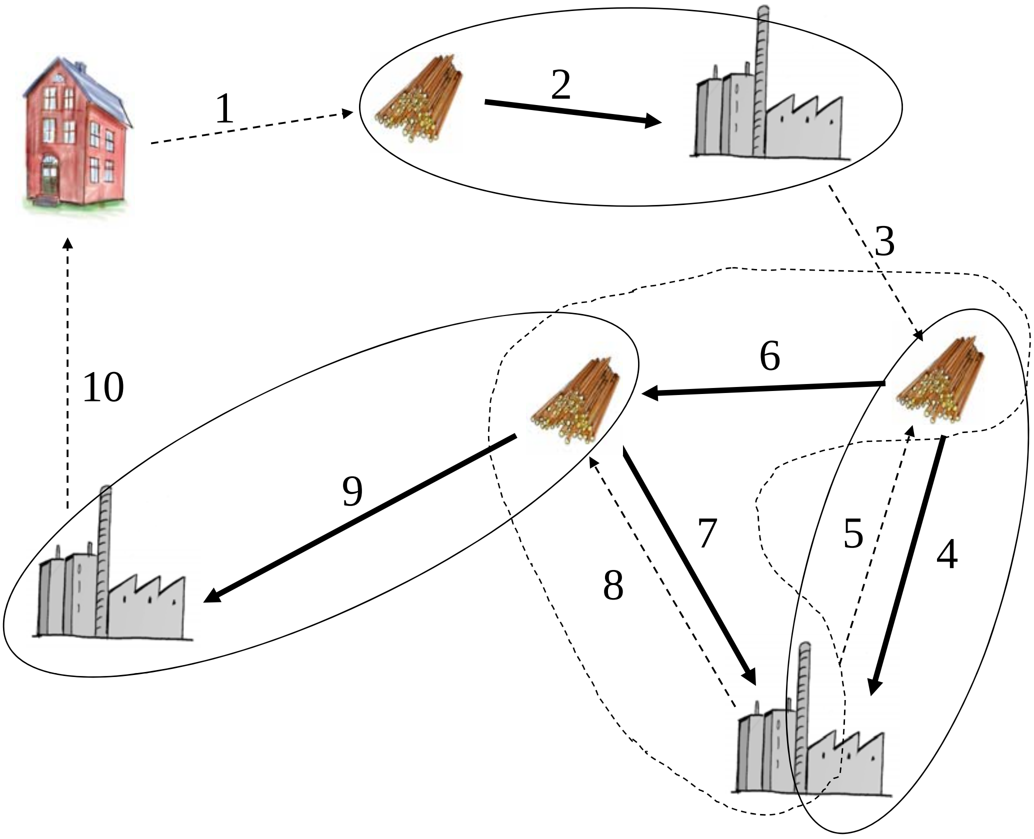


Table 1. Information on the case studies.

	Case 1	Case 2	Case 3	Case 4
Number of trucks	12	110	10	10
Number of hauliers (transporters)	8	79	3	8
Number of industries (demand nodes)	22	74	8	19
Number of demand points	24	113	8	19
Number of supply nodes	167	665	26	65
Number of supply points	410	2 531	48	98
Number of time periods (days)	3	5	3	3
Total demand volume (tons)	7 511	101 018	4 033	4 440
Total supply volume (tons)	33 331	261 260	4 033	4 440

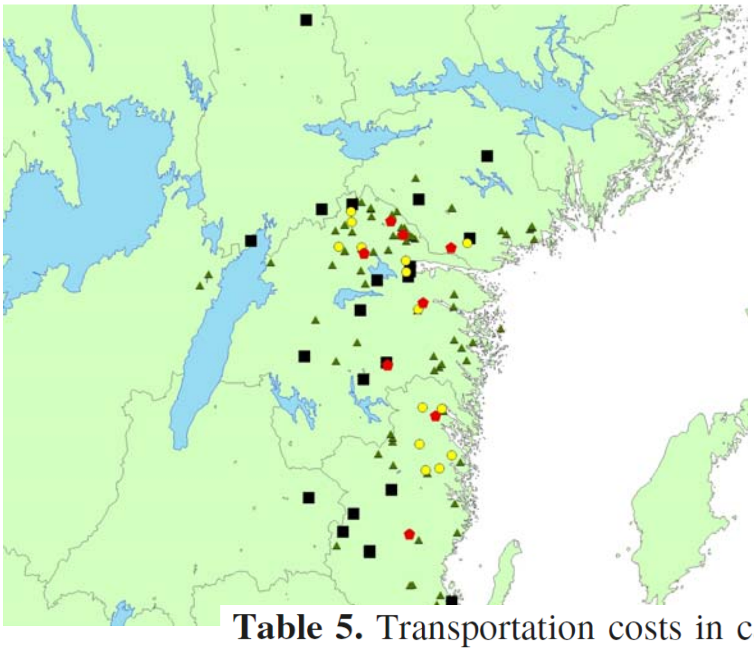
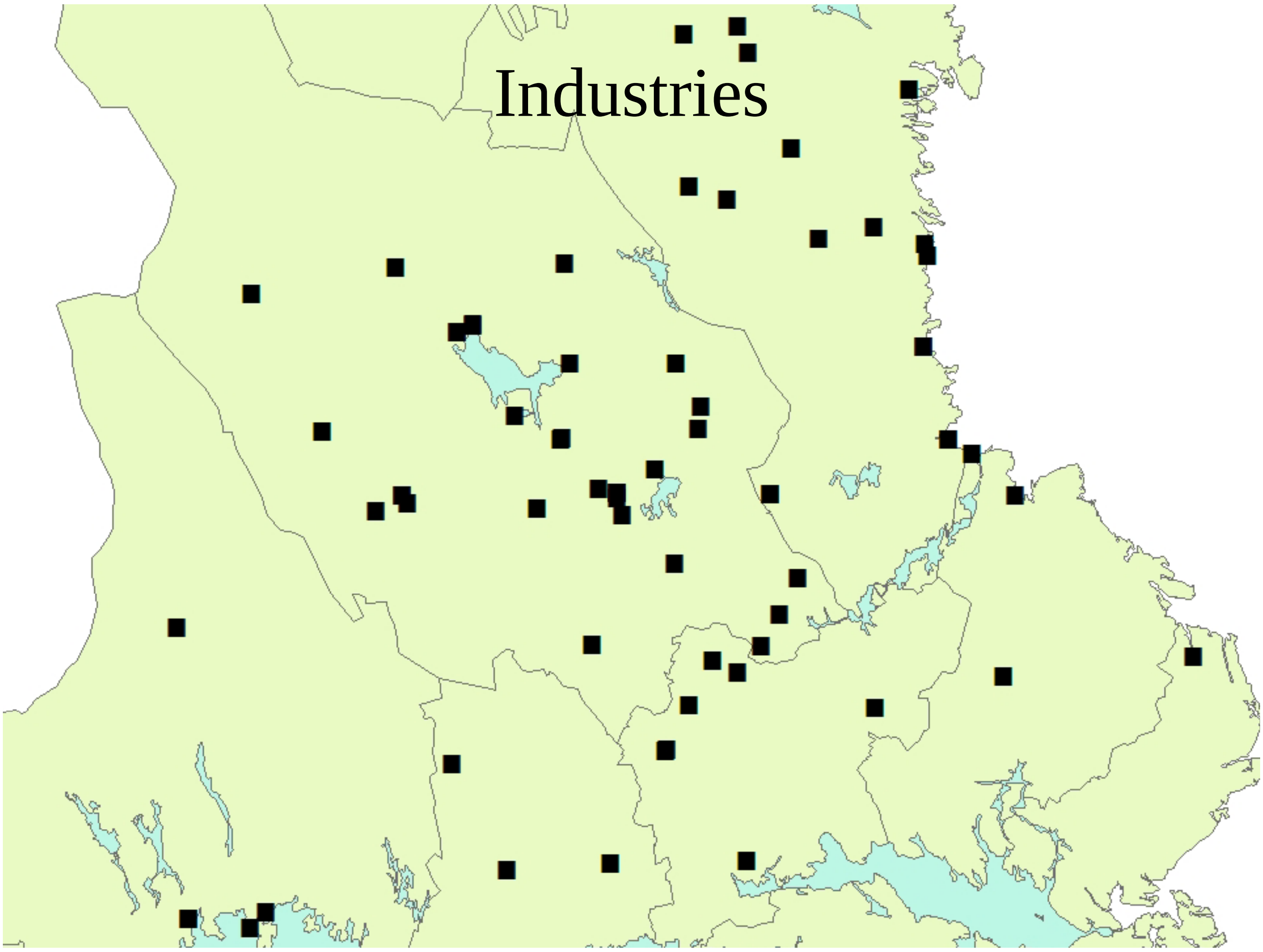


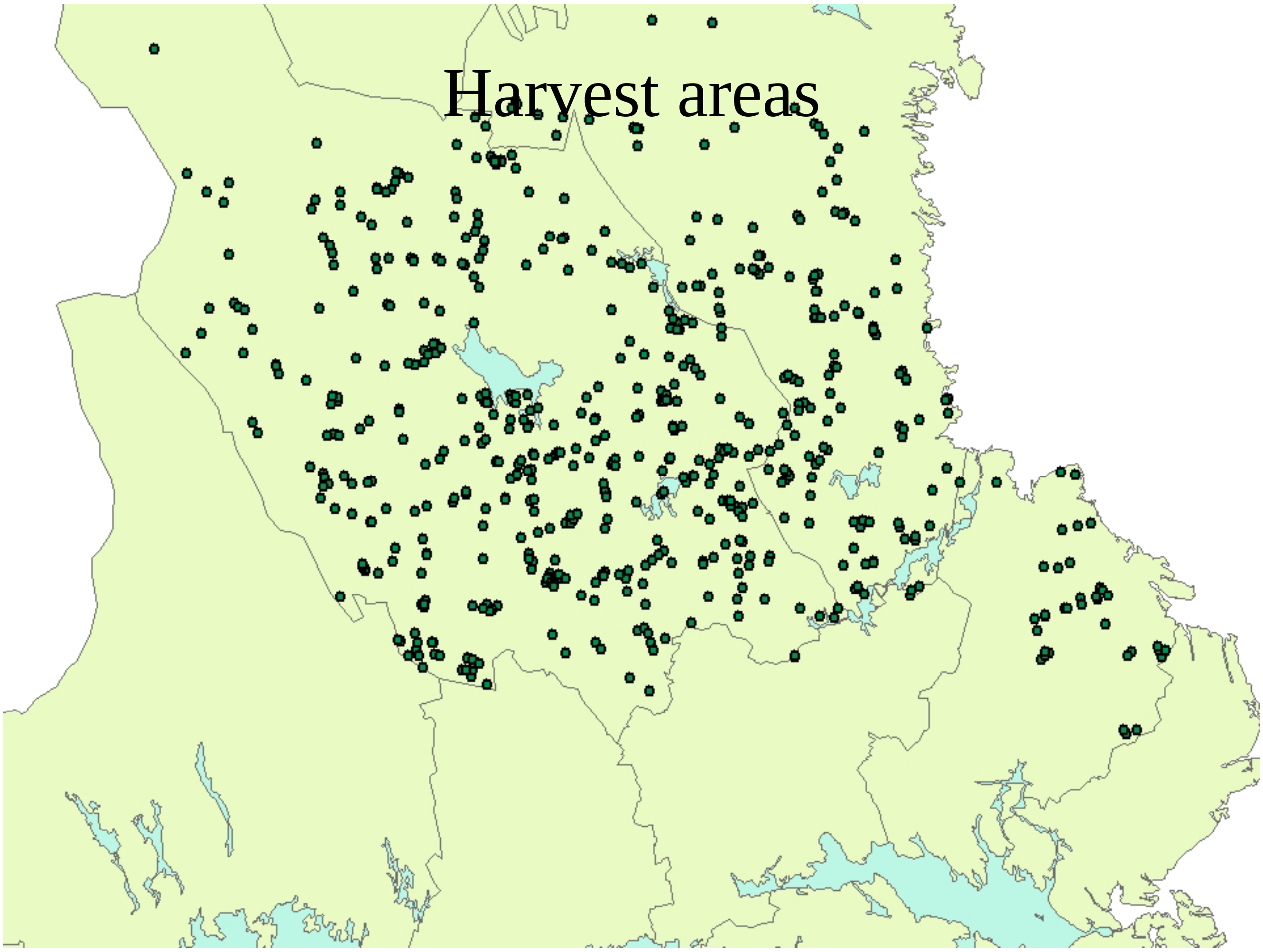
Table 5. Transportation costs in case study 4.

Case	Description	Transportation cost	Imp (%)
4-0	Manual	101 142	0
4-1	Eight areas, fixed destination	90 515	10.5
4-2	One area, fixed destination	84 568	16.4
4-3	One area, free destination	82 185	18.7

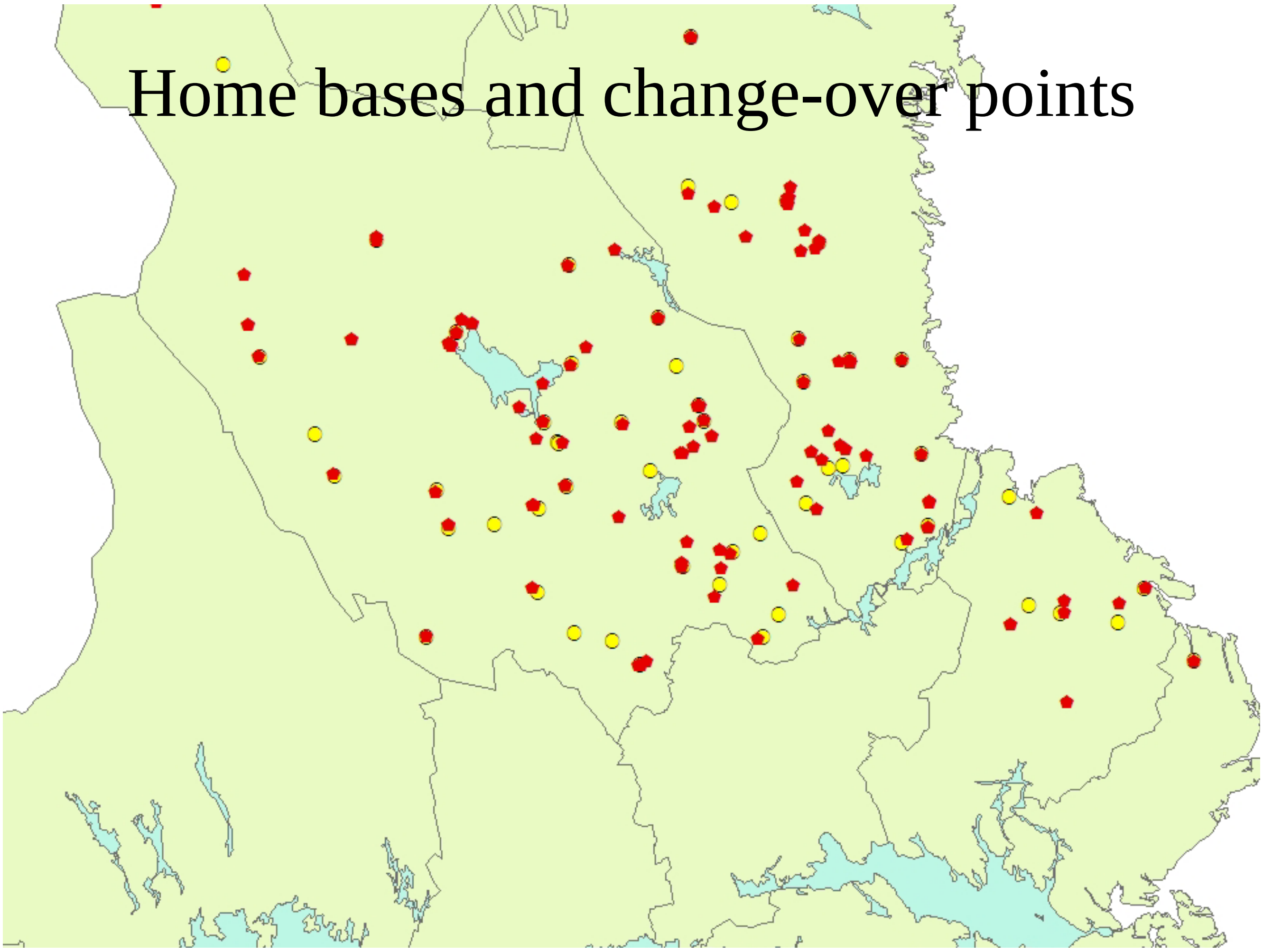
Industries



Harvest areas



Home bases and change-over points



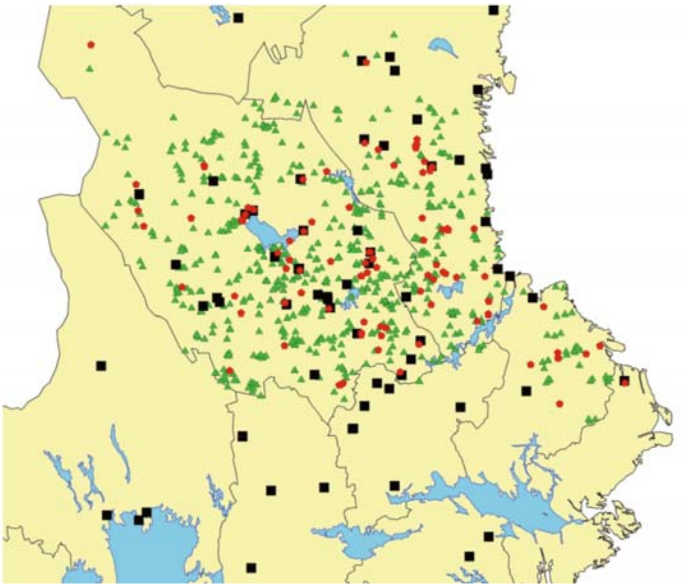
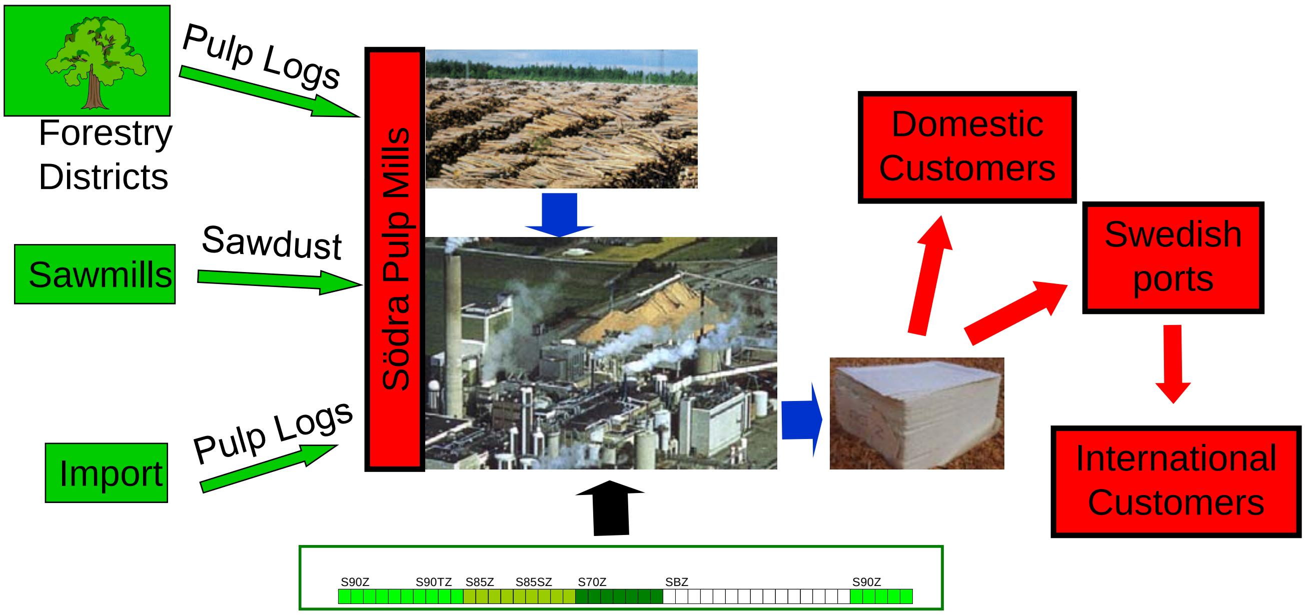


Table 3. Transportation costs in case study 2.

Case	Description	Transportation cost	Imp (%)
2-0	Base case	5 607 674	0
2-1	All industries opened 24 h/day	5 579 636	0.5
2-2	Loaders only load trucks without cranes	5 600 428	0.1
2-3	Decrease loading time with 20%	5 383 367	4.0
2-4	No fixed location for change of drivers	5 102 983	9.0

Operational planning –
Production & inventory planning

Supply chain structure



Forestry Districts

Pulp Logs

Sawmills

Sawdust

Import

Pulp Logs

Södra Pulp Mills

Domestic Customers

Swedish ports

International Customers

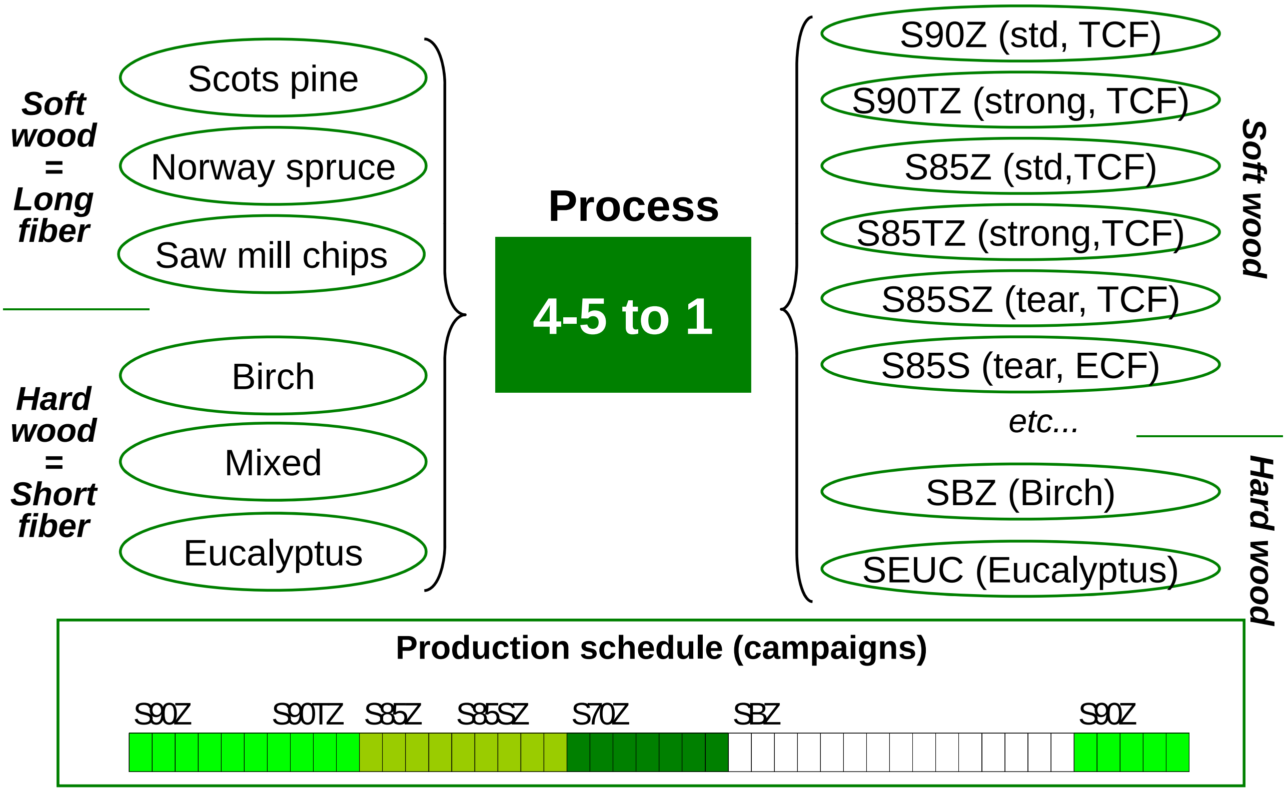
Production Plans

Supply chain - Transports

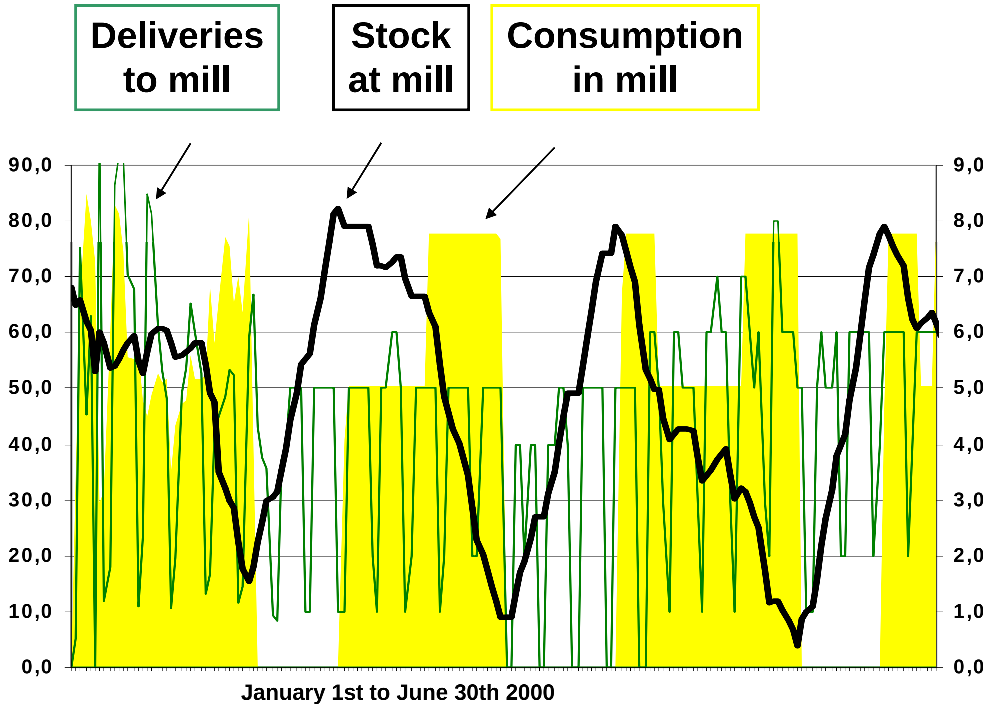
To the mills

From the mills

Södra Cell, Supply Chain – production recipes



Daily variation due to batch (campaign) production: Assortment pine



Challenges

- New planing process
- Large scale problem
- Campaign batching with harvesting, flows and inventories

Modeling work

- Minimise total supply chain costs
- Daily time discretisation (during 3 months)
- Aggregation of international demand
- Production variables
  - Column generation of full 3-month production plans
- Flow and Storage Variables
  - eg flow of log type *a* from forest district *d* to pulp mill *j* in time period *t*
  - eg storage of pulp product type *p* at pulp mill *j* in time period *t*
- Constraints
  - Flow conservation, flow/storage capacities, demand

$$l^F_{ia,t-1} + H_{iat} - \sum_{j \in M} x_{ijat} = l^F_{iat} \quad \forall i,a,t$$ Storage in forests

$$l^H_{jp,t-1} + w_{jpt} - v_{jpt} = l^H_{jpt} \quad \forall j,p,t$$ Storage at domestic harbours

$$\sum_{a \in A} f_{ja} \le T^M_j \quad \forall j$$ Inflow levels

$$0.9 f_{ja} \ge \sum_{i \in F} x_{ijat} \le 1.1 f_{ja} \quad \forall j,a,t$$ Inflow levels

$$\sum_{j \in M} \sum_{a \in A} x_{ijat} \le T^D_i \quad \forall i,t$$ Capacity levels in forests

$$\sum_{j \in M} y_{jdpt} = D^D_{dpt} \quad \forall d,p,t$$ Domestic demand

$$\sum_{j \in M} v_{jpt} = D^E_{pt} \quad \forall p,t$$ International demand

---

$$l^A_{ja,t-1} + \sum_{i \in F} x_{ijat} - \sum_{q \in Q_j} \sum_{r \in R_j} R^{in}_{jra} \delta_{jqrt} z_{jq} - l^A_{jat} = 0 \quad \forall j,a,t$$ dual: α_{jat}

$$l^P_{jp,t-1} + \sum_{q \in Q_j} \sum_{r \in R_j} R^{out}_{jrp} \delta_{jqrt} z_{jq} - w_{jpt} - \sum_{d \in D} y_{jdpt} - l^P_{jpt} = 0 \quad \forall j,p,t$$ dual: β_{jpt}

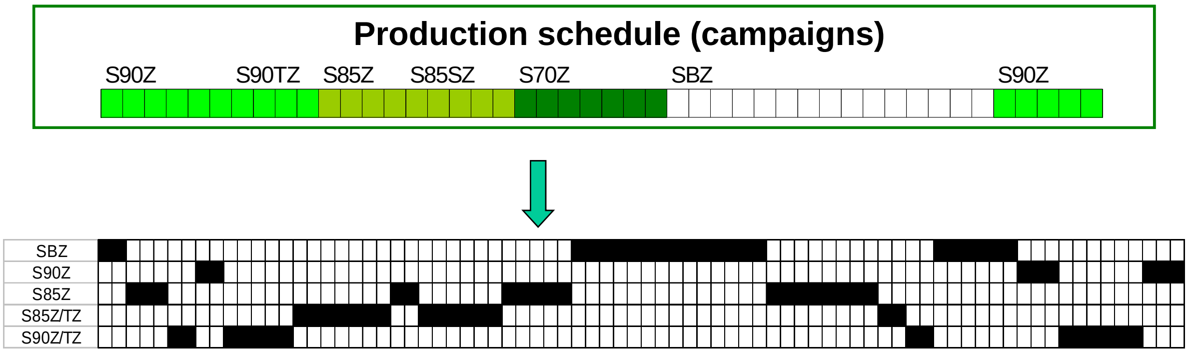
$$\sum_{q \in Q_j} z_{jq} = 1 \quad \forall j$$ dual: γ_j

R^{in}_{jra} = amount of assortment a used in one time period when running recipe r at pulp mill j

R^{out}_{jrp} = amount of product p produced in one time period when running recipe r at pulp mill j

δ_{jqrt} = 1 if recipe r runs in production plan q during time period t at pulp mill j, 0 otherwise

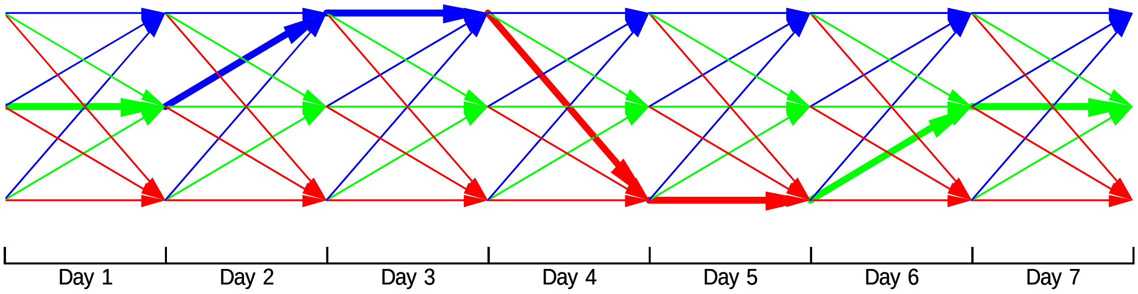
Solution method - column generation



Each campaign has a minimum and maximum duration

There is a fixed cost to switch products

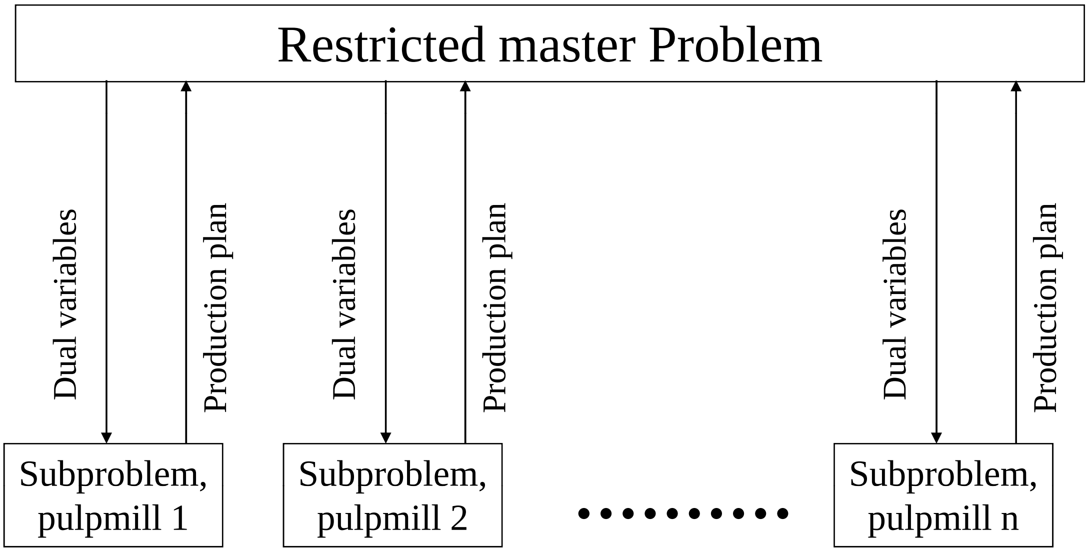
Solution balances transportation and setup costs



- Find best reduced cost production plan

$$\overline{c_{jq}} = C^{Z}_{jq} + \sum_{a,t,r} \delta_{jqrt} R^{in}_{jra} \alpha_{jat} - \sum_{p,t,r} \delta_{jqrt} R^{out}_{jrp} \beta_{jpt} - \gamma_{j}$$

- Subproblem: a shortest path problem
  - Arcs represent campaigns
  - Arc costs reflect dual prices on log / pulp inventory constraint and production / changeover costs



Restricted master Problem

Dual variables

Production plan

Dual variables

Production plan

Dual variables

Production plan

Subproblem, pulpmill 1

Subproblem, pulpmill 2

…………

Subproblem, pulpmill n

- Normal variable branching is not effective
  - There are very few 0/1-variables with value 1 (out of a very large number of possible)
  - The 1-branch is too strong (most often creating infeasible solutions)
  - The 0-branch is too weak (there are many similar production plans)
  - Procedure creates a huge Branch and Bound tree

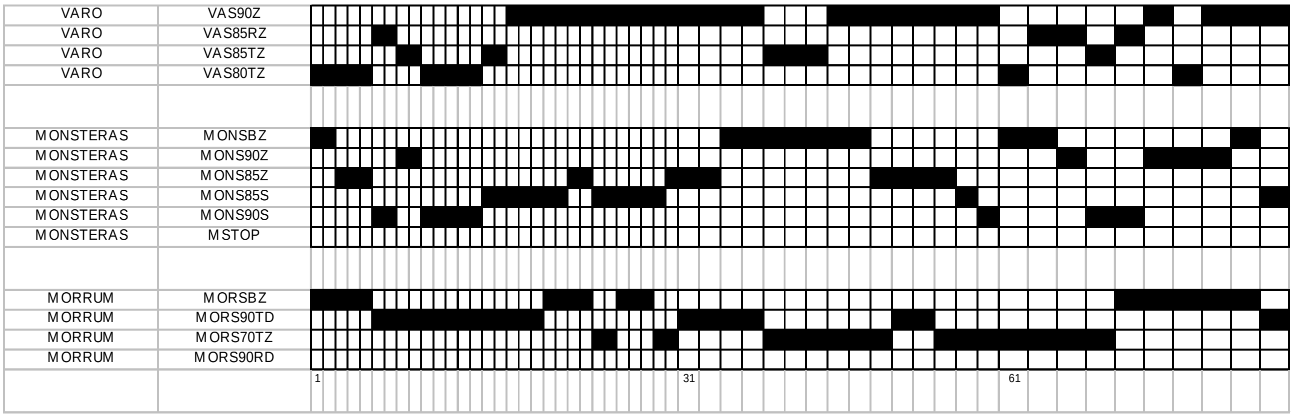
- Constraint branching enables a more efficient strategy
- Given a fractional LP-solution:
  - Sum the fractional usage of each receipe for each time period and pulp mill
  - choose the usage closest to 1.0 and branch on this
    - for example: use receipe S90Z at day 14 in mill Mönsterås
  - the branch is easy to implement in the subproblem i.e. simply remove certain arcs

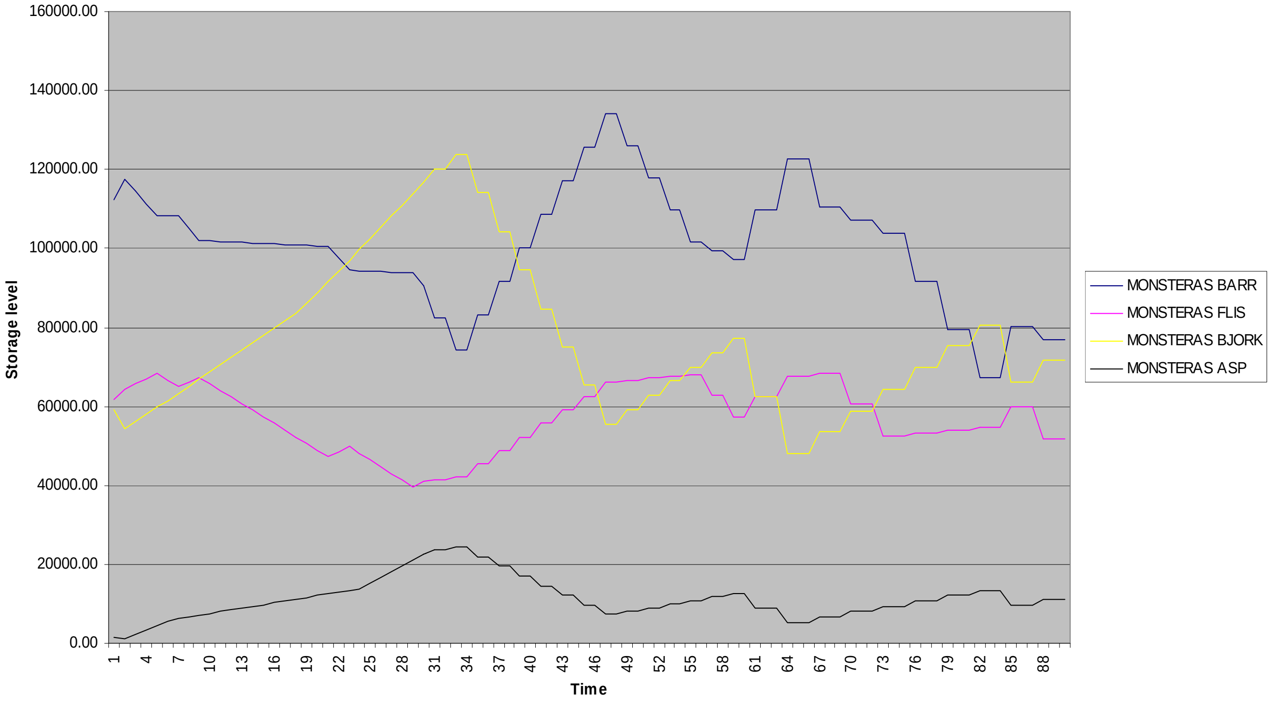
---

- Initial tests with 90 time periods gave a master problem with about 28,000 constraints and a unpractical solution time of several days …..
- New model with flexible aggregation of time periods
  - Main problem:
    - Example: Month 1: 1 day, Month 2: 2 days, Month 3: 3 days
  - Subproblem:
    - Column generation subproblem use most detailed level of time periods e.g. one day

- 3 Swedish pulp mills
- Comparison with manual plan
- 10 forest districts producing 4 log types
- 15 products (specific recipes per pulp mill)
- 90 days planning giving 90 time periods (or aggregated 55 time periods)
- Model:
  - Master: 9,500 constraints; 31,800 variables+1,500 generated
  - Sub: Production Plan Generator:
    - 300,000 arcs (full subproblem)
    - 5,500 arcs (lower bounds on campaign length)

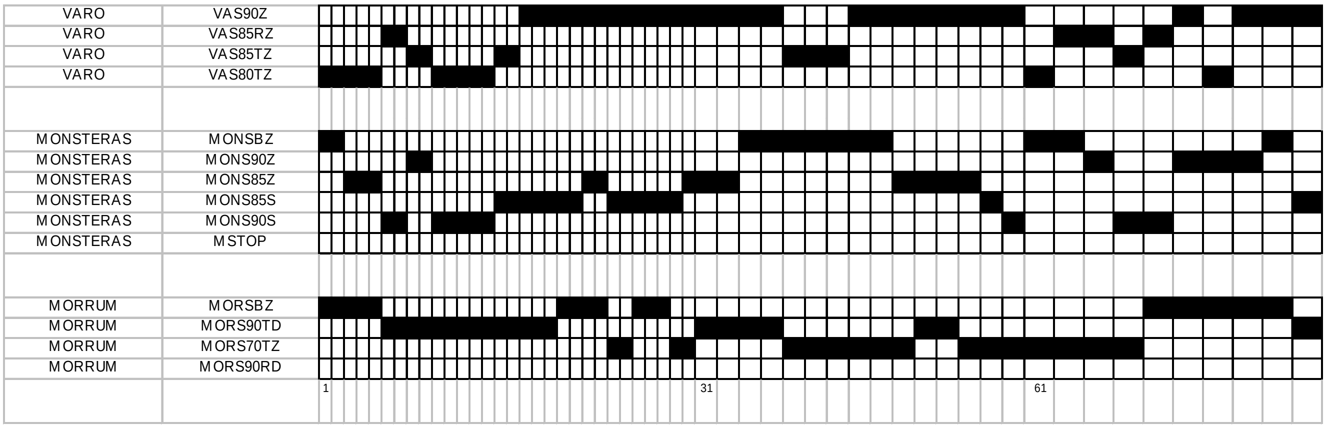
Production plans





Production plans

- Comparison with manual plans
  - Change over (manual 2.7 MSEK, opt 4,7 MSEK)



Total (manual 119.5 MSEK, opt 108.8 MSEK)

Tactical planning – Annual resource planning

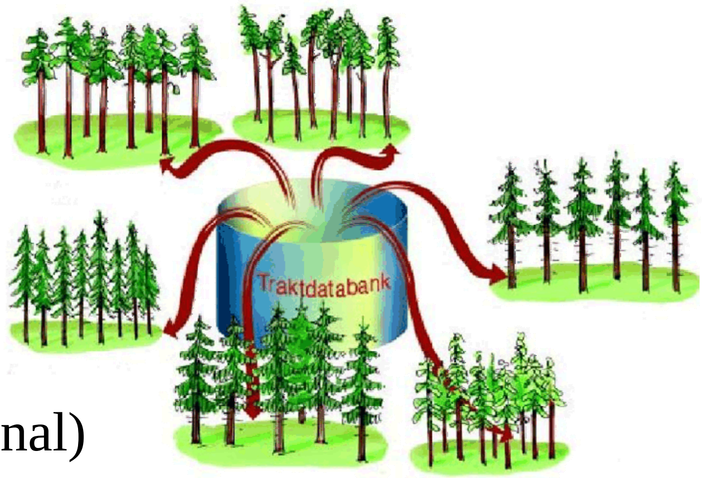
Case study at SCA

- 46 machines in 23 teams
- Harvesters: 22 small, 6 medium and 18 large
- Forwarders: 33 small, 10 medium and 8 large
- Each machine:
  - average capacity of 2400 hours
  - average cost 70-130 euros per hour
- 14 home bases
- 968 harvest areas with 8,971 hectares and 1,33 million cubic meters
- 4 seasons: winter 18 – weeks, spring – 9 weeks, summer – 16 weeks and autumn – 8 weeks

Harvest machines

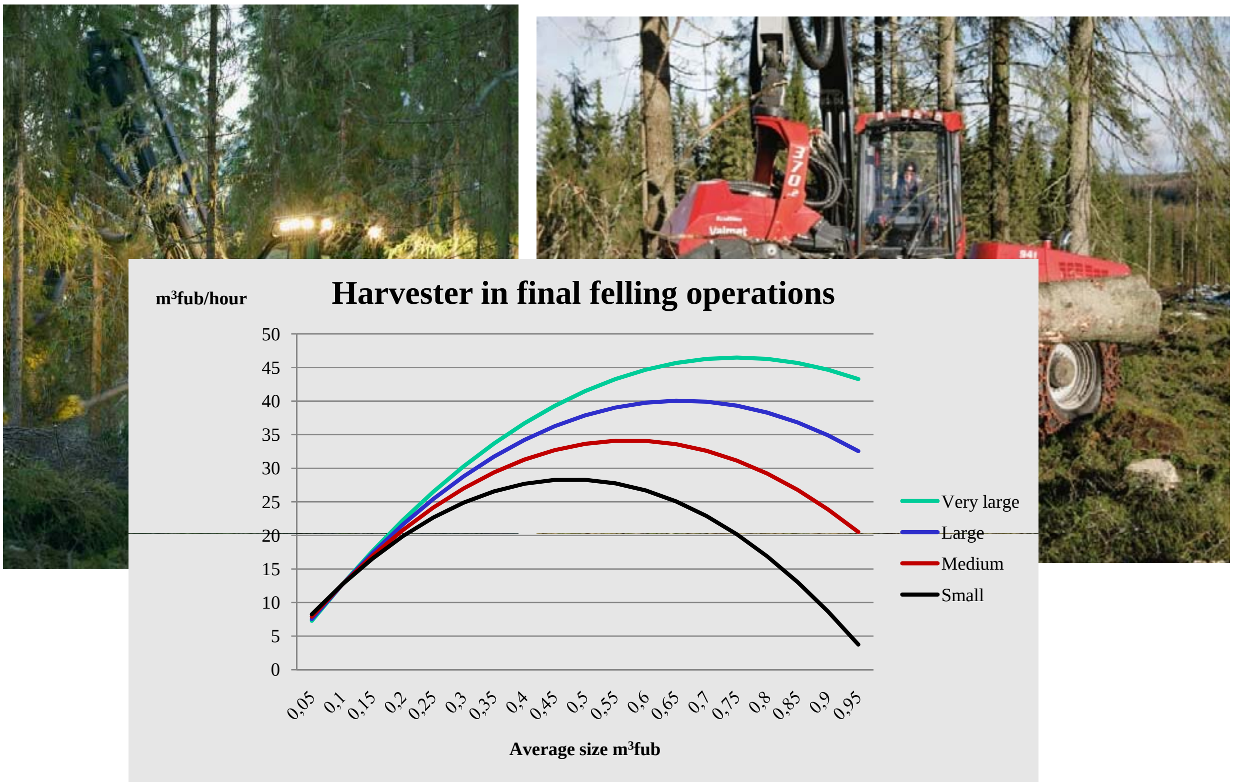
- Harvest team connection
- Machine type (harvester/ forwarder/ harwarder)
- Size (small, medium, large, very large)
- Efficiency (evaluated by the planner)
- Operating cost (SEK per hour)
- Available G_0 hours for thinning and final felling operations, respectively (combined for both)

Harvest areas

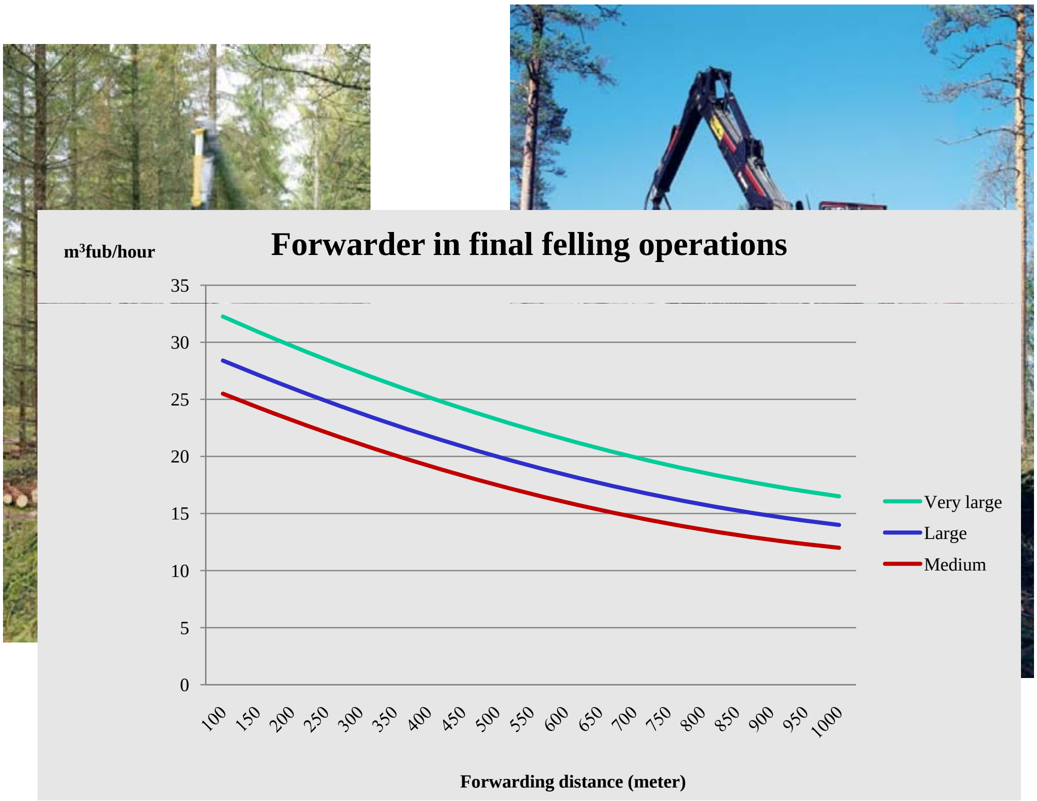


- GIS coordinates
- Ownership (own or external)
- Thinning or final felling operations
- Ground condition
- Area (square meter)
- Average size of a tree (cubic meter)
- Fowarding distance
- Volume
- Possible harvest periods (winter, spring, summer, autumn)

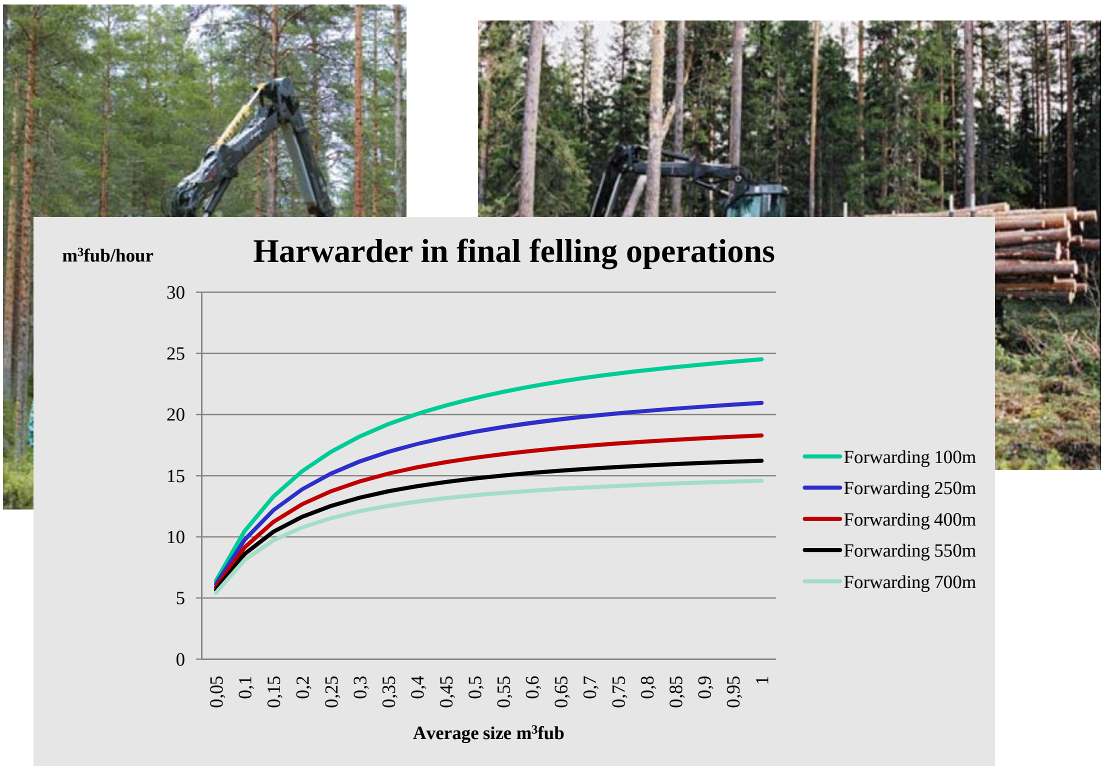
Performance functions harvesters



Performance functions - forwarders

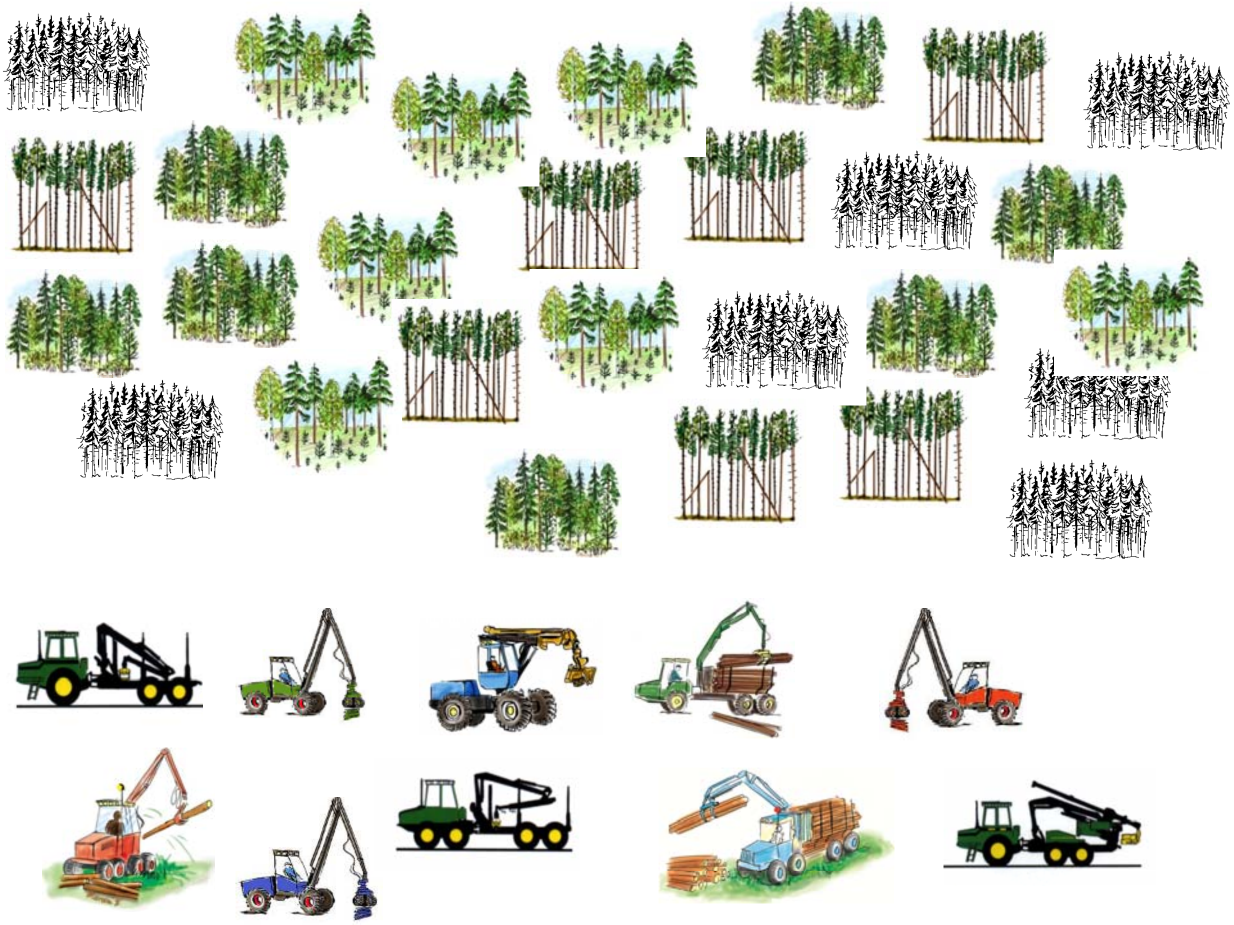


Performance functions - harwarder



Cost components

- Production cost
  - Harvesting cost
  - Forwarding cost
- Travel cost
  - Daily travel between home base and harvest area (based on km)
- Moving cost
  - Moving of equipment between harvest areas
  - Depending on distance:
    - Short: machine moves itself
    - Longer. machine put on a trailer



Optimization model - decisions

- Allocate machines to harvest areas
  - each harvest areas has two tasks: harvesting and forwarding
  - Note that each forwarder and harvester do only one task while a harwarders does two.
- Schedule and route the machines given their allocated harvest areas over the year
- Model: integrated location and routing problem

$$
\begin{array}{lcl}
y_{mit} & = & \begin{cases} 1, & \text{if machine } m \text{ is used in harvest area } i \text{ during season } t \\ 0, & \text{otherwise} \end{cases} \\
s_i & = & \begin{cases} 1, & \text{if harvest area } i \text{ is in the pool} \\ 0, & \text{otherwise} \end{cases} \\
x_{mjk} & = & \begin{cases} 1, \text{ if machine } m \text{ moves between harvest area } i \text{ and harvest area } j \\ 0, \text{ otherwise} \end{cases} \\
o_{mtt'} & = & \text{overlap time used for machine } m \text{ between time period } t \text{ and } t'
\end{array}
$$

$$
\begin{aligned}
z_{production} &= \sum_{m \in M} \sum_{i \in I_m} \sum_{t \in T} (c^h_{mi} + c^f_{mi}) y_{mit} \\
z_{traveling} &= \sum_{m \in M} \sum_{i \in I_m} \sum_{t \in T} h_{mi} y_{mit} \\
z_{moving} &= \sum_{m \in M} \sum_{i \in I_m} \sum_{j \in A} g_{mij} x_{mij} \\
z_{pool} &= \sum_{i \in I} \gamma v_i s_i
\end{aligned}
$$

$$
\text{min} \quad z = \quad z_{production} + z_{traveling} + z_{moving} + z_{pool}
$$

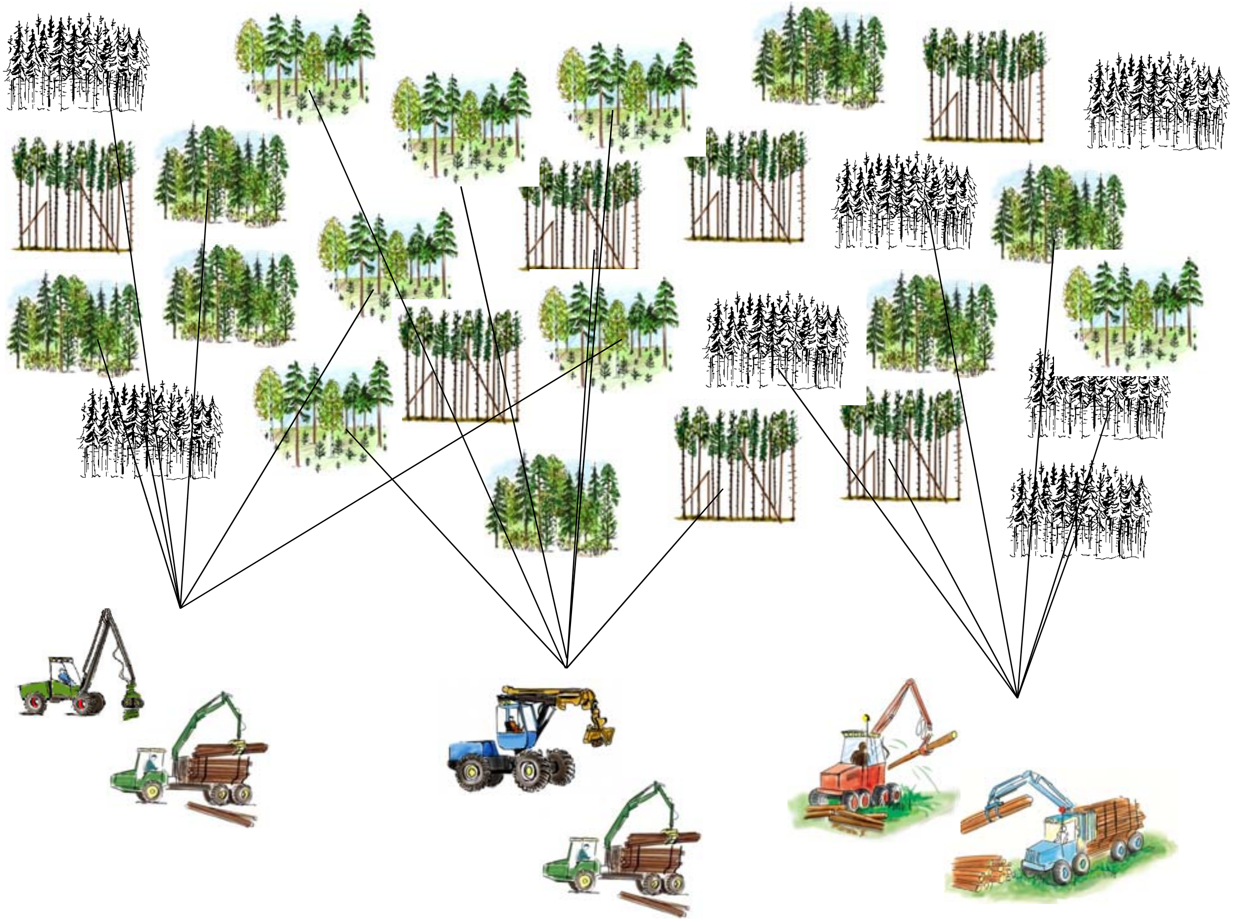
$$
\begin{array}{lrcll}
\text{s.t.} & \sum_{m \in M_h} \sum_{t \in T} y_{mit} + \sum_{m \in M_d} \sum_{t \in T} y_{mit} + s_i & = & 1, & i \in I & (1) \\
& \sum_{m \in M_f} \sum_{t \in T} y_{mit} + \sum_{m \in M_d} \sum_{t \in T} y_{mit} + s_i & = & 1, & i \in I & (2) \\
& \sum_{i \in I_m} (t^h_{mi} + t^f_{mi}) y_{mit} & \leq & t_{mt}, & m \in M, t \in T & (3) \\
& \sum_{t \in T} (\sum_{i \in I_f} (t^h_{mi} + t^f_{mi}) y_{mit} - & & & & \\
& a^w_m \sum_{i \in I} (t^h_{mi} + t^f_{mi}) y_{mit}) & \geq & 0, & m \in M, w = t, f & (4) \\
& \sum_{m \in M} \sum_{t \in T} \sum_{i \in I_e} v_m s_m & \leq & b^w, & w = t, f & (5) \\
& \sum_{m \in M} \sum_{i \in I_m} \sum_{j \in I_m} x_{mij} & = & \sum_{t \in T} y_{mjt}, & j \in I & (6) \\
& \sum_{m \in M} \sum_{i \in I_m} \sum_{j \in I_m} x_{mij} & = & \sum_{t \in T} y_{mit}, & i \in I & (7) \\
& \sum_{i \in S} \sum_{j \in S} x_{mij} & \leq & \mid S \mid -1, & 2 \leq \mid S \mid \leq \mid I \mid, m \in M & (8) \\
& y_{mit} & & \in \{0,1\}, & \forall m \in M, i \in I_m, t \in T & (9) \\
& x_{mij} & & \in \{0,1\}, & \forall m \in M, i, j \in I_m & (10) \\
& s_i & & \in \{0,1\}, & \forall i \in I & (11) \\
& y_{mit} & & = 0, & \forall m \in M, i \notin I_m, t \in T & (12)
\end{array}
$$

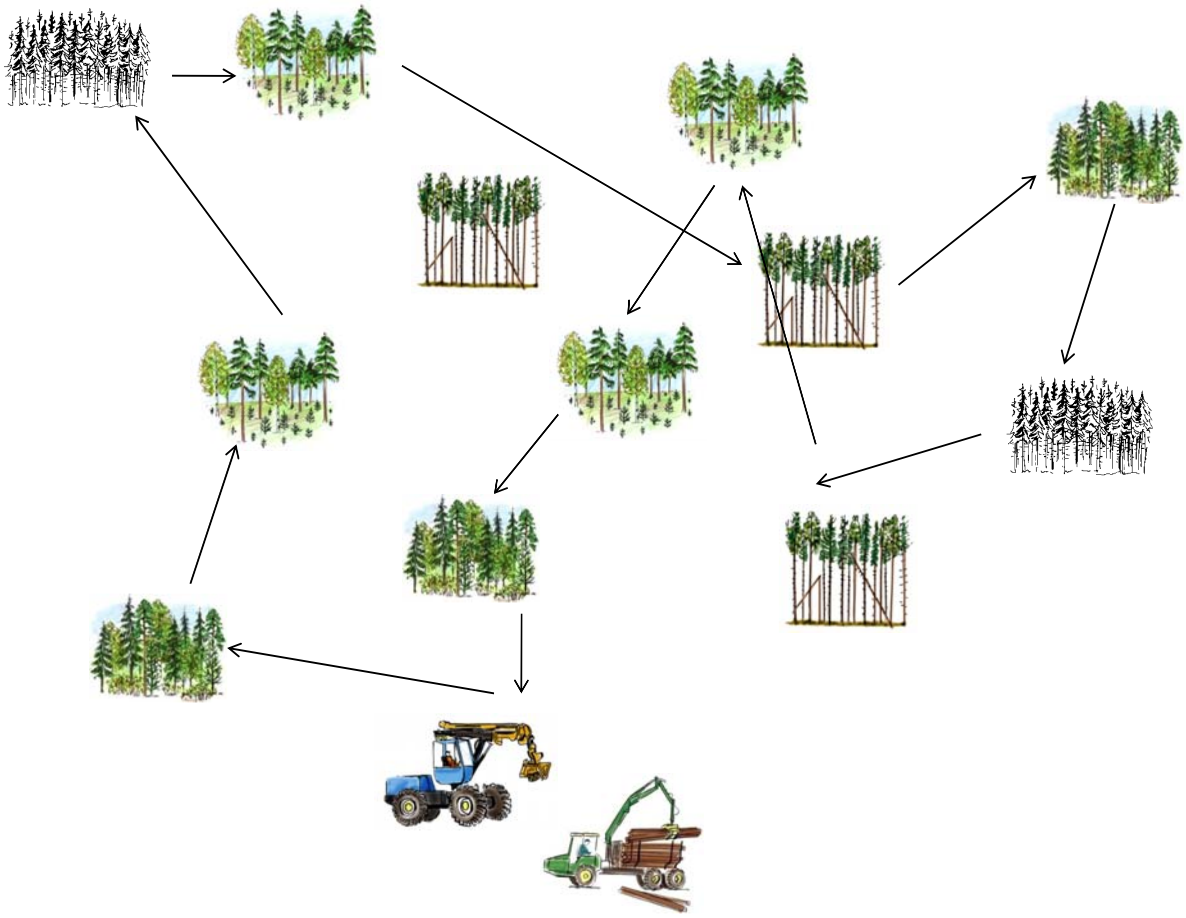
Optimization method

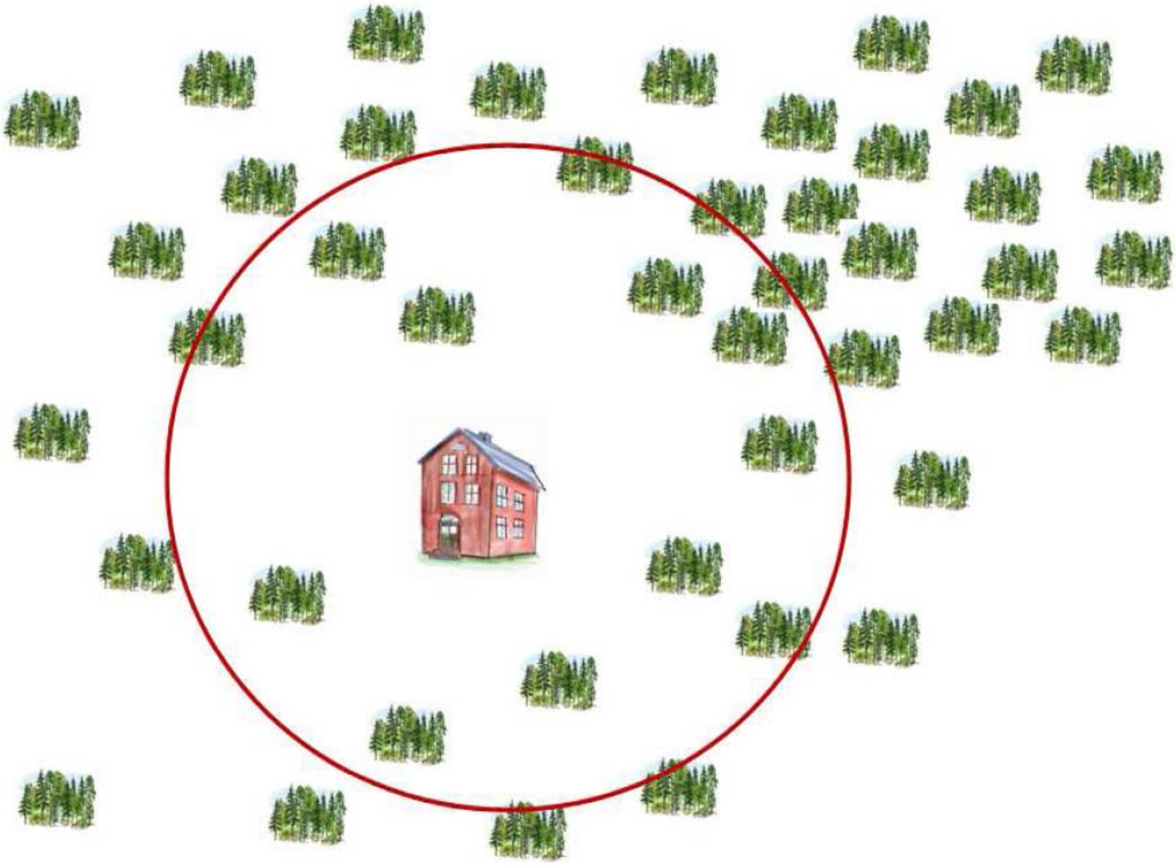
- We solve the problem in two phases:
- Phase 1: (Generalized assignment problem)
  - Decisions: Allocation of machines to harvest areas
  - Objective: production + traveling costs + pool cost + artifical to approximate moving cost
  - Constraints: all except scheduling

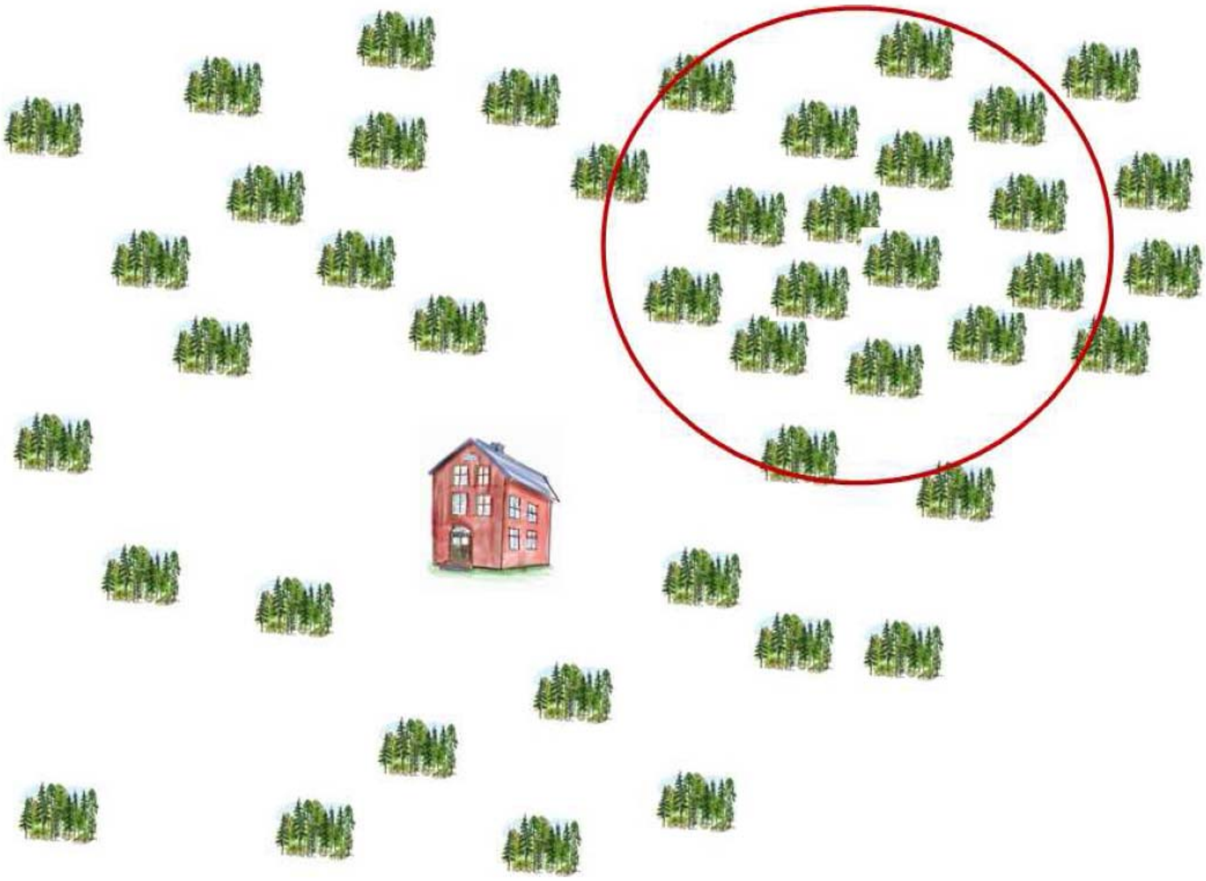
$$\sum_{i\in I_m} \alpha_1 * \alpha_2^{d[i,a]} y_{mit}$$

- Phase 2: (Traveling salesman problem)
  - Decisions: schedule the harvest areas allocated to each machine (take into accound seasons & overlap)
  - Objective: moving cost
  - Constraints: scheduling constraints, seasons & overlap



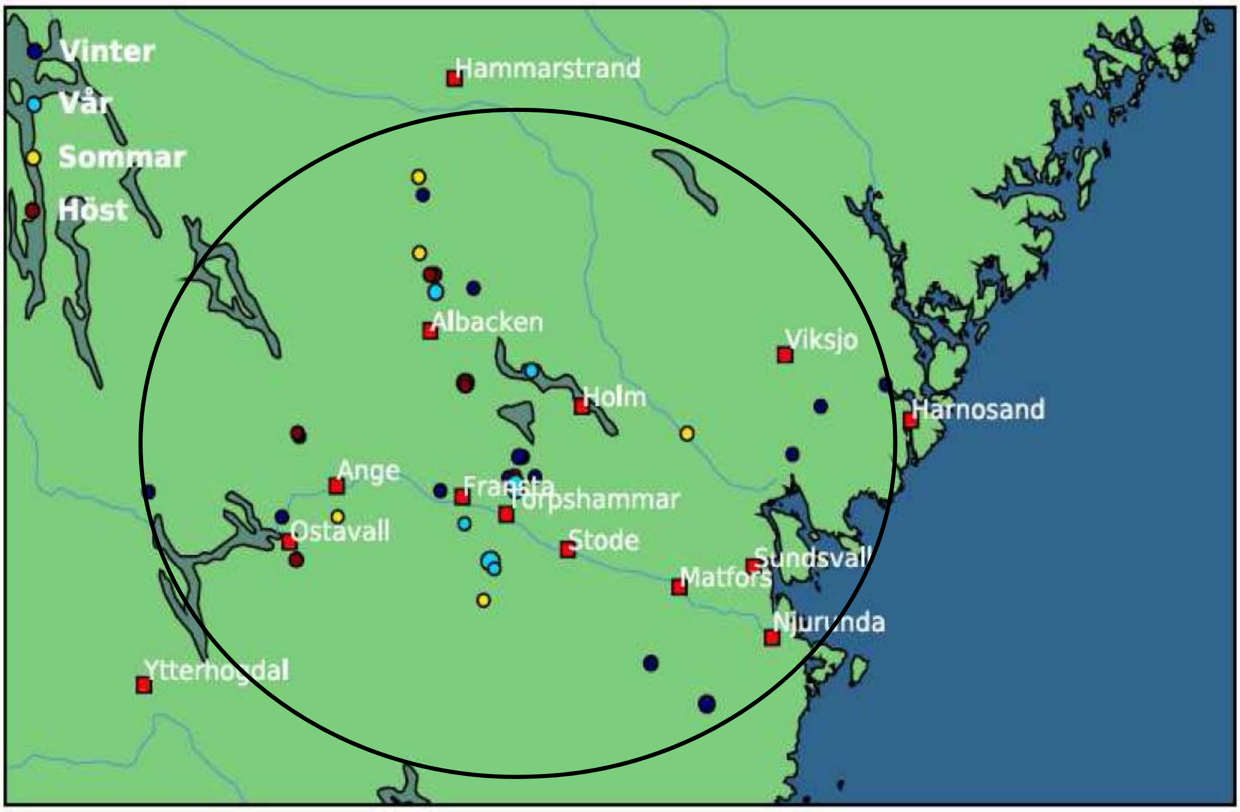






Implementaion and result generation

- Implementation using AMPL (with CPLEX) & Excel
- Input data:
  - one excel sheet
- Optimization
  - AMPL (model and developed method)
- Output result:
  - One Excel sheet with specified results
  - Aggregated result down to detailed
  - Maps with allocation and season scheduling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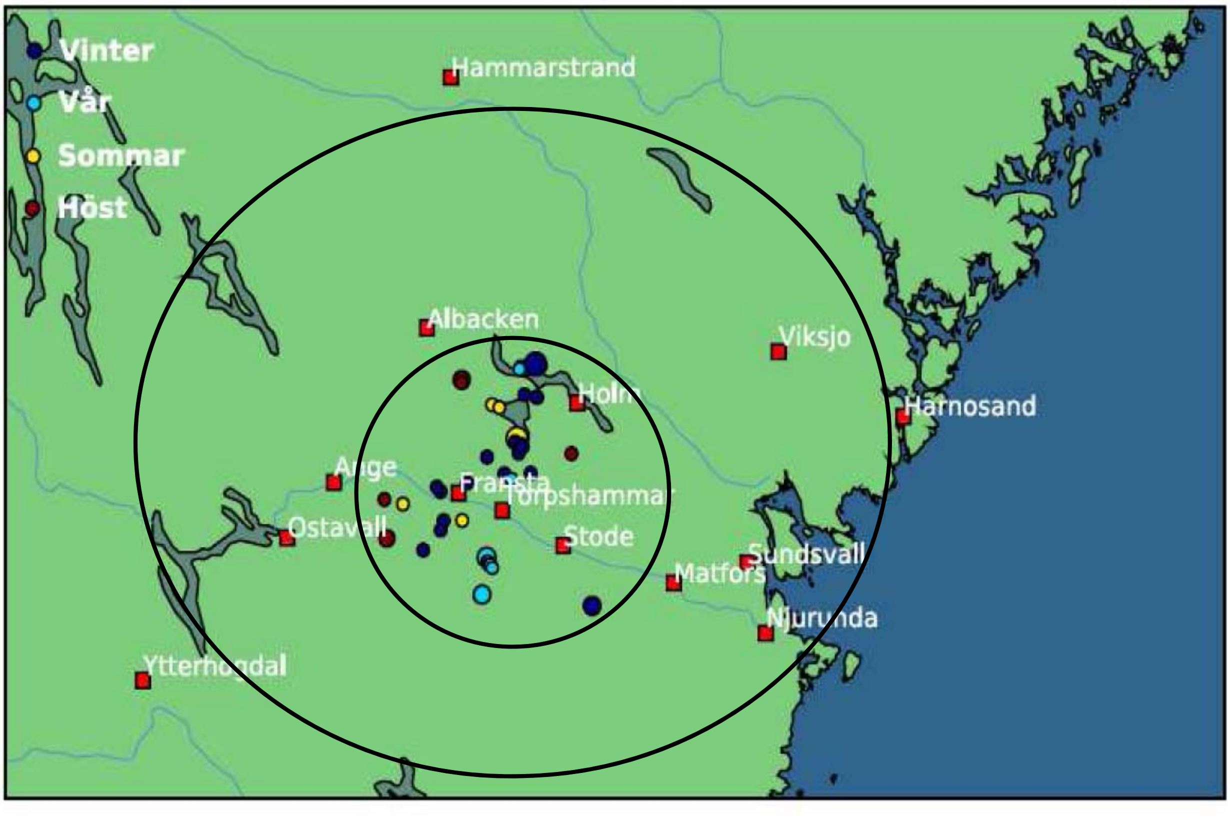
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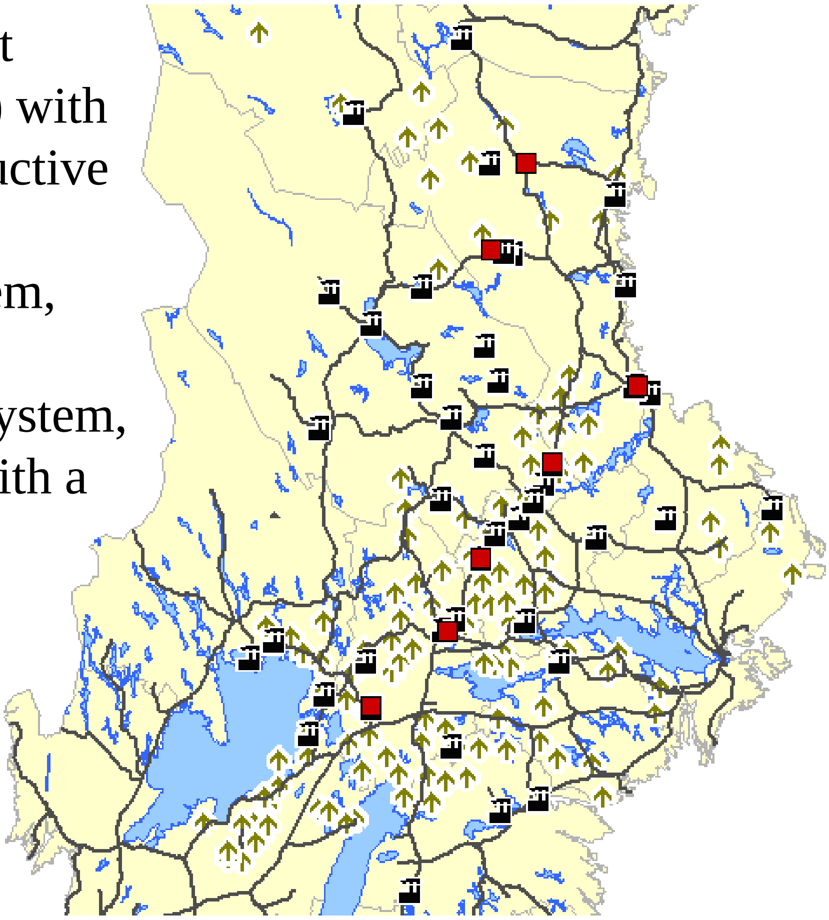
Stode
Sundsvall
Matfors
Njurunda
Ytterhogdal

Supply chain design

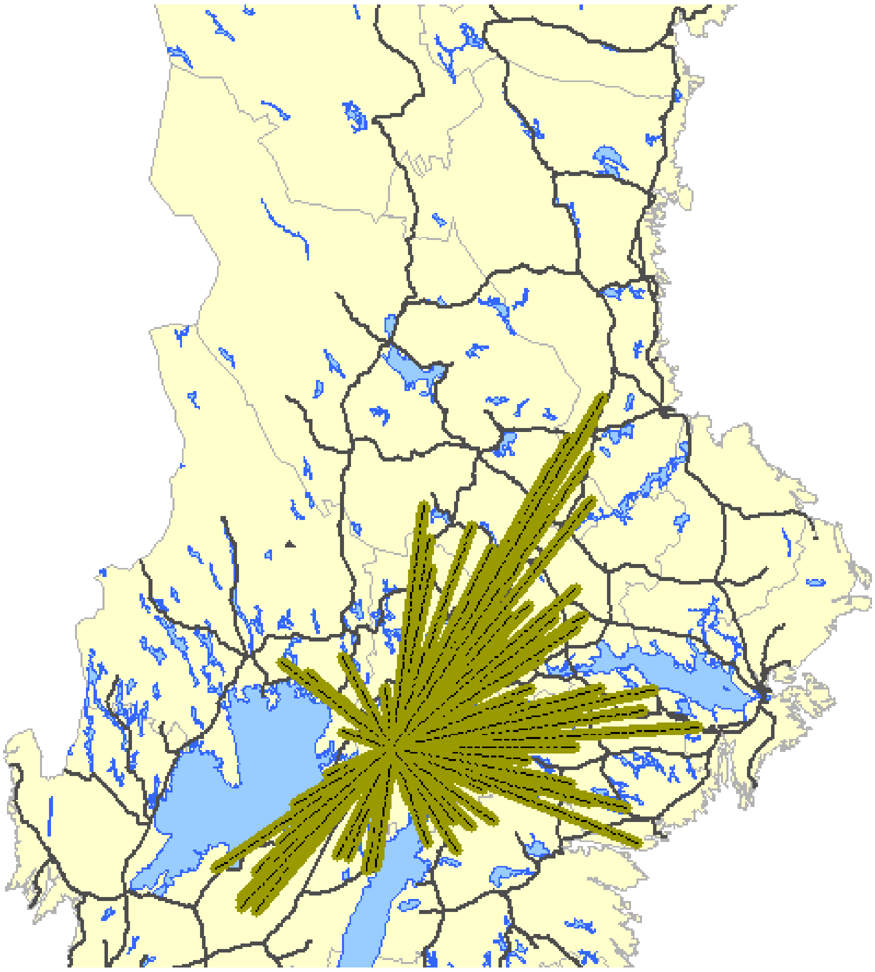
Train / terminal structure

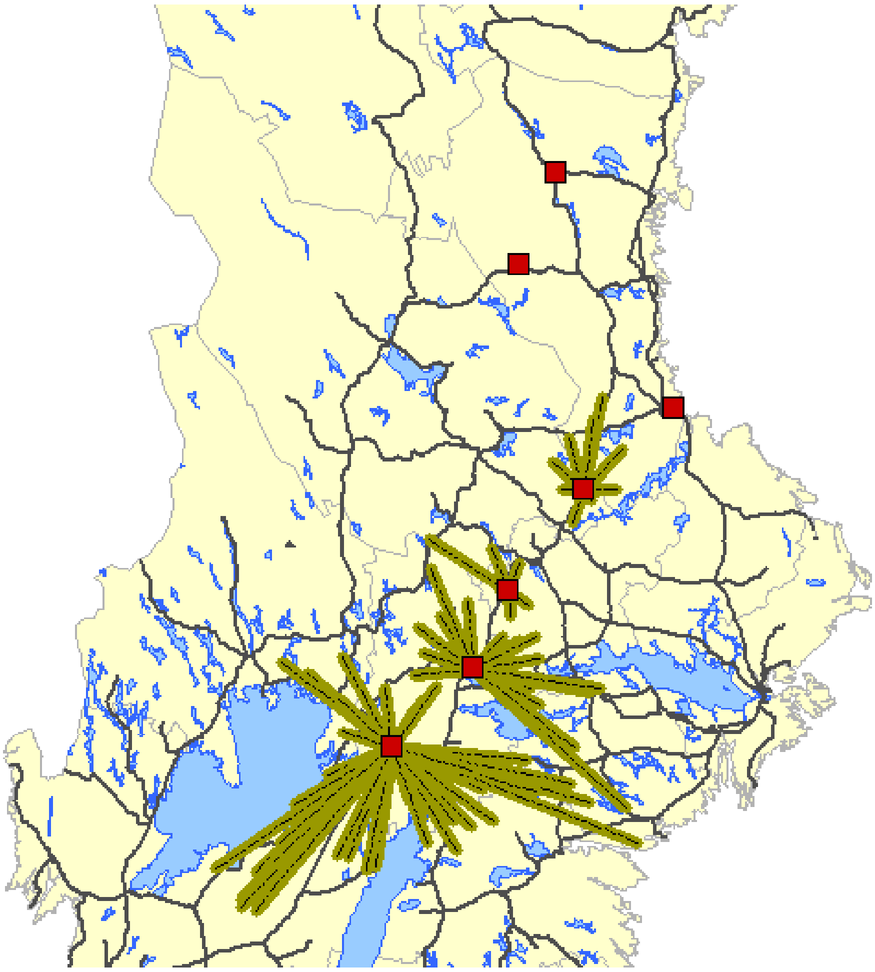
- Major Swedish forest company (Sveaskog) with 16% of overall productive forest area
- Using one train system, Trätåget
- Study to use a new system, Bergslagspendeln, with a number of potential terminals



Case study

- 1,500 supply points, 220 industrial demands,
- 5 train routes, 10 potential terminals,
- 12 products, 8 product groups, five scenarios.
- 3,000 constraints, 30 million variables
- Solution time 1 minute – several hours
- Truck transports reduced by 35% and overall energy 20%





Concluding remarks

Summary and future OR opportunities/ challenges

- Typical savings from optimization: 5-10%
- Specialized models and methods required
  - Important with ”real world” models and data
  - Quick and flexible/robust solution methods
- Forest industry is an area with open optimization problems
- Opportunities:
  - Robust models to meet uncertainties
  - New applications e.g. forest fuel supply chain
  - Consider faulty data in the planing process
  - Integrate several steps of the supply chain
  - Environmental considerations (CO2, bio-diversity, recreational, ..)
  - Operations Research vital for ongoing industrial success

Articles

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- *Articles on cutting are not included due to confidentiality requirements from companies*