Optimization of Forest Industry Operations

AMSI 2019, PERTH

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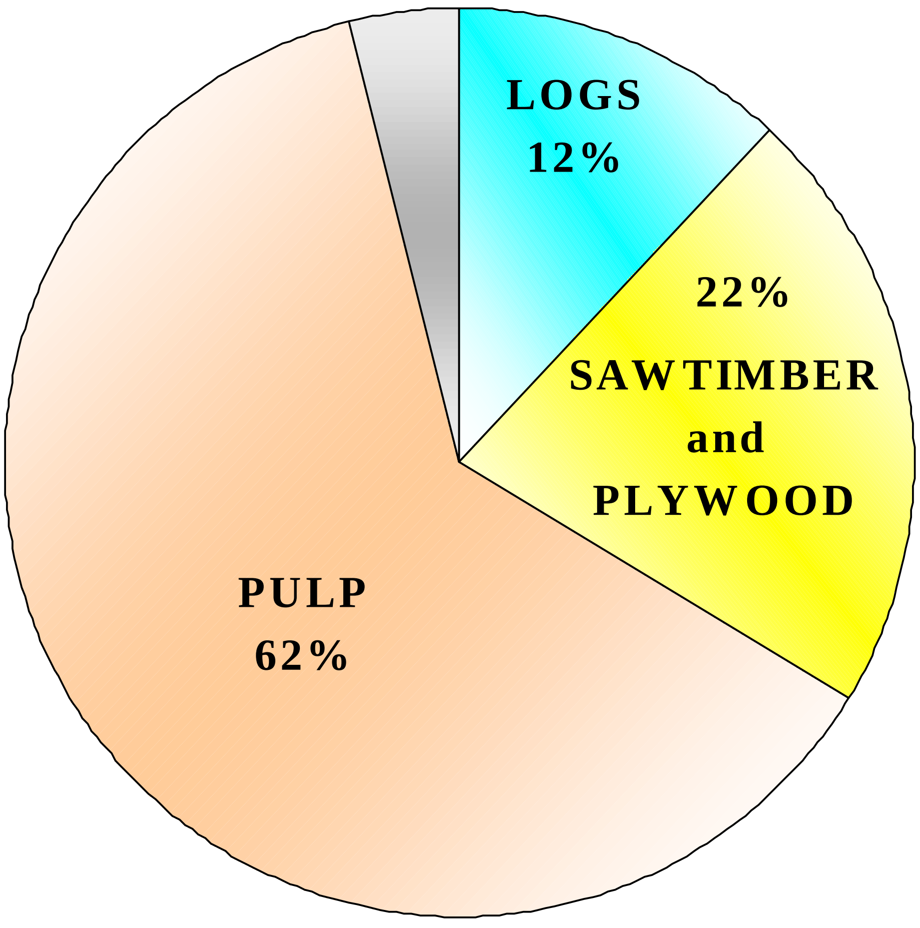
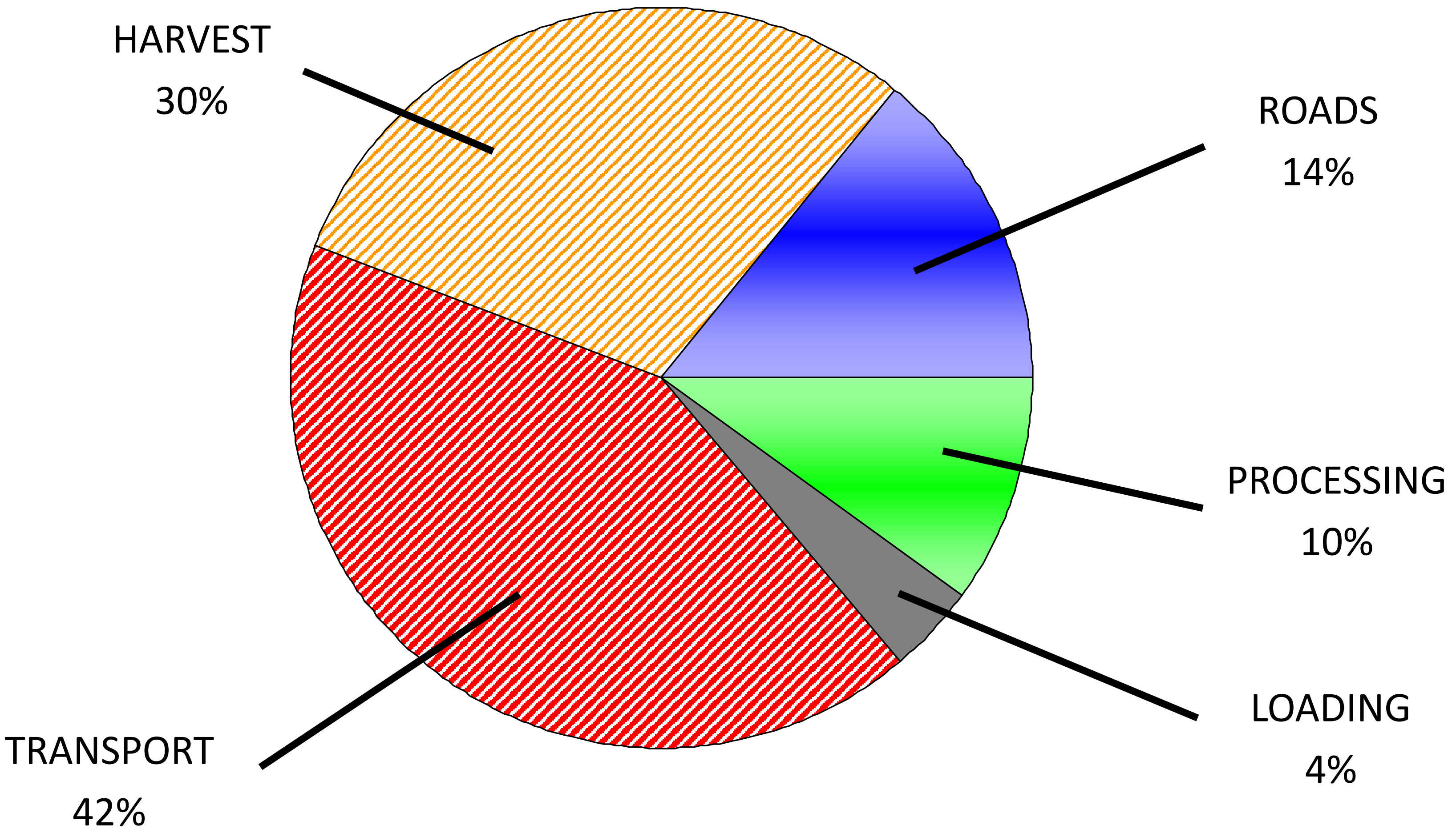
Forest Industry

- Multiple processes: where to focus?
- Highly competitive, hard work.
- Driven by cost:
  - Efficiency is mandatory.

Forest Industry



Forest Industry



Decision Levels

Focused on Main Problems

OPERATIONAL PROBLEMS

Transportation

Harvesting

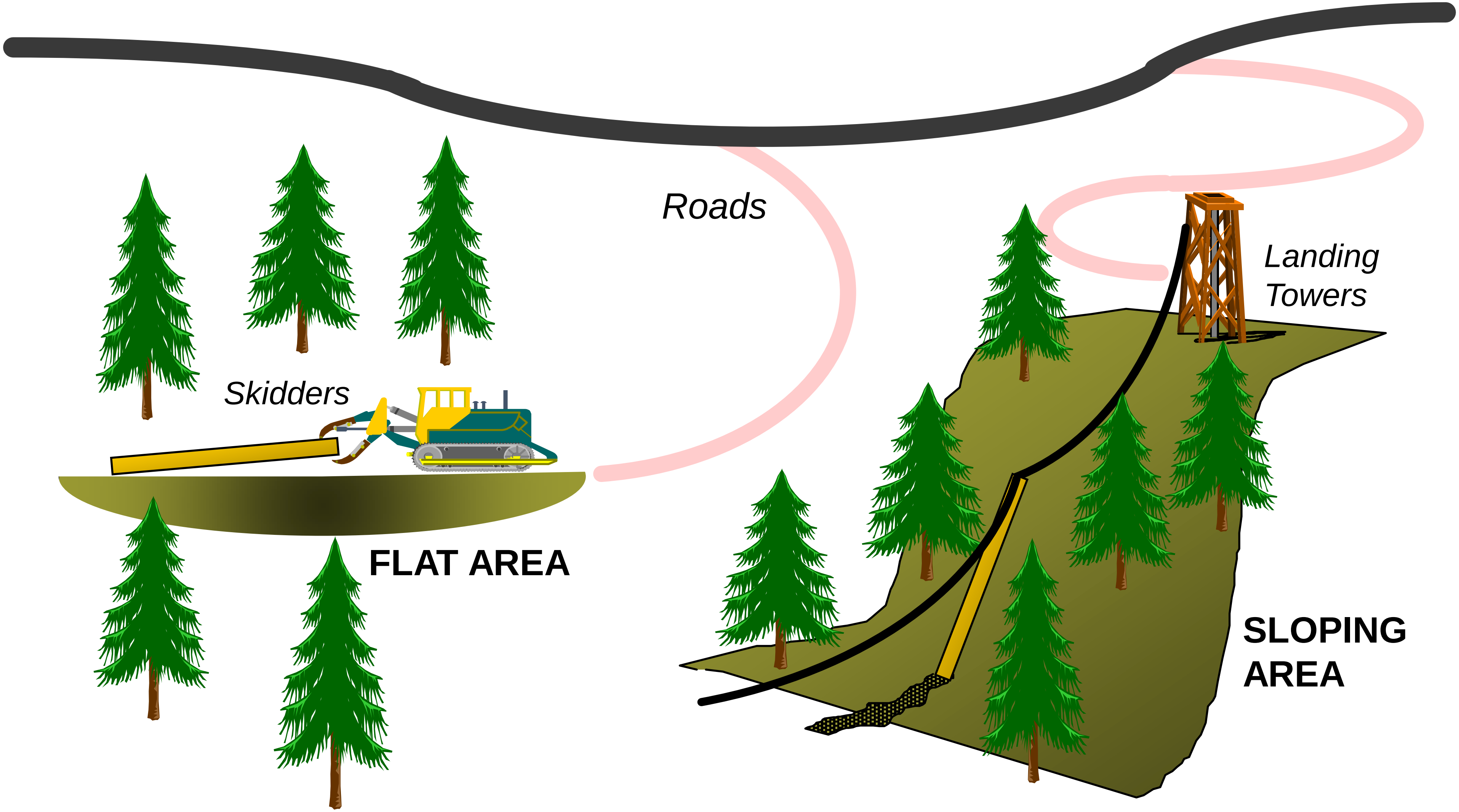
Timber Use

Harvesting Planning Analytics using GIS

Harvesting Planning

- Main decisions:
  - Where to locate the harvesting machinery.
  - Which areas to each machine.
  - The road network needed for extraction.

Harvesting Planning



Harvesting Planning

Harvesting Planning

- The objective: minimize the total cost (road + harvesting).

- Main constrains:
  - Technical constrains for the harvesting machinery:
    - Maximum forwarding slope.
    - Maximum side slope.
  - Technical constrains for the roads:
    - Maximum slope.
    - Turning angle for the forest trucks.
  - Environmental constrains:
    - Protected areas.
    - Earth movement.

Harvesting Planning

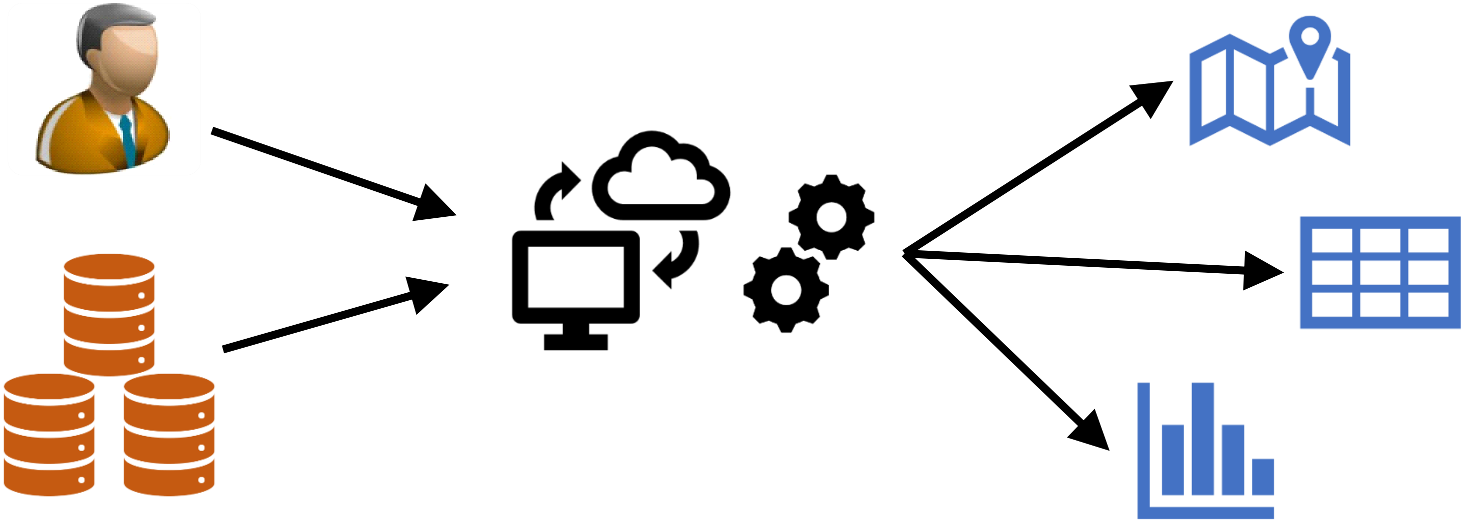
- Traditional approach:
  - An iterative process between a well experienced planning engineer and in-field analysis.

- Main drawbacks:
  - The iteration process is slow and inefficient.
  - Such experience is hard to obtain.
  - The results can be easily biased from said experience.

  - Given its complexity, it is impossible for a human to incorporate all the variables in the analysis.

Harvesting Planning

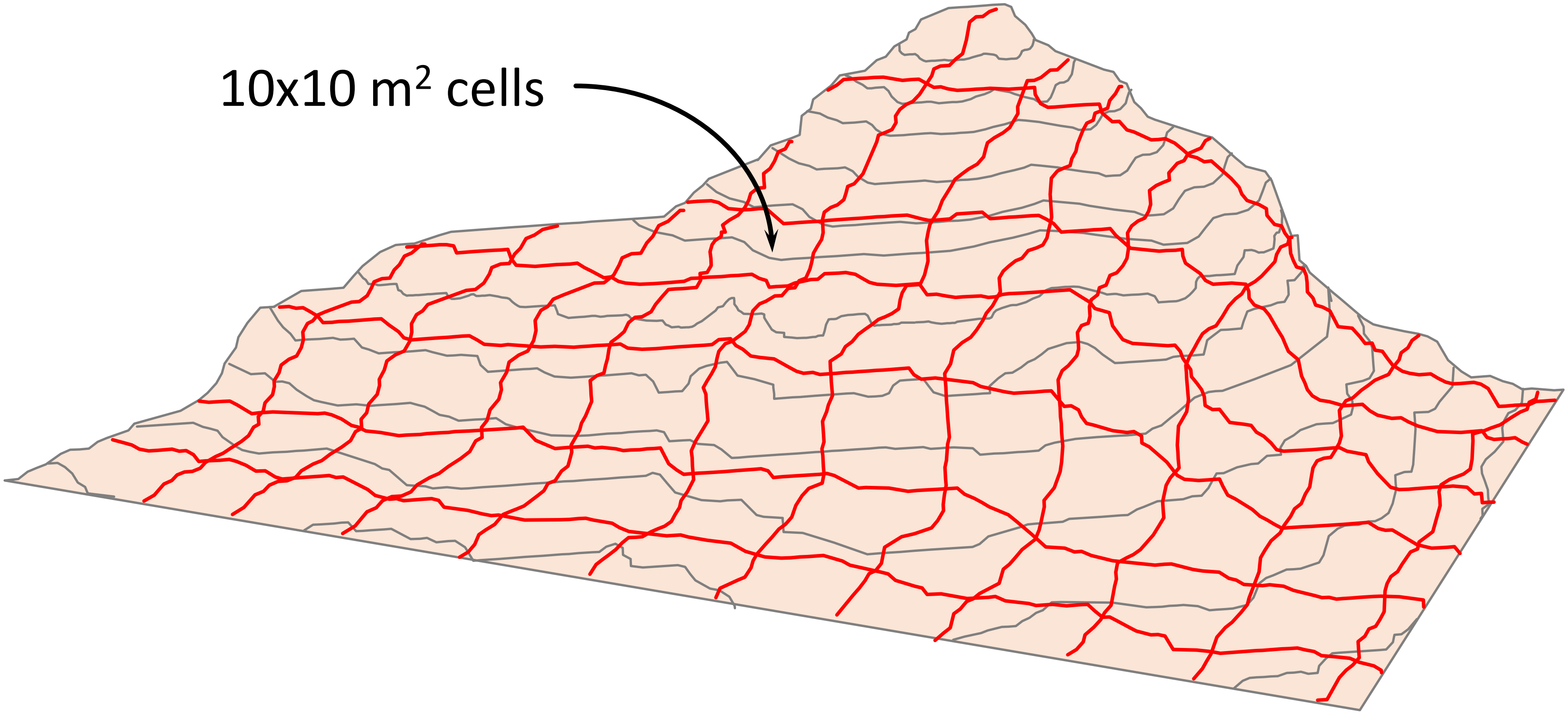
- Analytical approach:
  - With the use of geographical data, we solve the problem with an optimization model.



Harvesting Planning Analytics using GIS

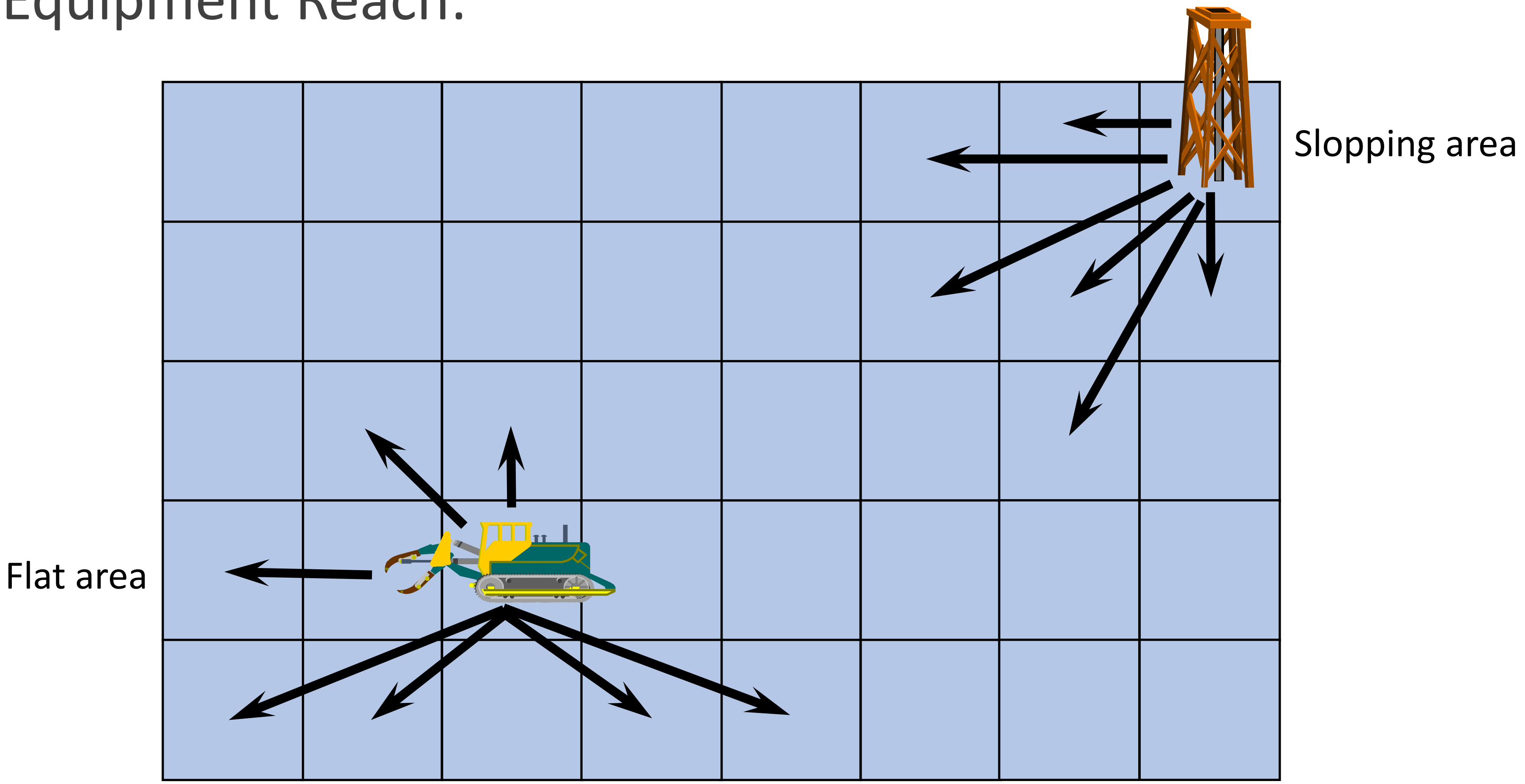
- Area divided in 10x10 m^2 cells.
- GIS provides topological information.
- Uncapacitated Network Design Model:
  - Route a single product from different origins to destinies.
  - Fixed-charge for using an arc.
  - Per unit flow costs on each arc.
  - NP-hard (special case: Steiner Tree).
- Solved heuristically.

Harvesting Planning Analytics using GIS



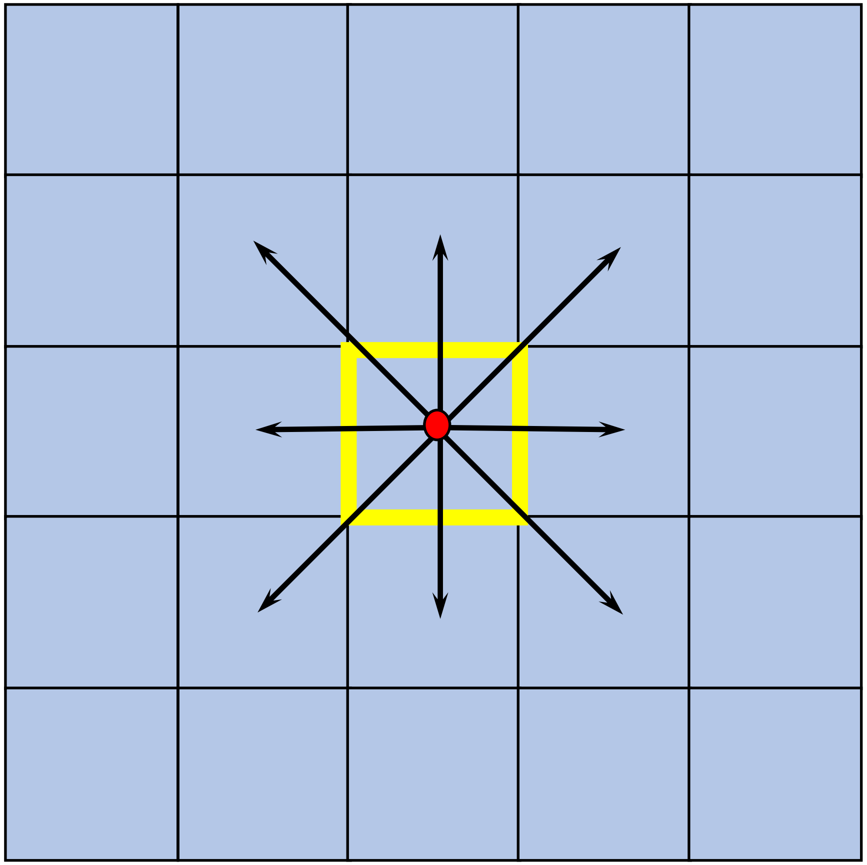
Harvesting Planning Analytics using GIS

- Equipment Reach:



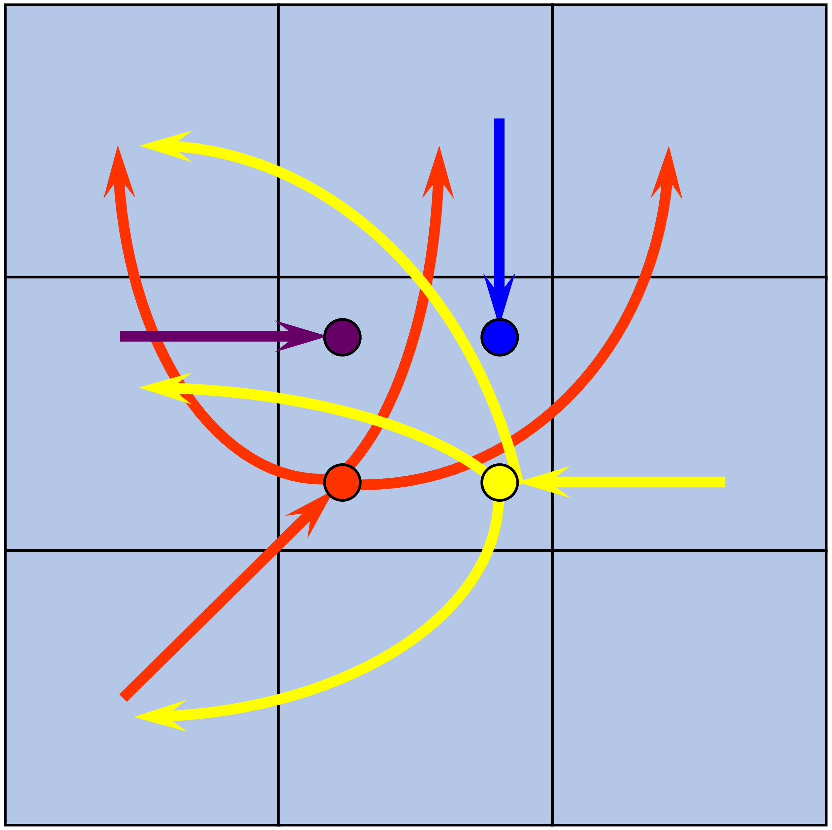
Harvesting Planning Analytics using GIS

- Road Segments:

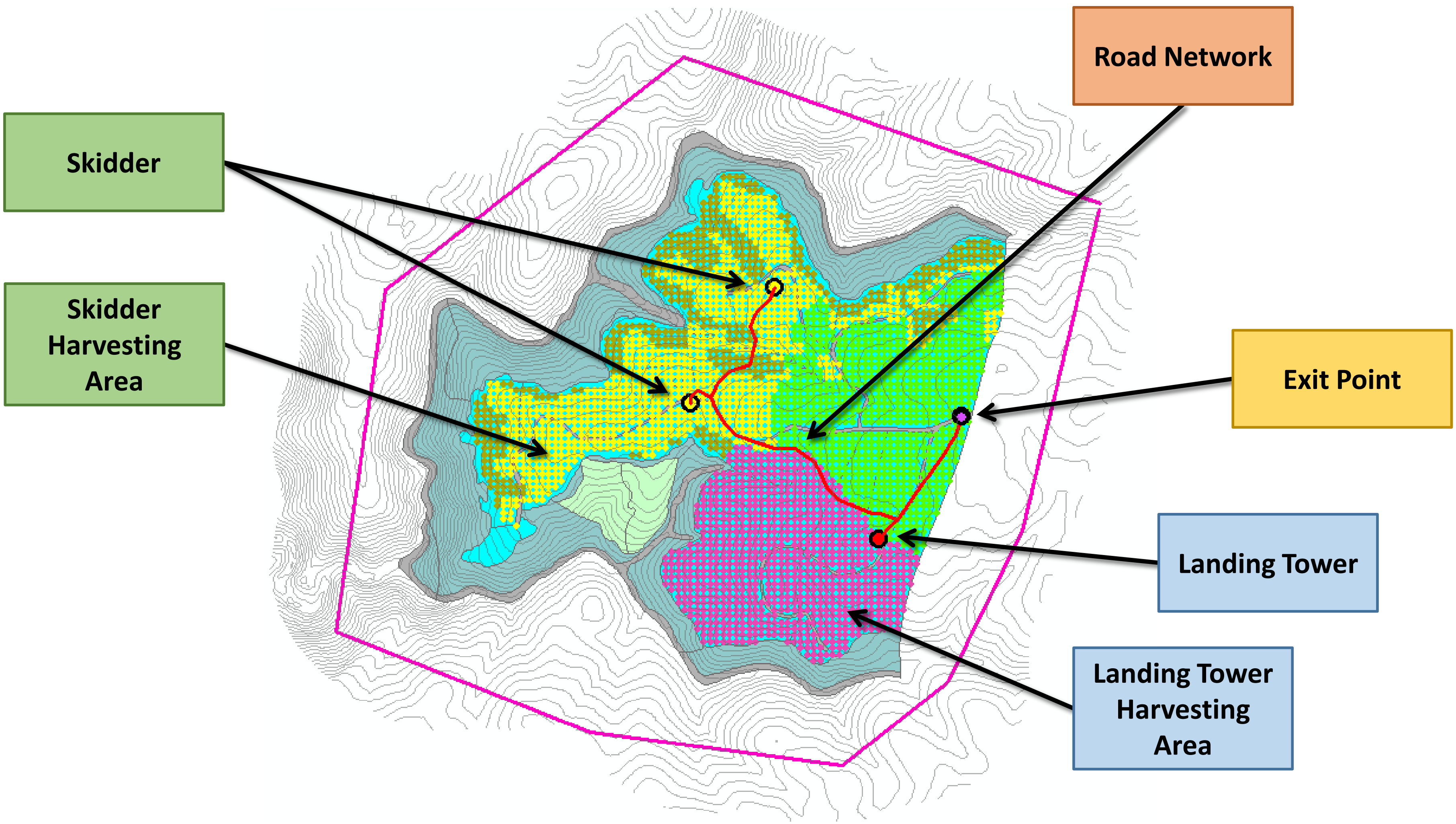


Harvesting Planning Analytics using GIS

- Feasible Turns:

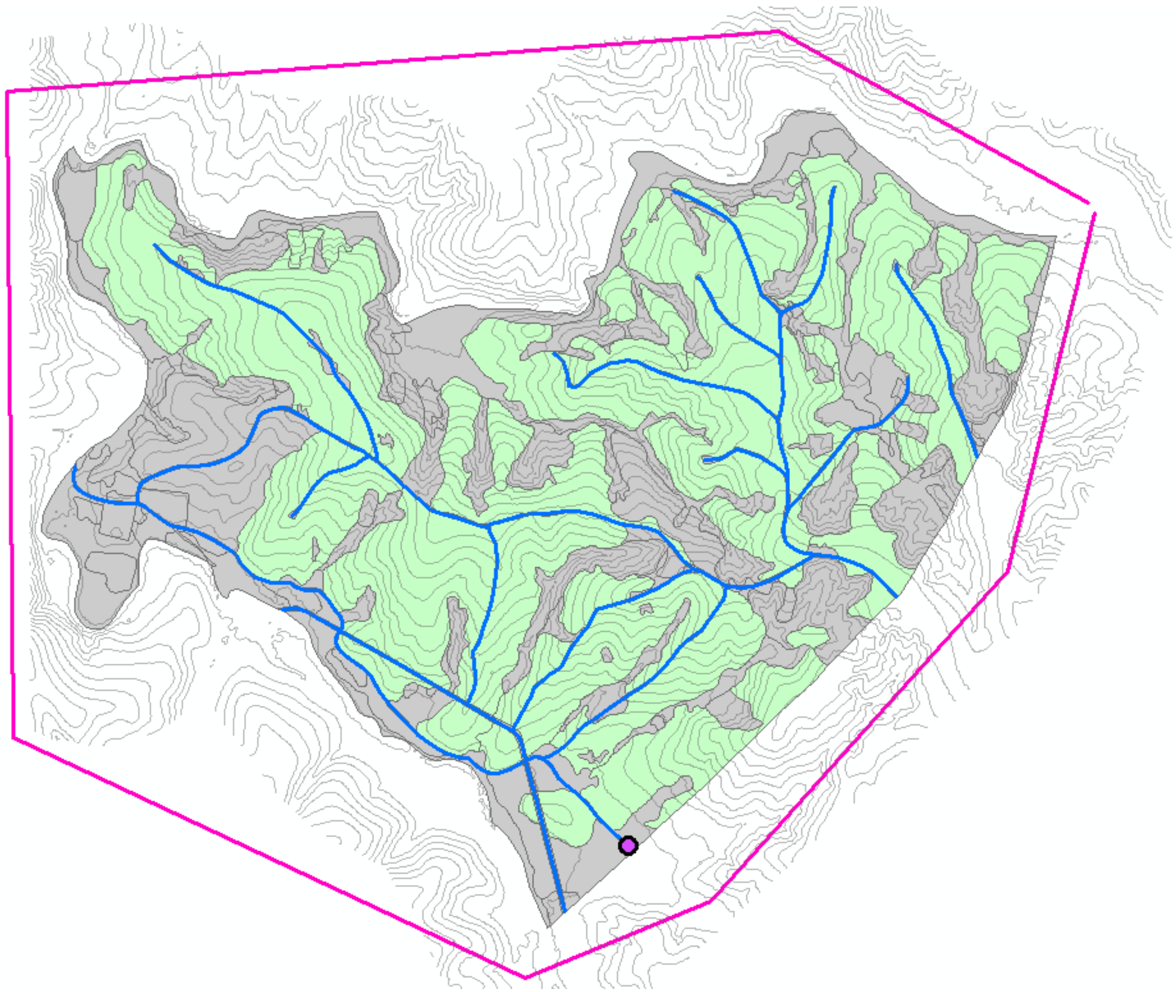


Harvesting Planning Analytics using GIS



Harvesting Planning Analytics using GIS

- Example:
- Green areas are plantations.
- The field has existing roads.

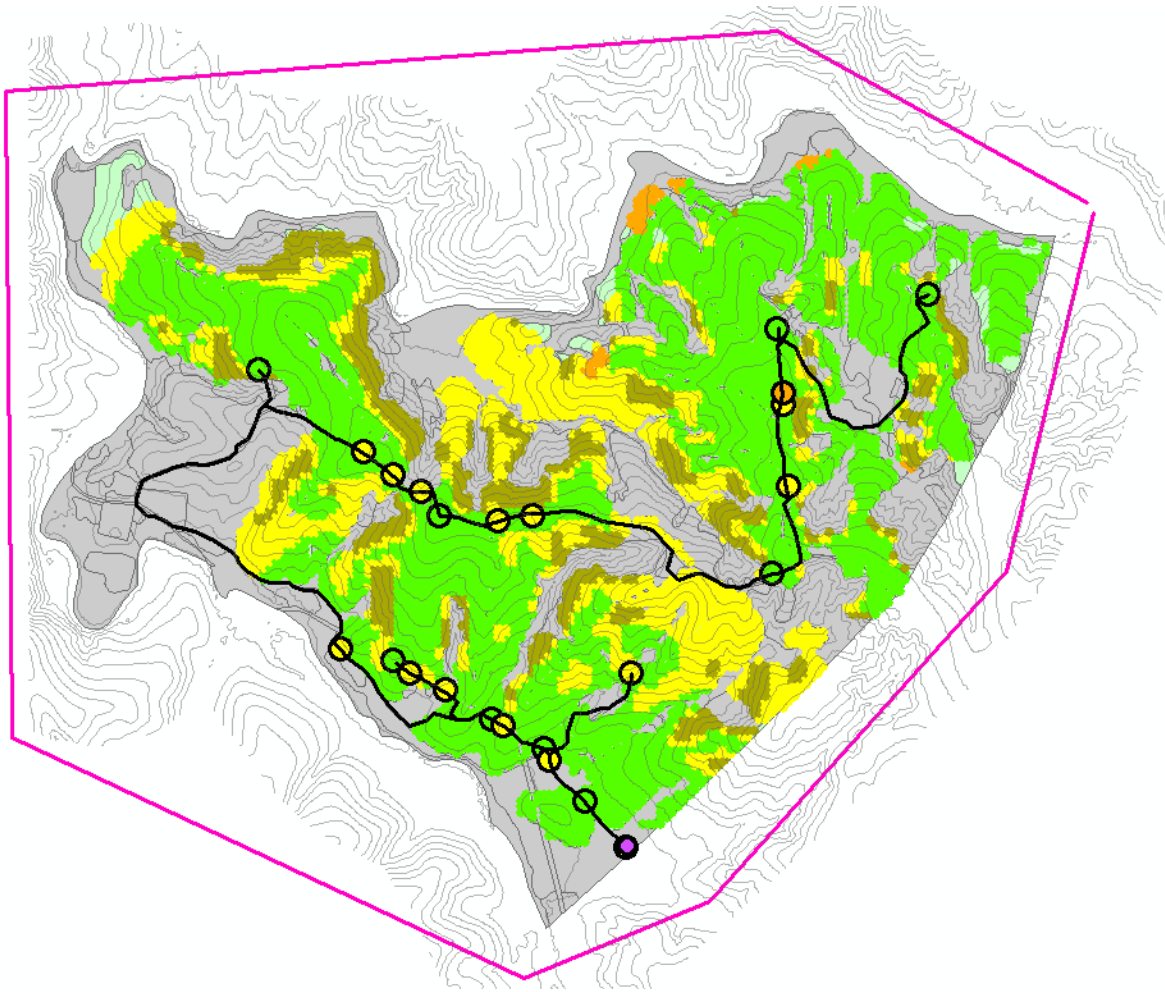


Harvesting Planning Analytics using GIS

- Solution:

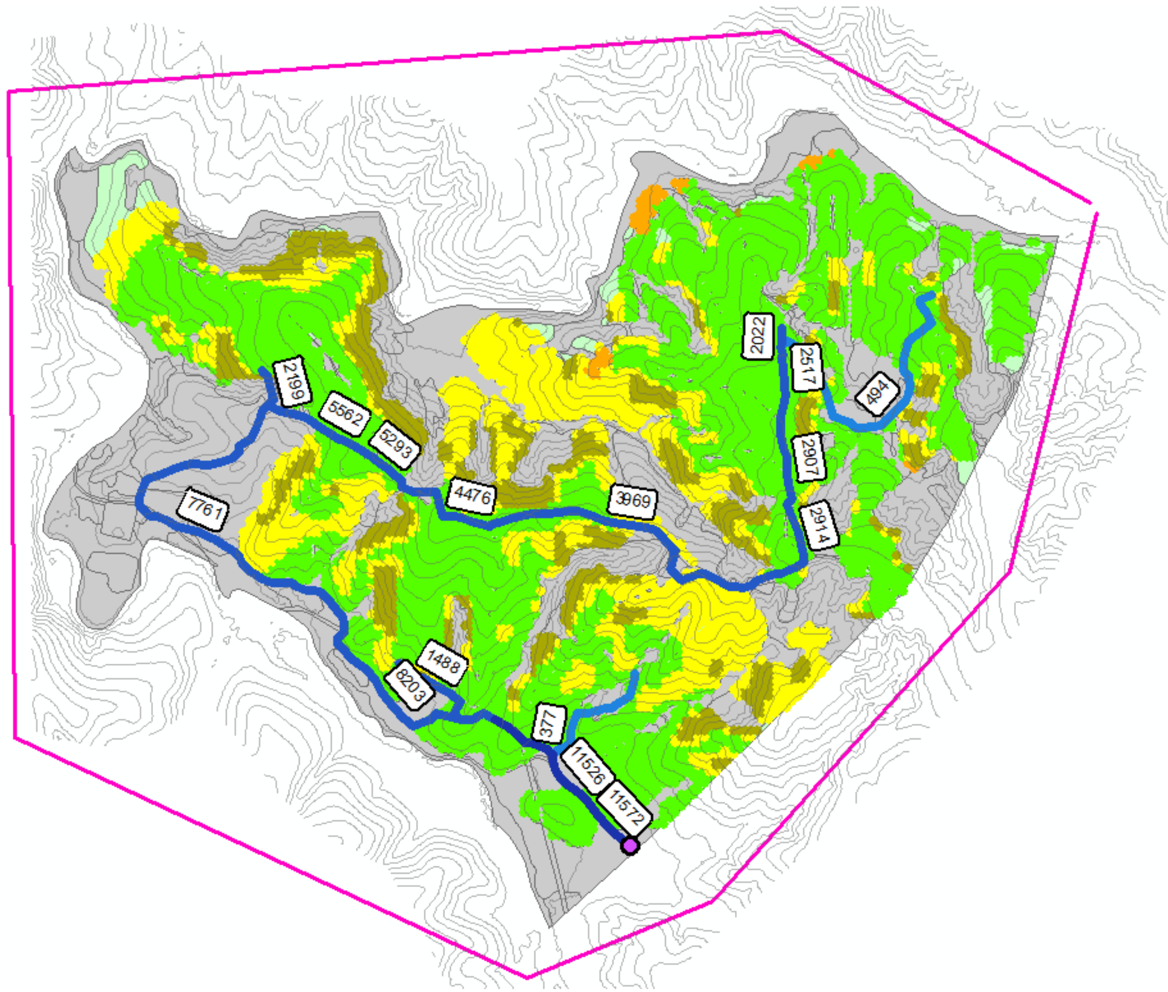
- Different machinery allocation with its corresponding harvesting areas.

- Road network needed for extraction.



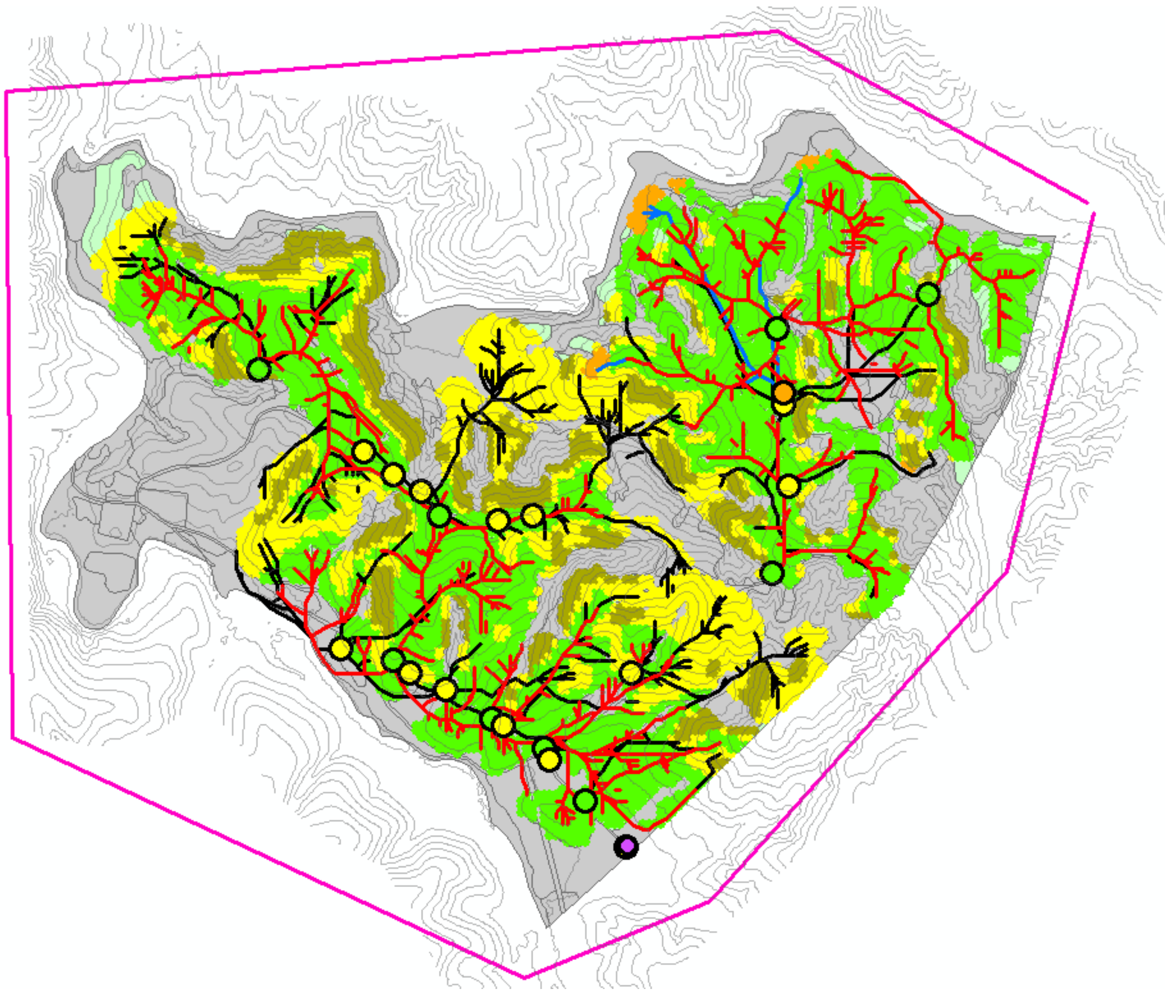
Harvesting Planning Analytics using GIS

- Solution:
- For each road segment, it shows the timber volume that is transported.
- It is used to determine the amount of gravel needed.



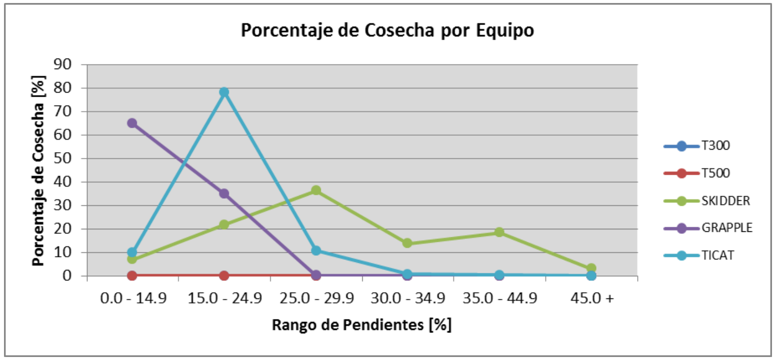
Harvesting Planning Analytics using GIS

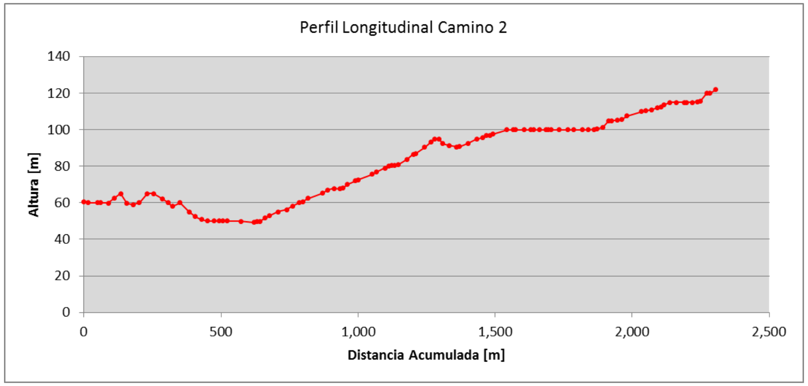
- Solution:
- Skidder harvesting routes.
- It measures the impact of the harvesting in the field.

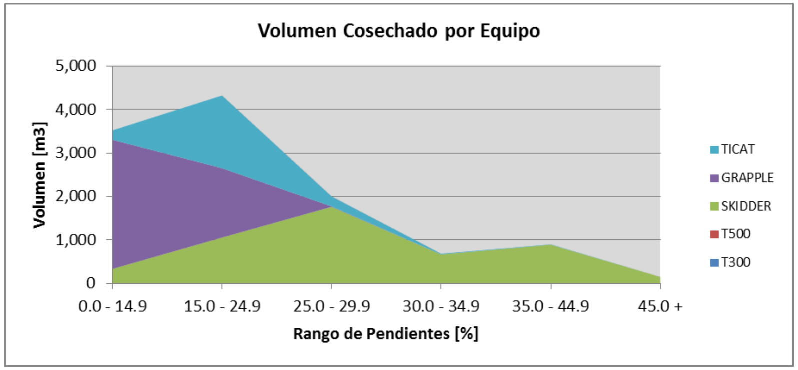


Harvesting Planning Analytics using GIS

Tramo ID	Tipo Camino	Largo [Km]	Pendiente [%]	Costo Faja [US$]	Costo Ripio [US$]	Costo Mant. [US$]	Vol Mov Tie [m3]	Costo Mov Tie [US$]	Flujo Madera [m3]	Cto Flu Trans [US$]	Cto Per Sue [US$]
1	Nuevo	0.02	0.2	18	0	0	0.43	0	10,659	0	28
2	Viejo Tierra	0.29	6.0	0	0	0	0.00	0	10,659	0	406
3	Nuevo	0.06	2.3	52	0	0	33.69	28	10,289	0	85
4	Viejo Tierra	0.43	5.5	0	0	0	0.00	0	10,289	0	610
5	Nuevo	0.38	4.7	321	0	0	214.43	183	9,777	0	527
6	Viejo Tierra	0.09	5.7	0	0	0	0.00	0	9,543	0	126
7	Nuevo	0.17	5.7	148	0	0	111.36	95	9,543	0	242
8	Viejo Tierra	0.23	8.6	0	0	0	0.00	0	8,090	0	320
9	Nuevo	0.21	4.2	175	0	0	206.82	175	7,328	0	287
10	Viejo Tierra	0.38	1.7	0	0	0	0.00	0	6,303	0	538
11	Nuevo	0.10	4.9	87	0	0	99.88	84	5,425	0	143
12	Viejo Tierra	0.02	4.6	0	0	0	0.00	0	5,425	0	32
13	Nuevo	0.03	4.5	29	0	0	47.88	41	5,425	0	48
14	Viejo Tierra	0.03	9.5	0	0	0	0.00	0	4,908	0	46
15	Nuevo	0.02	0.0	19	0	0	0.00	0	4,908	0	31
16	Viejo Tierra	0.14	4.9	0	0	0	0.00	0	4,908	0	202
17	Nuevo	0.18	5.0	151	0	0	254.09	215	3,705	0	246
18	Viejo Tierra	0.23	3.8	0	0	0	0.00	0	3,705	0	317
19	Nuevo	0.04	6.1	36	0	0	17.77	16	3,112	0	58
20	Viejo Tierra	0.09	3.4	0	0	0	0.00	0	3,112	0	122
21	Nuevo	0.28	4.7	241	0	0	368.71	314	832	0	394
22	Viejo Tierra	0.15	3.6	0	0	0	0.00	0	832	0	208
23	Nuevo	0.02	1.6	21	0	0	13.52	11	832	0	34
Sub-Total		**3.60**	**4.4**	**1,298**	**0**	**0**	**1,368.57**	**1,162**	**10,659**	**0**	**5,050**







Harvesting Planning Analytics using GIS

- Roads:
  - Operational:

Existent road:	2.5	[Km]
Existent road used:	1.8	[Km]
Proposed road used:	0.2	[Km]
New road used:	1.1	[Km]
Total road used:	5.6	[Km]
Earth movement:	1,320	[m3]

  - Economical:

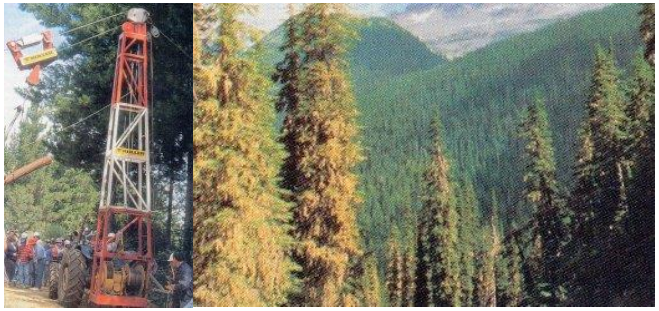
Road maintenance cost:	900	[US$]
Road construction cost:	1,950	[US$]
Gravel cost:	168,000	[US$]
Earth movement cost:	1,320	[US$]
Total road cost:	172,170	[US$]

Harvesting Planning Analytics using GIS

- Harvesting:
  - Operational:
    - Total volume: 30,000 [m3]
    - Harvested volume: 29,000 [m3]
    - Total area: 150 [ha]
    - Harvested area: 145 [ha]
  - Economical:
    - Total harvesting cost: 362,000 [US$]

Harvesting Planning Analytics using GIS

- KPIs:
  - Roads:
    - Average road cost per road Km [US$/Km]
    - Average road cost per volume [US$/m3]
  - Harvesting:
    - Road density [ha/Km]
    - Average harvesting distance [m]
    - Average harvesting slope [%]
  - Total:
    - Average cost [US$/m3]

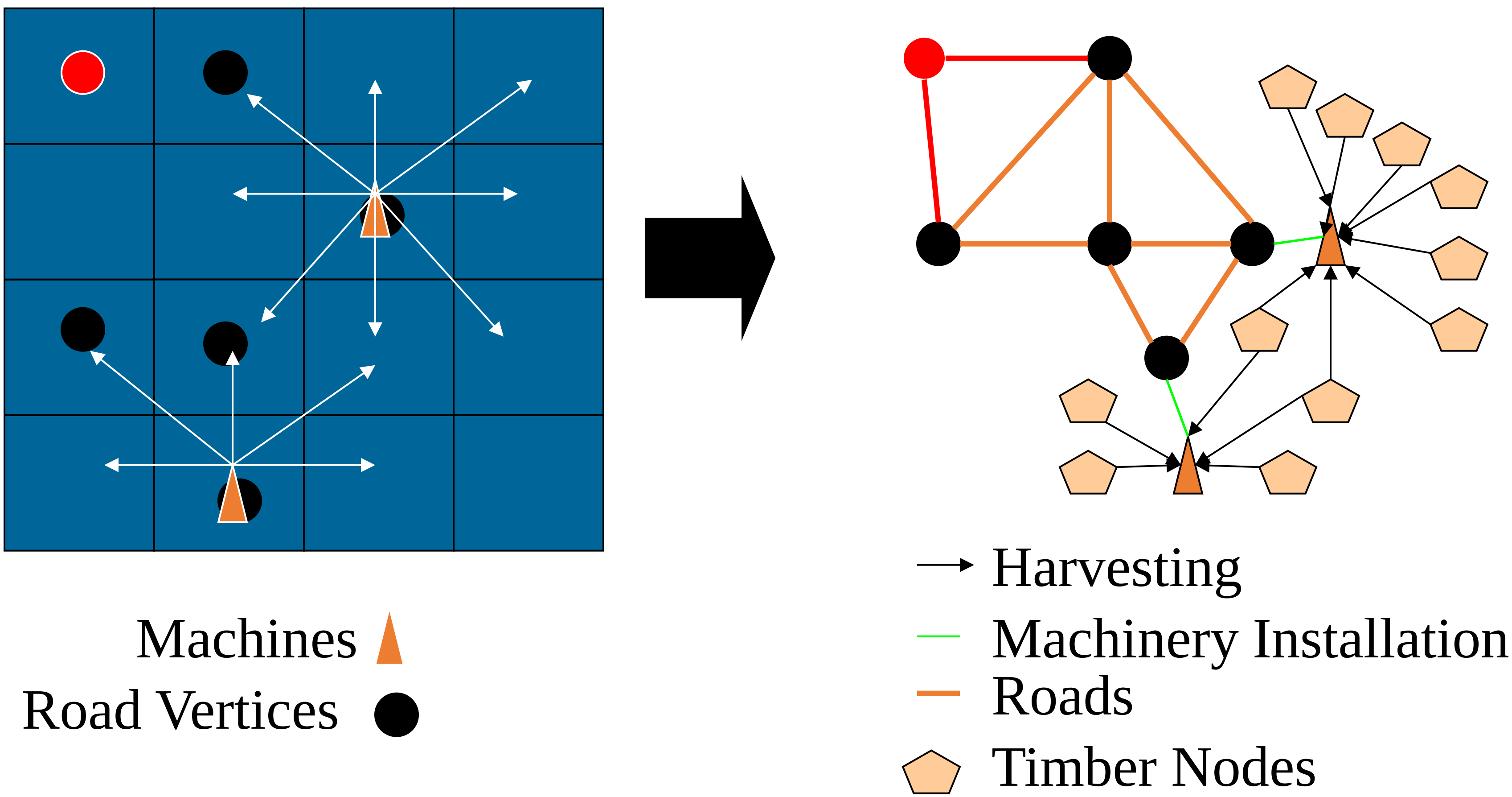


Harvesting Planning Analytics using GIS

- Benefits:
  - SAVINGS:
    - Fewer roads.
    - Better location of harvesting machinery.
  - ENVIRONMENTAL:
    - Fewer roads.
    - Reduced erosion and water sedimentation.
  - ORGANIZATIONAL:
    - Better analysis quality.
    - Analyst time reduced.
    - It guarantees certifications.

Optimization Background Theory

New Approach: Linear Relaxation



New Approach: Linear Relaxation

$$Min \sum_{\{i,j\}\in A} F_{ij} x_{ij} + \sum_{\{i,j\}\in A} c_{ij} f_{ij} + c_{ji} f_{ji}$$

st

$$\left. \begin{array}{l} f_{ij} \leq M \cdot x_{ij} \\ f_{ji} \leq M \cdot x_{ij} \end{array} \right\} \quad \forall \{i,j\} \in A$$

M: total timber volume

$$\sum_{j \in N} f_{ji} - \sum_{j \in N} f_{ij} = \begin{cases} \mathrm{s}_{\mathrm{i}} & \text{si } i \in N_T \\ \mathrm{D} & \text{si } i = EXIT \\ 0 & \sim \end{cases} \qquad \forall i \in N$$

Relaxation gives poor results.

$$f_{ij}, f_{ji} \geq 0 \qquad \forall \{i,j\} \in A$$

$$x_{ij} \in \{0,1\} \qquad \forall \{i,j\} \in A$$

Multi-commodity Model

- Separate timber from each origin cell into a different commodity.
- Flow in each arc is represented with different variables, one for each commodity:

  Fraction of commodity k that

  flows through arc {i,j}.

- Model increases in size.
- Linear relaxation gives good results.

MC Model (Undirected)

$$Min \sum_{\{i,j\}\in A} F_{ij} x_{ij} + \sum_{k\in K} \sum_{\{i,j\}\in A} (c_{ij}^k f_{ij}^k + c_{ji}^k f_{ji}^k)$$

Sujeto a

$$f_{ij}^k \leq x_{ij}$$

$$f_{ji}^k \leq x_{ij} \qquad \forall\{i,j\} \in A, \forall k \in K$$

$$\sum_{j\in N} f_{ji}^k - \sum_{j\in N} f_{ij}^k = \begin{cases} -1 & si \;\; i = O(k) \\ 1 & si \;\; i = D(k) \\ 0 & \sim \end{cases} \qquad \forall i \in N, \forall k \in K$$

$$f_{ij}^k, f_{ji}^k \geq 0 \qquad \forall\{i,j\} \in A$$

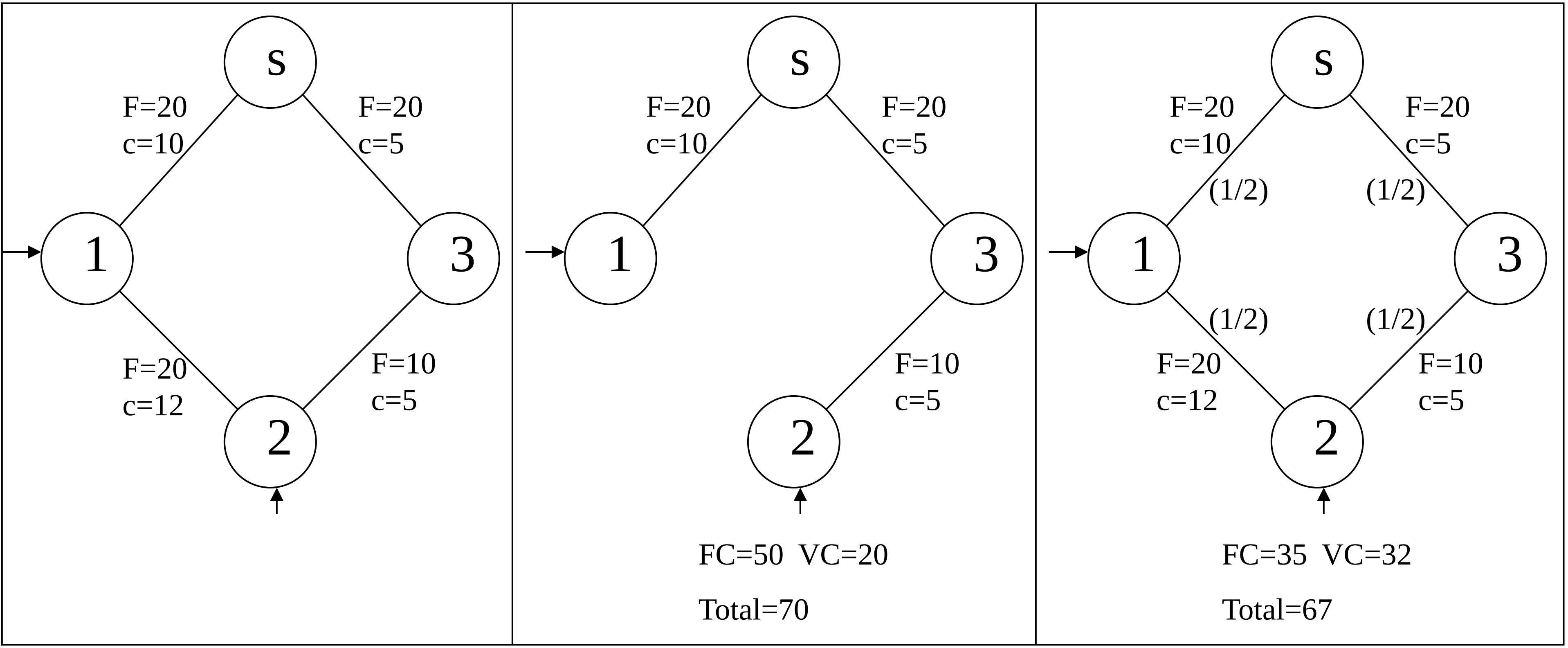
$$x_{ij} \in \{0,1\} \qquad \forall\{i,j\} \in A$$

Multi-commodity Model

- Model can be improved using special problem features:
  - Uncapacitated network.
  - All commodities share the same destiny.
  - Same transport cost per volume unit.

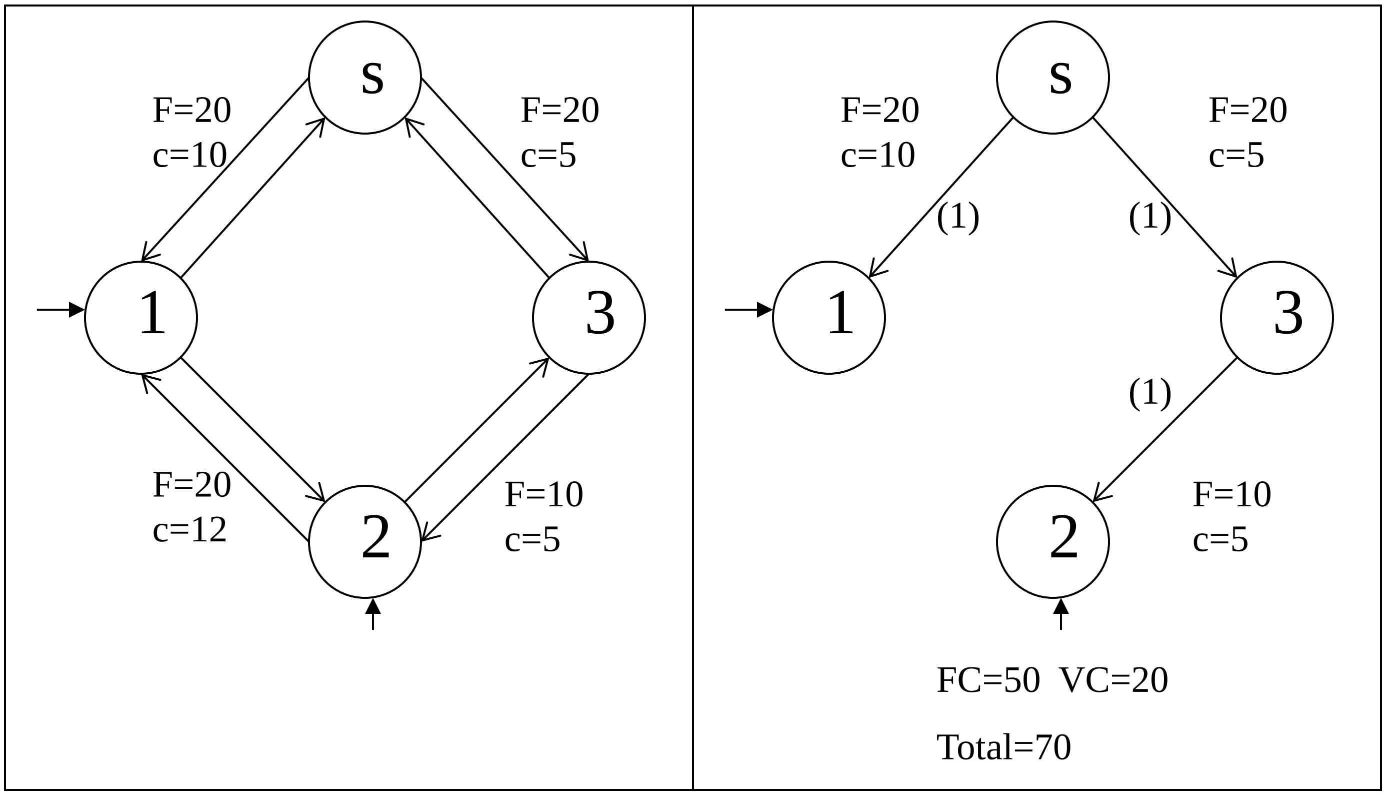
- Tree-like solutions, one-way flow on each arc.
- **Directed Network** strengthens the model.
- Better solutions obtained.

Example



Undirected Network - relaxation produces gap.

Example



Directed Network - strengthens relaxation

Directed Formulation

$$Min \sum_{(i,j)\in A} F_{ij} x_{ij} + \sum_{k\in K} \sum_{(i,j)\in A} c_{ij}^{k} f_{ij}^{k}$$

Sujeto a

$$f_{ij}^{k} \leq x_{ij} \qquad \forall (i,j) \in A, \forall k \in K$$

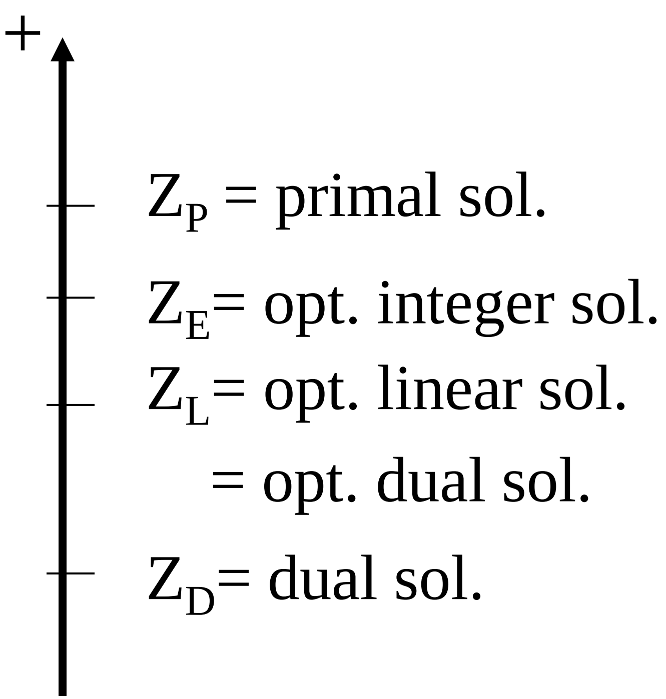
$$\sum_{j \in N} f_{ji}^{k} - \sum_{j \in N} f_{ij}^{k} = \begin{cases} -1 & \text{si } i = O(k) \\ 1 & \text{si } i = D(k) \\ 0 & \sim \end{cases} \qquad \forall i \in N, \forall k \in K$$

$$f_{ij}^{k} \geq 0 \qquad \forall (i,j) \in A$$

$$x_{ij} \in \{0,1\} \qquad \forall (i,j) \in A$$

Problem Solving

Approach: Improve Linear Relaxation



- New Multicommodity formulation improves linear relaxation.
- Model increases rapidly as the problem is scaled, medium and large instances cannot be solved exactly.
- Approximation for the dual problem of the linear relaxation of the model (lower bound).

Problem Solving

- Linear relaxation of the MC model optimally solves small-scale networks, but cannot solve bigger problems.
- **Dual Ascent Procedure**: approximately solves the dual problem of the relaxed MC formulation.
- Medium and Large scale networks can be solved through this approach.

Dual Ascent Procedure

- Based on B-M-W (1989).
- Gives as output:
  - Dual Objective Function Value (lower bound).
  - Sub-set of arcs that build a feasible solution of the problem.
- Feasible solution can be improved, obtaining a good solution for the problem (upper bound).
- Quality of the solution can be evaluated using the duality gap.

Dual Ascent Procedure

$$Max \quad z_D = \sum_{k\in K} v^k_{D(k)}$$

Sujeto a

$$v^k_j - v^k_i \leq c^k_{ij} + w^k_{ij} \qquad \forall (i,j) \in A, \forall k \in K$$

$$\sum_{k \in N} w^k_{ij} \leq F_{ij} \qquad \forall (i,j) \in A$$

$$w^k_{ij} \geq 0 \qquad \forall (i,j) \in A, \forall k \in K$$

$$Max \quad v^k_{D(k)}$$

Sujeto a

$$v^k_j - v^k_i \leq \hat{c}^k_{ij} \qquad \forall (i,j) \in A, \forall k \in K$$

donde

$$\hat{c}^k_{ij} = c^k_{ij} + w^k_{ij}$$

- Fix w-values
- Shortest-path problem, separated by commodity, from node O(k) to D(k).
- Increase the appropriate w-values, in order to increase ZD, the dual OF value.

Finding Good Feasible Solutions

- Dual-Ascent: gives a smaller feasible network.

- Two different approaches over this network:
  - Solve the relaxed MC model.
  - Solve NF formulation introducing cuts (row generation).

Finding Good Feasible Solutions

- Problem can be reduced considerably:
  - Eliminate some “unfeasible” arcs.
  - Eliminate flow balance constraints, as many nodes can’t be reached by all commodities.

- Model size reduces considerably, can be solved in medium-large instances.

Di-Cut Formulation

P-Dicut

$$Min \sum_{\{i,j\}\in A} F_{ij} x_{ij} + \sum_{\{i,j\}\in A} c_{ij} f_{ij} + c_{ji} f_{ji}$$

st

$$\sum_{(i,j)\in\delta+(S)} x_{ij} \geq 1 \qquad \forall S \subset V, S \cap N_T \neq \phi, EXIT \in (V \setminus S)$$

$$f_{ij} \leq M_{ij} \cdot x_{ij} \qquad \forall (i,j) \in A$$

$$\sum_{j \in N} f_{ji} - \sum_{j \in N} f_{ij} = \begin{cases} \mathrm{s_i} & \text{si } i \in N_T \\ \mathrm{D} & \text{si } i = EXIT \\ 0 & \sim \end{cases} \qquad \forall i \in N$$

$$f_{ij}, f_{ji} \geq 0 \qquad \forall \{i,j\} \in A$$

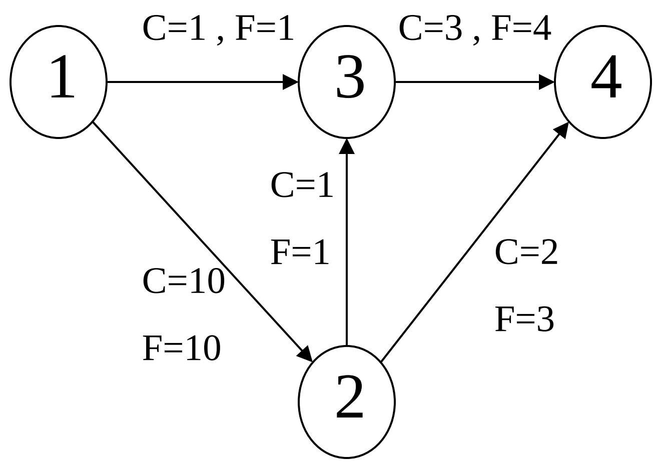
$$x_{ij} \in \{0,1\} \qquad \forall \{i,j\} \in A$$

Di-Cut Formulation

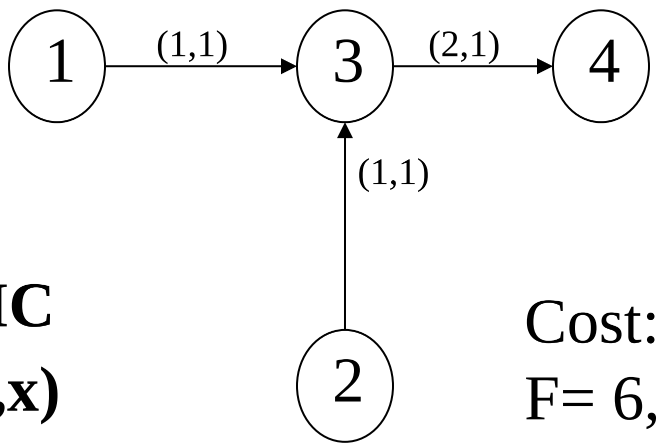
- Model increases exponentially in size.
- Cutting Plane Formulation : detect cut violations with Max-Flow from each origin to EXIT.
- Di-Cut and MC formulation are equivalent if $c_{ij}=0$ (Steiner Tree).
- If $c_{ij}>0$, formulations are not equivalent.
- Heuristic procedure to round up the solution.

Di-Cut Formulation

Origins:
{1,2}

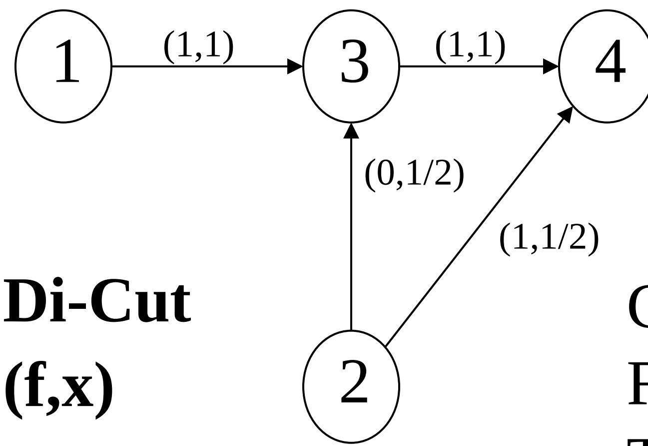


MC
(f,x)



Cost:
F= 6, C= 8
T= 14

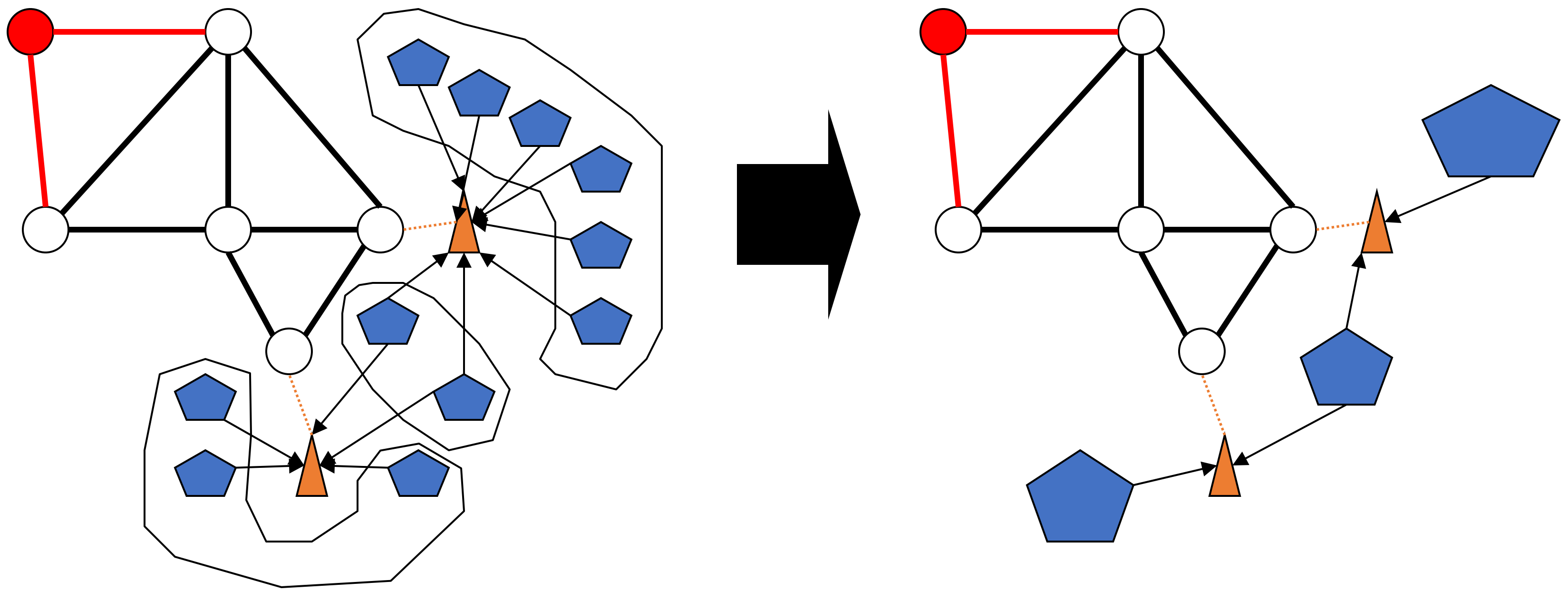
Di-Cut
(f,x)



Cost:
F= 7, C=6
T= 13

Network Reductions

Commodity Grouping



Computational Results

Test Problems

Nº	Terrain Extension [h]	Timber Nodes	Vertex Nodes	Possible Roads	Possible Machines	Total Nodes
S	2	25	8	13	9	43
SM	10	1016	14	17	10	1041
M	40	3635	106	154	63	3805
L	200	21001	264	364	238	21504
Lnr	200	3843	264	364	238	4346

} Small

} Medium

} Large

} Reduced

- Much smaller than real-scale problems (road network is less dense).

Computational Results

Nº	Optimal OF Value	Dual OF Value	**Dual-Ascent Time [secs]**	Feasible (Primal) Solutions		
				CPLEX	**duality gap**	iterations
S	4723.50	4723.50	**<2**	4723.50	**0.00%**	252
SM	28824.17	28817.42	**7**	28824.17	**0.02%**	1321
M	N/A	69935.68	**310**	70655.93	**1.03%**	36619
L	N/A	610703.5	**6205**	624640.81*	**2.28%**	90308
Lnr	N/A	610802.7	**552**	624614.6	**2.26%**	25055

- Gaps below 2.5%.
- CPU time is relatively small.

Computational Results

Results on Row Generation (Dicut Formulation) + Heuristic

Prob	Lower Bound	Dicut	Time (s)	Heuristic	Gap
S	4723.50	4714.22	<1	4938	4.5%
SM	28817.42	28824.2	765	28824.2	0.0%
M	69935.68	70656	64525	70656	1.0%
L	610703.5	624590	359046	653007	6.9%

Results

- Multicommodity Model:
  - Integer solutions on test problems.
  - Optimally solves small instances.
  - Together with the feasible solution given by the Dual-Ascent solves medium-large scaled problems to 2% of optimality.

Results

- Dicut Formulation:
  - Can solve larger instances.
  - Requires more CPU time.

- Better than other approaches (Lag. Relax.)
  - Lower CPU time, lower gaps, larger scale.

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