Imposing Old-growth Patch Constraints in Forest Harvest Scheduling Models

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Forest Harvest Scheduling

1. Maximize profits
2. Protect Environment

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2. Protect Environment

- Schedule "stands" for harvest

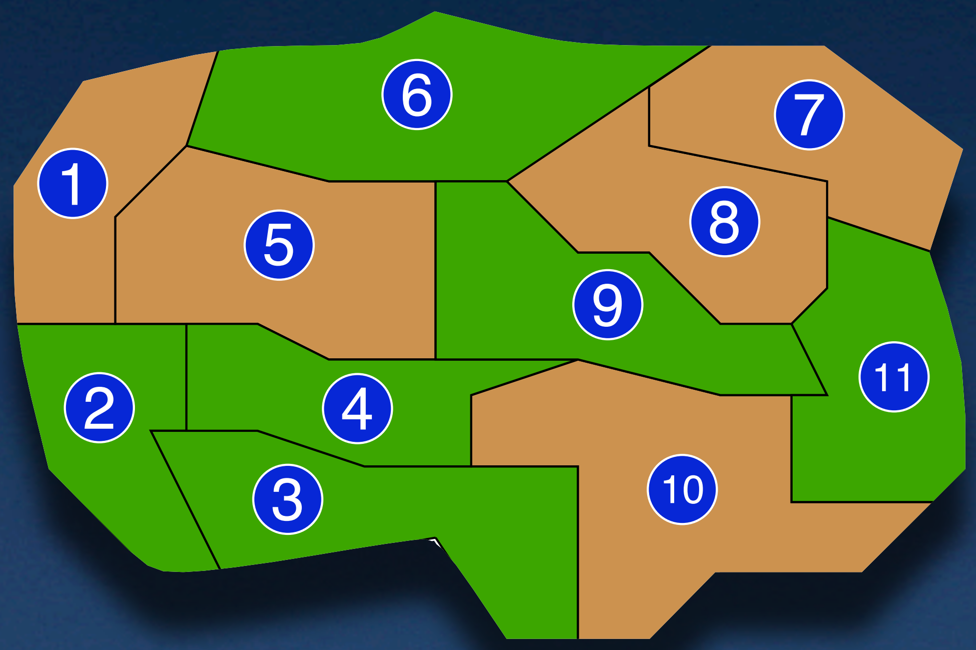
Protect Environment: Connectivity

- Forbid large clear-cut areas:
  - Area Restriction Model (ARM)
  - Good IP models (6000 stands)
  - Goycoolea, Murray, V. and Weintraub, 2009.
- Protect some contiguous areas:
  - Harder problems (400 stands)
  - Old-growth, reserve selection, wildlife corridors

Outline

- Introduction
- Connectivity Constraints
  - ARM
  - Area Protection
- Computational Example
- Conclusions and Future Work

IP Models for Harvest Scheduling

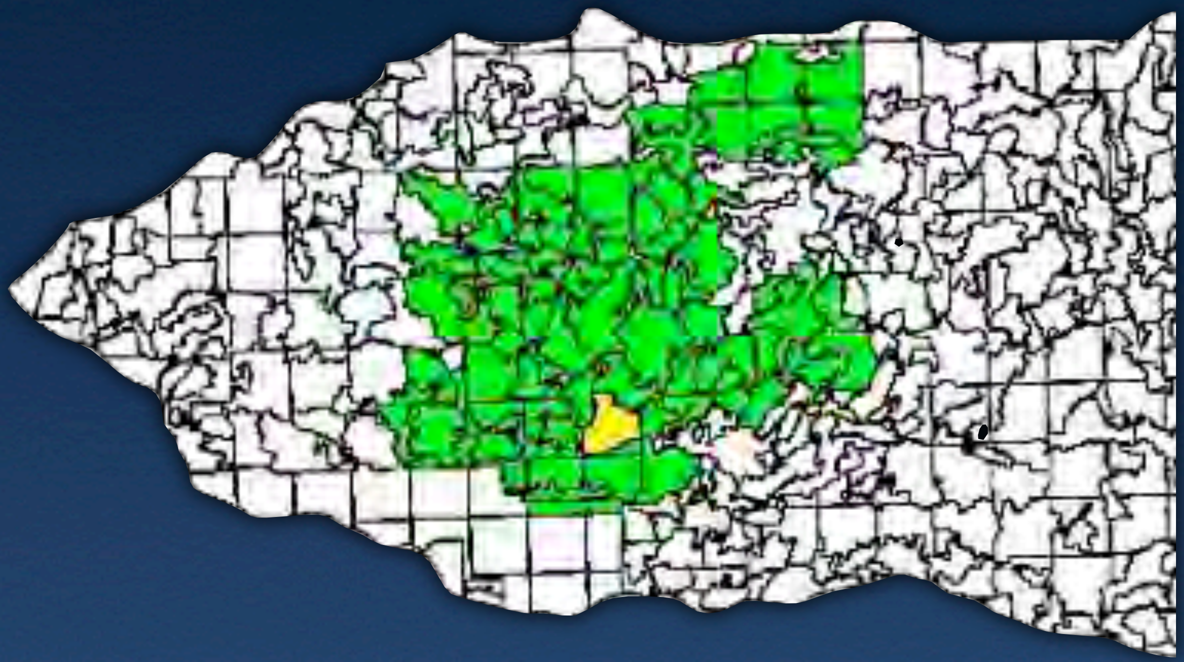


$$y_{v,t} = \begin{cases} 1 & \text{if stand } v \text{ is harvested} \\ & \text{in period } t. \\ 0 & \text{otherwise} \end{cases}$$

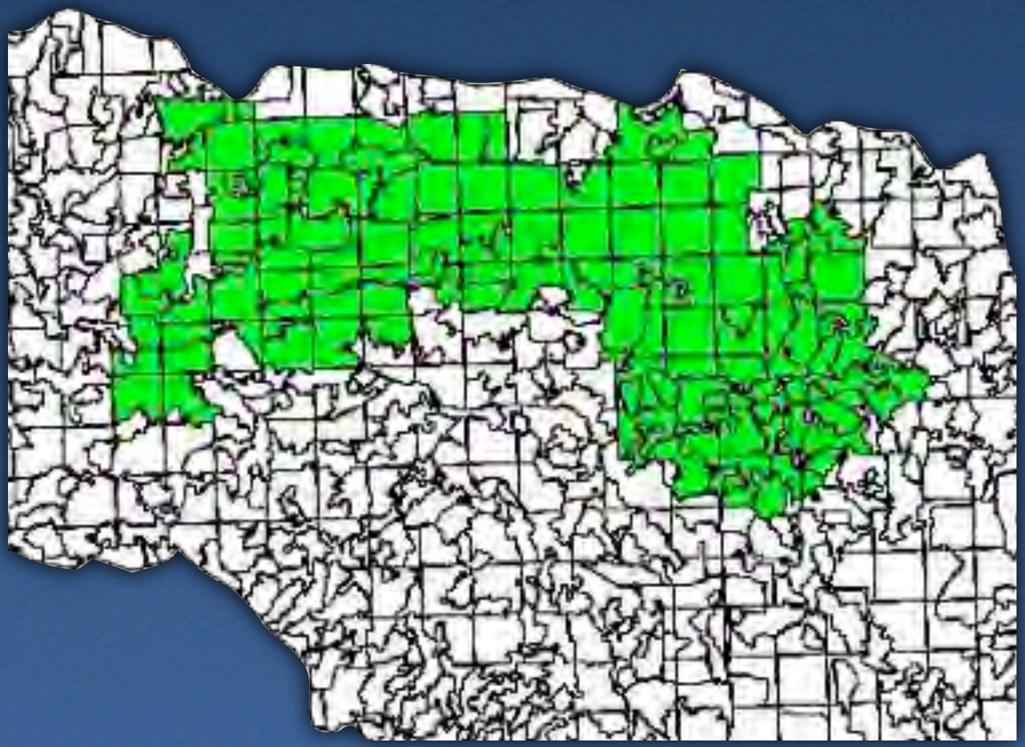
- Linear Constraints/Objective:
  - Profits, timber flow, ending age of forest, etc.
- Combinatorial Constraints:
  - Protect Environment

Connectivity: Single Patch

- Rooted



- Unrooted



Connectivity: Multiple Patches

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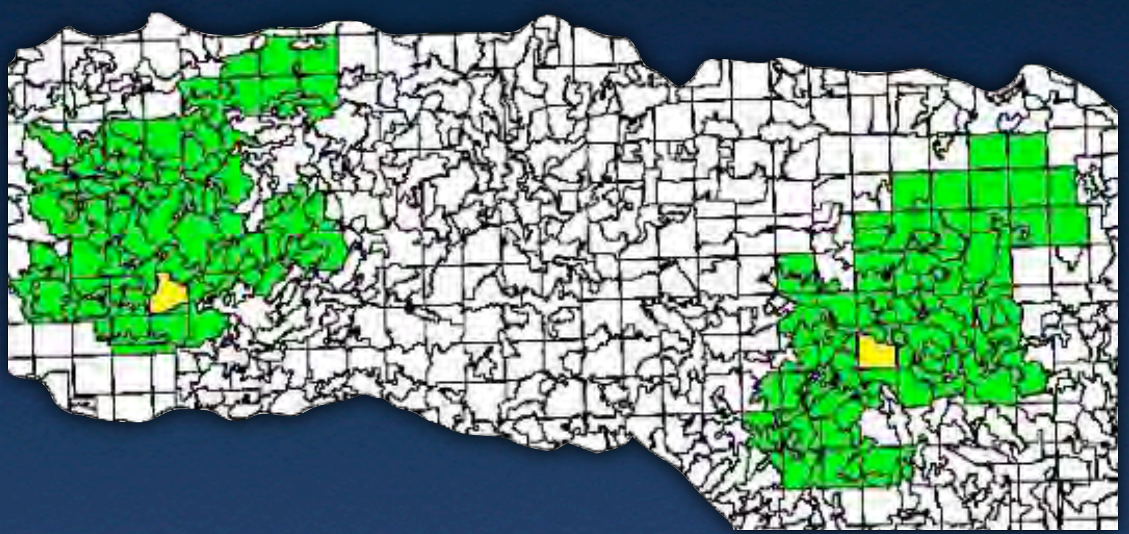
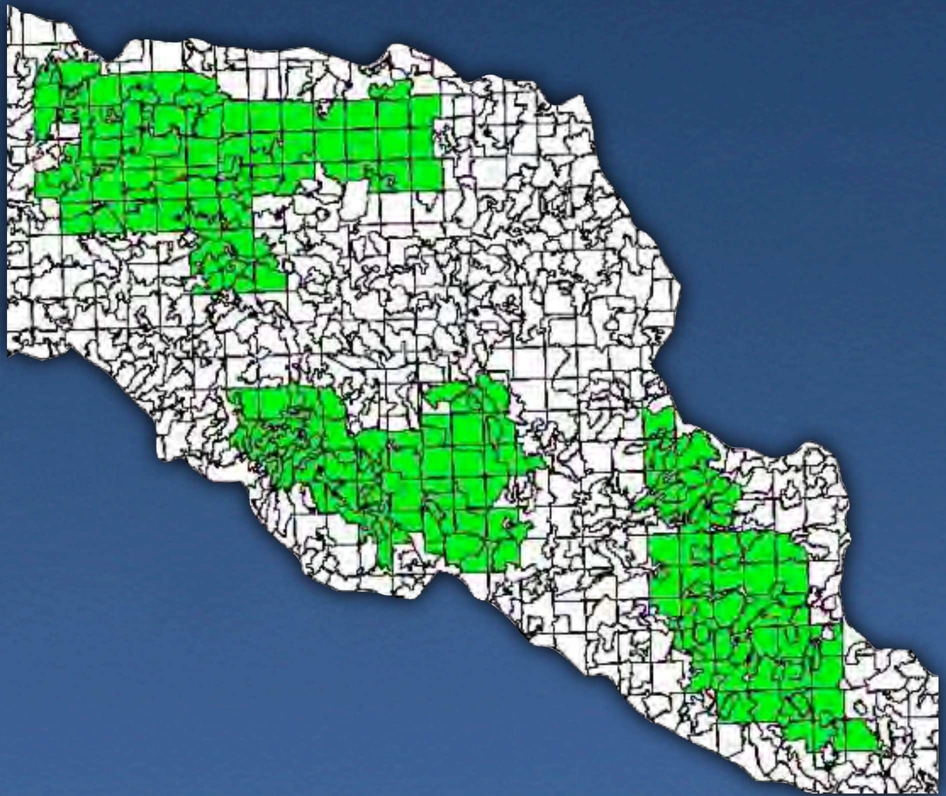
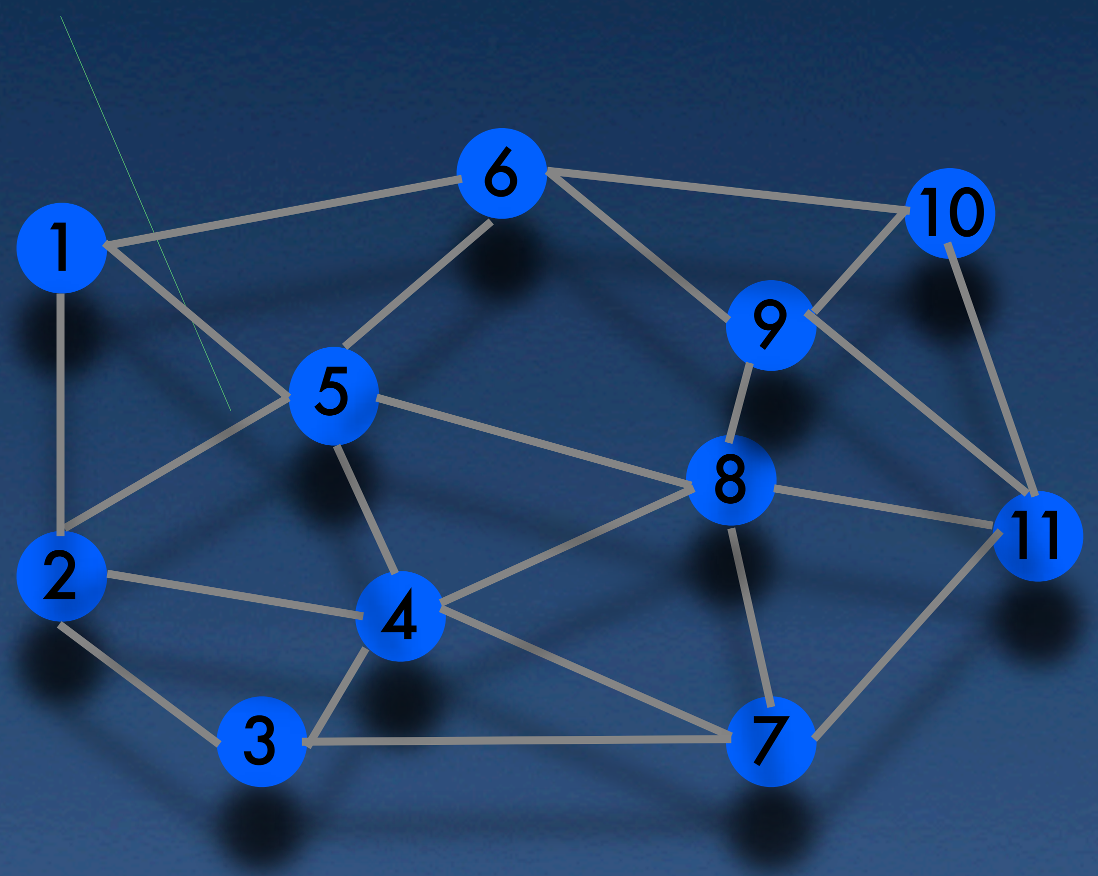


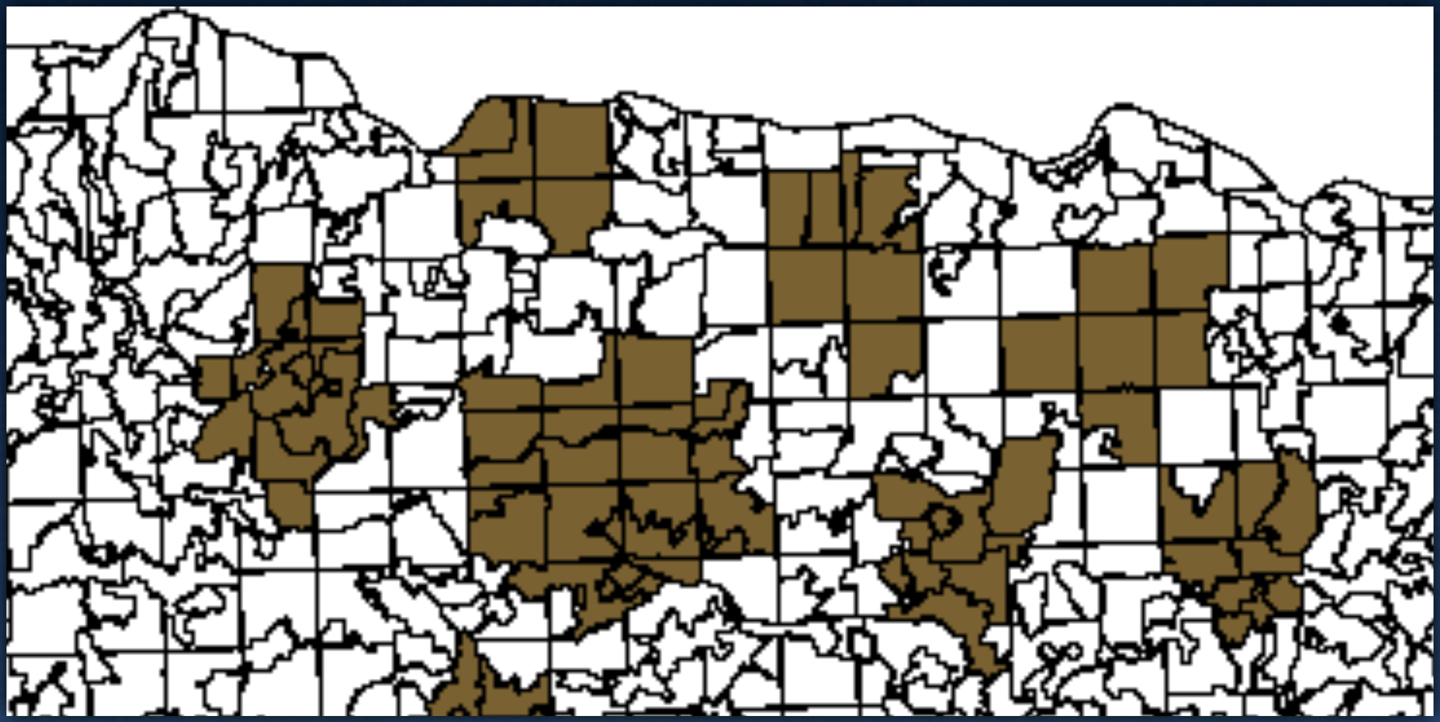
- Unrooted



Graph Representation of Forest

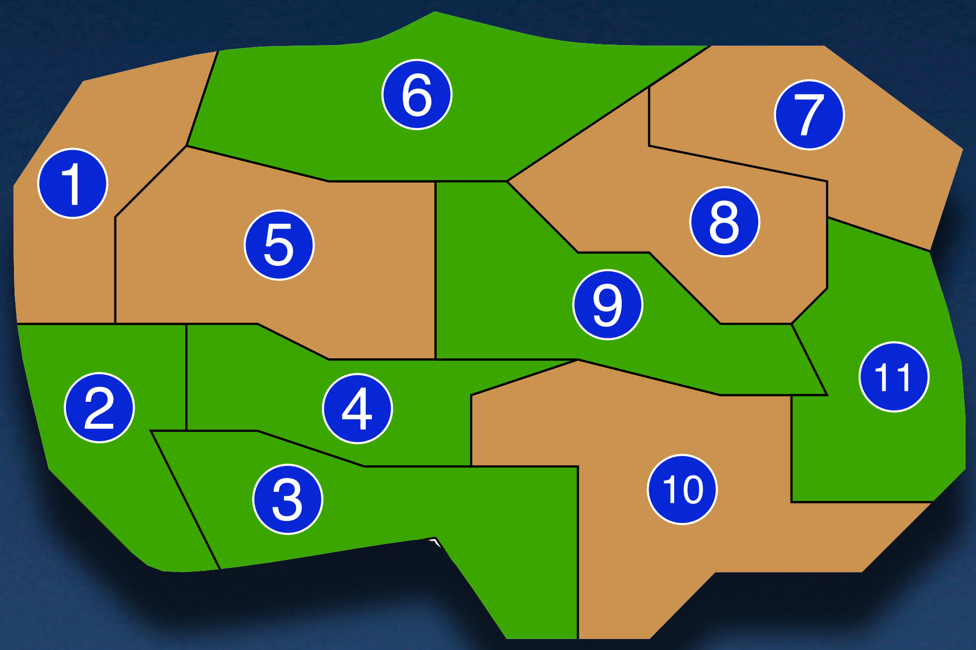


Area Restriction Model (ARM)



- Limit area of contiguous clear-cut region
- Unrooted multi-patch model:
  - Limit ***maximum area*** of patches

Assumptions and Notation

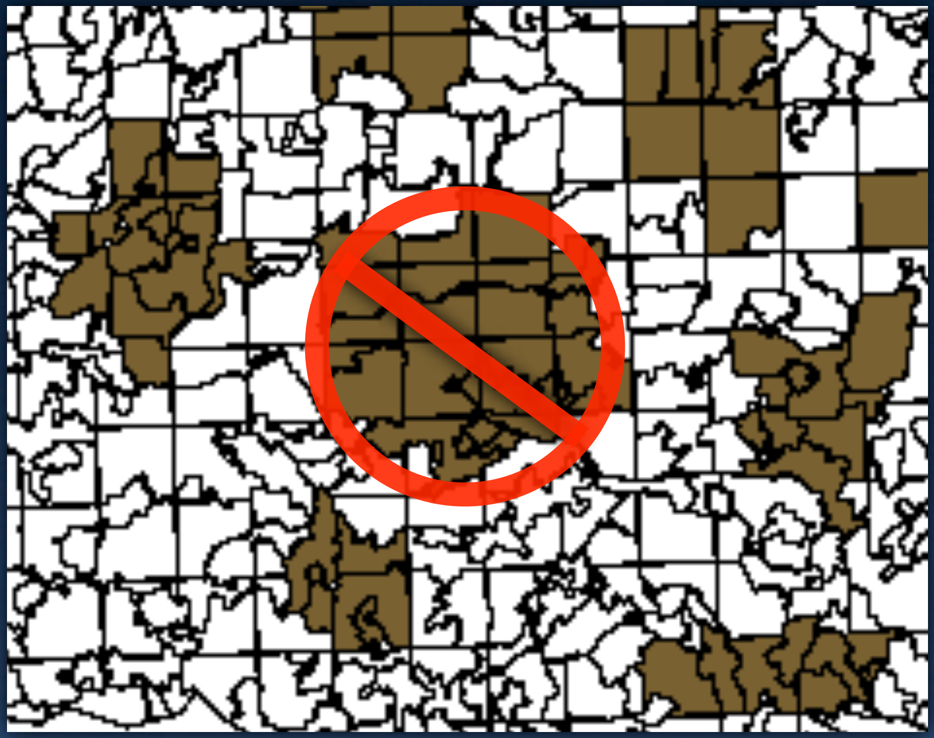


$$y_{v,t} = \begin{cases} 1 & \text{if stand } v \text{ is harvested} \\ & \text{in period } t. \\ 0 & \text{otherwise} \end{cases}$$

- Harvested stands are clear-cut and replanted
  - Stand harvested in t is clear-cut only in t
  - ARM constraints span only one period
- Stands can only be harvested once

ARM Constraints: Forbid Sets

- Connected set of stands C:
  - Area is strictly greater than ***maximum area***
  - Minimal with respect to inclusion



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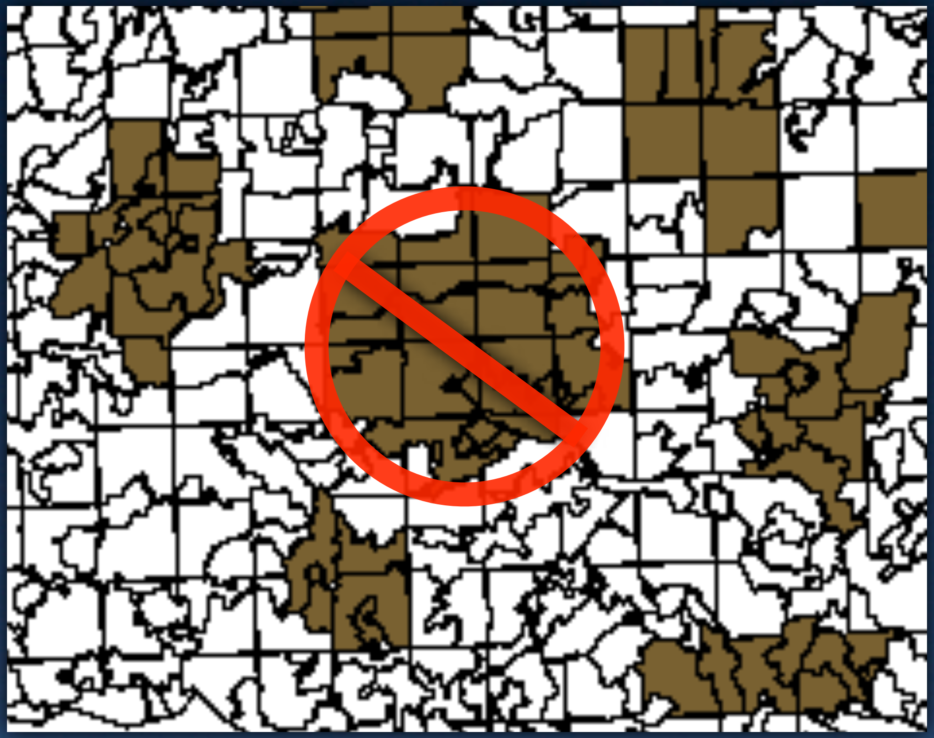

$$\sum_{v \in C} y_{v,t} \leq |C| - 1$$

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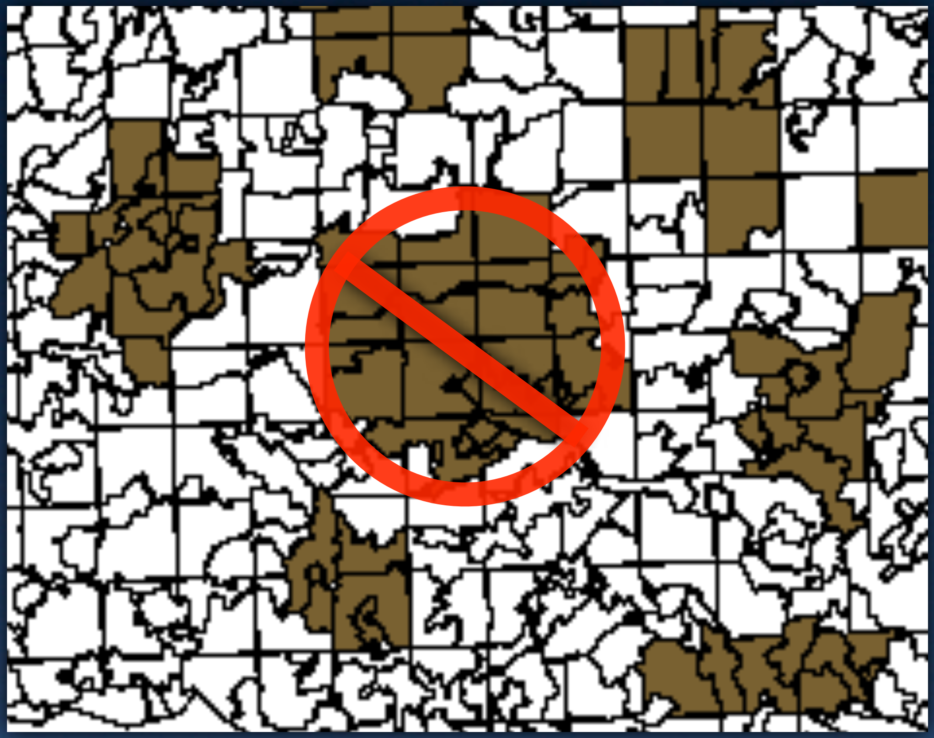


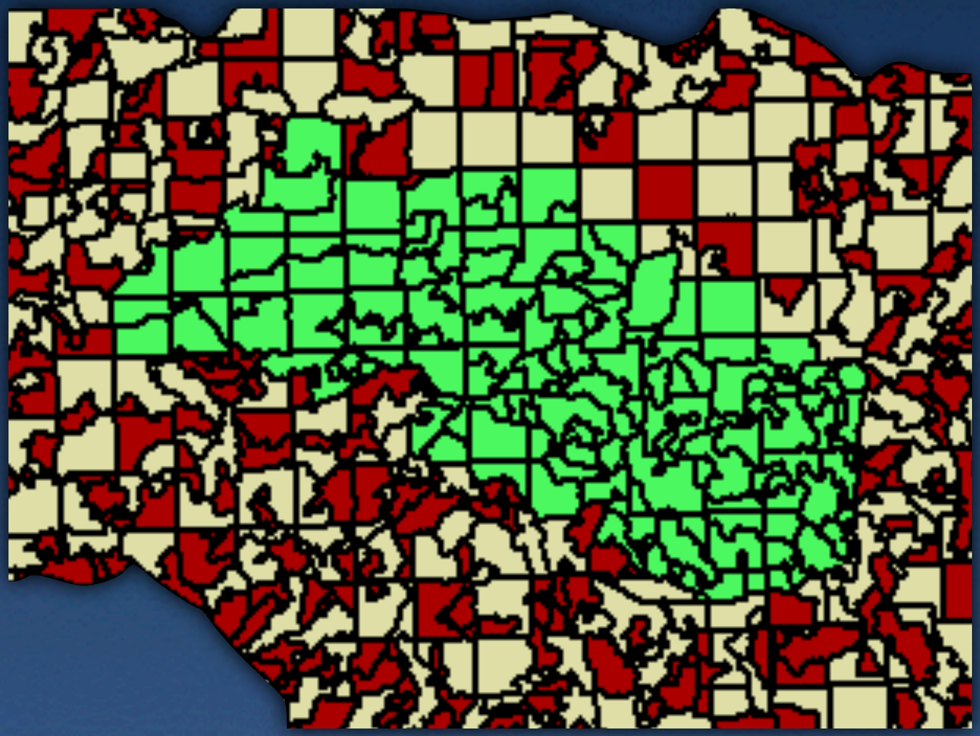
$$\sum_{v \in C} y_{v,t} \leq |C| - 1$$

✓ Usually few of these sets exist

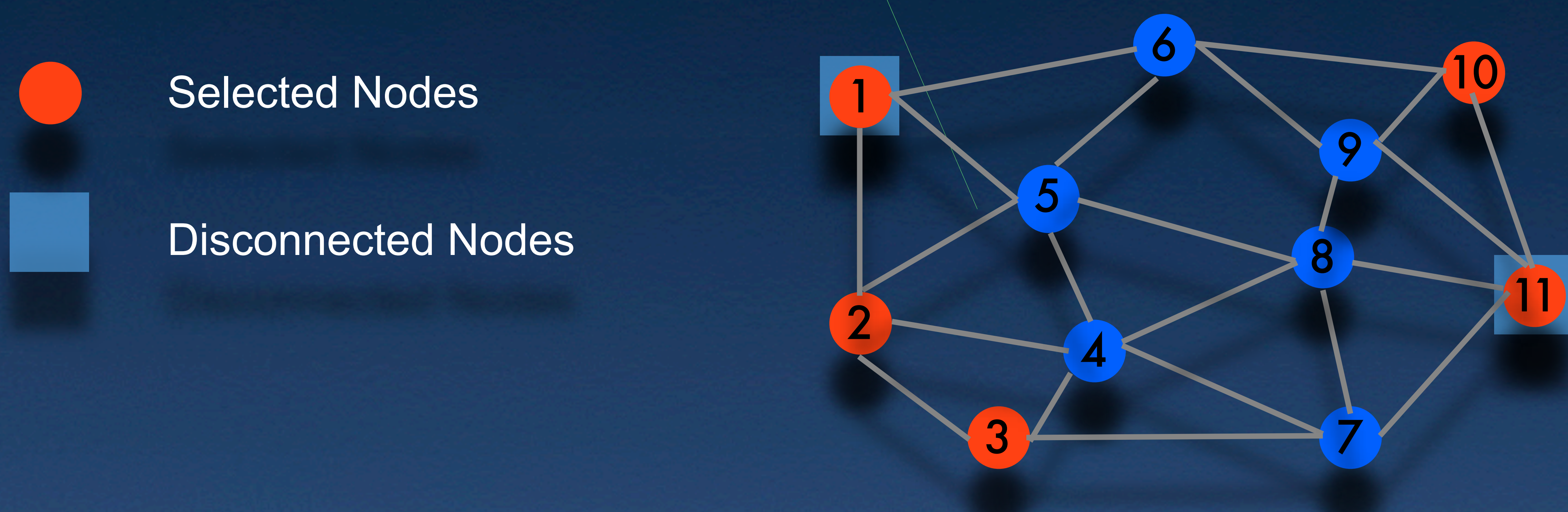
ARM solution = Fragmentation

Need Min Area Connected Patch

- 1+ connected regions:
  - ***minimum*** (average) area
  - is old-growth, contains animal population, contain water source, etc.
  - Other: shape, edge, etc.
- Force connectivity and add other constraints

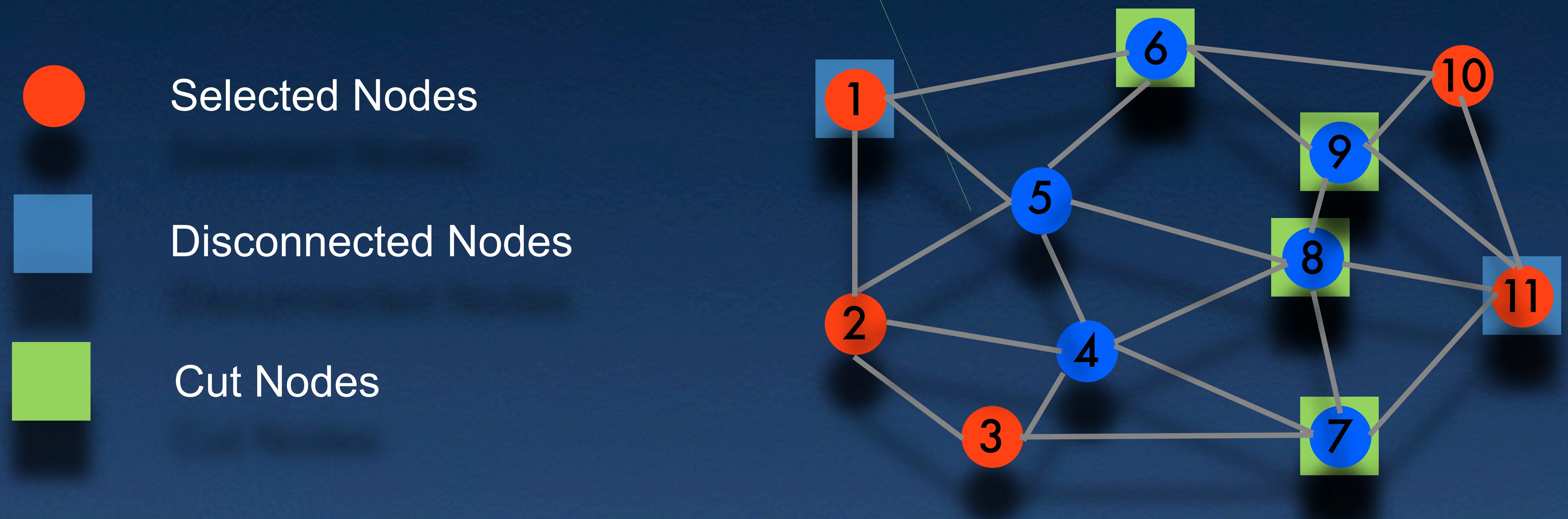


Unrooted (Lack of) Connectivity



- Select red nodes for old-growth/reserve
- Red nodes are disconnected because:

Unrooted (Lack of) Connectivity



- Select red nodes for old-growth/reserve
- Red nodes are disconnected because:
  - There is a node-cut separating 1 and 11 with no selected nodes

Selected Set Is Connected if ...

- Set is connected $\Leftrightarrow$ pairs of nodes are connected
- Pairs are connected $\Leftrightarrow$ every cut separating them intersects selected nodes

Selected Set Is Connected if ...

- Set is connected ⇔ pairs of nodes are connected
- Pairs are connected ⇔ every cut separating them intersects selected nodes

Selected pair of nodes

Other selected nodes

Separating cut

Separating cut intersects selected nodes

Force Connectivity Constraints

$$z_v = \begin{cases} 1 & \text{if stand } v \text{ is selected to be old-growth/reserve} \\ 0 & \text{otherwise} \end{cases}$$

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For every cut S separating u and v

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- Rooted: All selected stands connected to root r

$$\sum_{w \in S} z_w \geq z_v \qquad \forall\, v \qquad \text{For every cut } S \text{ separating } r \text{ and } v$$

Advantages and Disadvantages

- ☑ Can easily add extra requirements
  - e.g. minimum area

$$\sum_v a_v z_v \geq A_{\text{Min}} \qquad a_v = \text{area of stand } v$$

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☐ Too many separating-cut constraints

☑ Separating the constraints is easy

Cutting Plane Procedure

$$\sum_{w \in S} z_w \geq z_u + z_v - 1$$

$z^* =$ current solution

For every pair u, v

check if $z^*_u + z^*_v - 1 > 0$

Find cut S^* that separates u, v and minimizes $\sum_{w \in S^*} z^*_w$

Use max-flow solver

If $\sum_{w \in S^*} z^*_w < z^*_u + z^*_v - 1$

add cut

Problem Specification

1. Maximize NPV of harvest schedule s.t.:
   - ARM Constraints: maximum clear-cut
   - Volume flow constraints
   - Bound on average ending age of forest
2. Additionally:
   - Reserve 10% of forest area as a contiguous old-growth path (unrooted model)

Instances and Solvers

- 5-period instances from FMOS repository:

Instance	Stands	Total area	Max CC Area
El Dorado	1363	52,255.5	120
Shulkell	1039	11,116.65	40
NBCL5A	5581	149,235	80
FLG9A	850	24,708.1	80

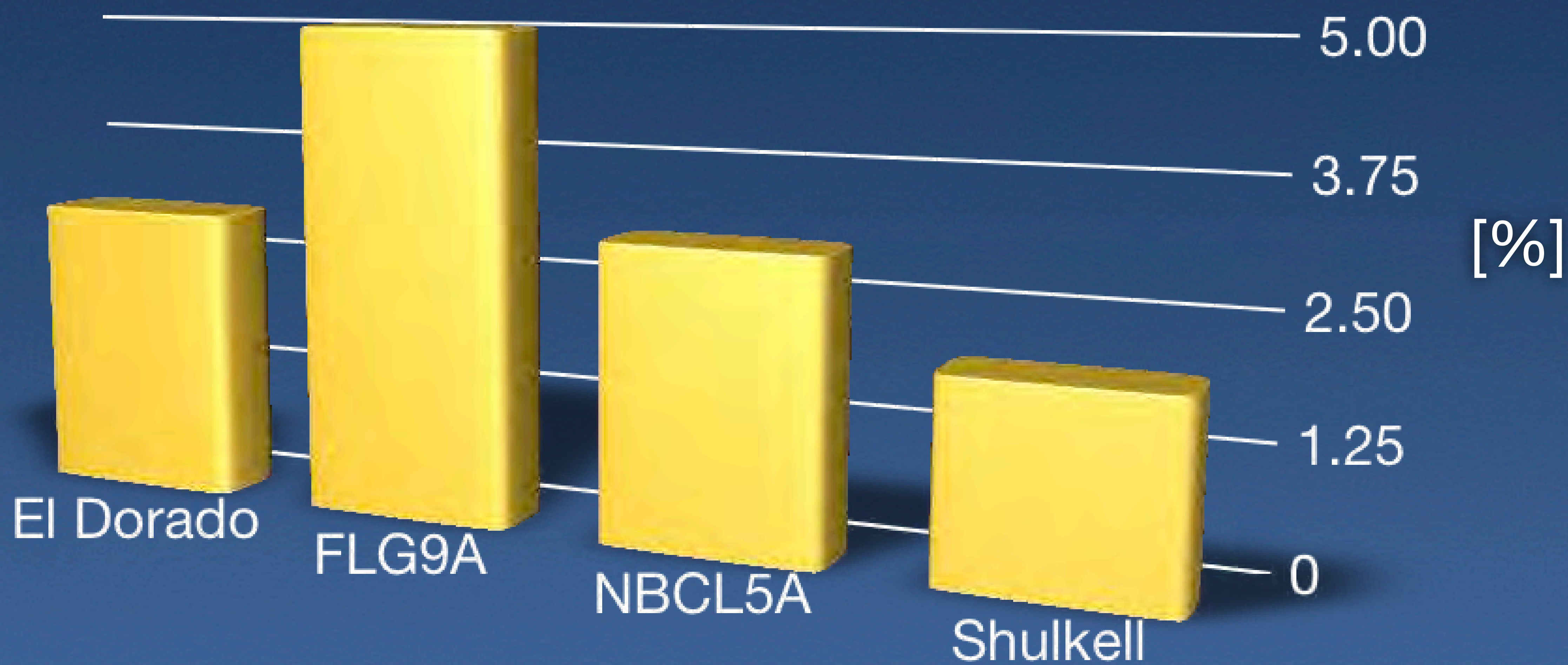
- CPLEX 11 on a Quad-core Xeon with 32Gb RAM

Results: Time limit of 4 hours

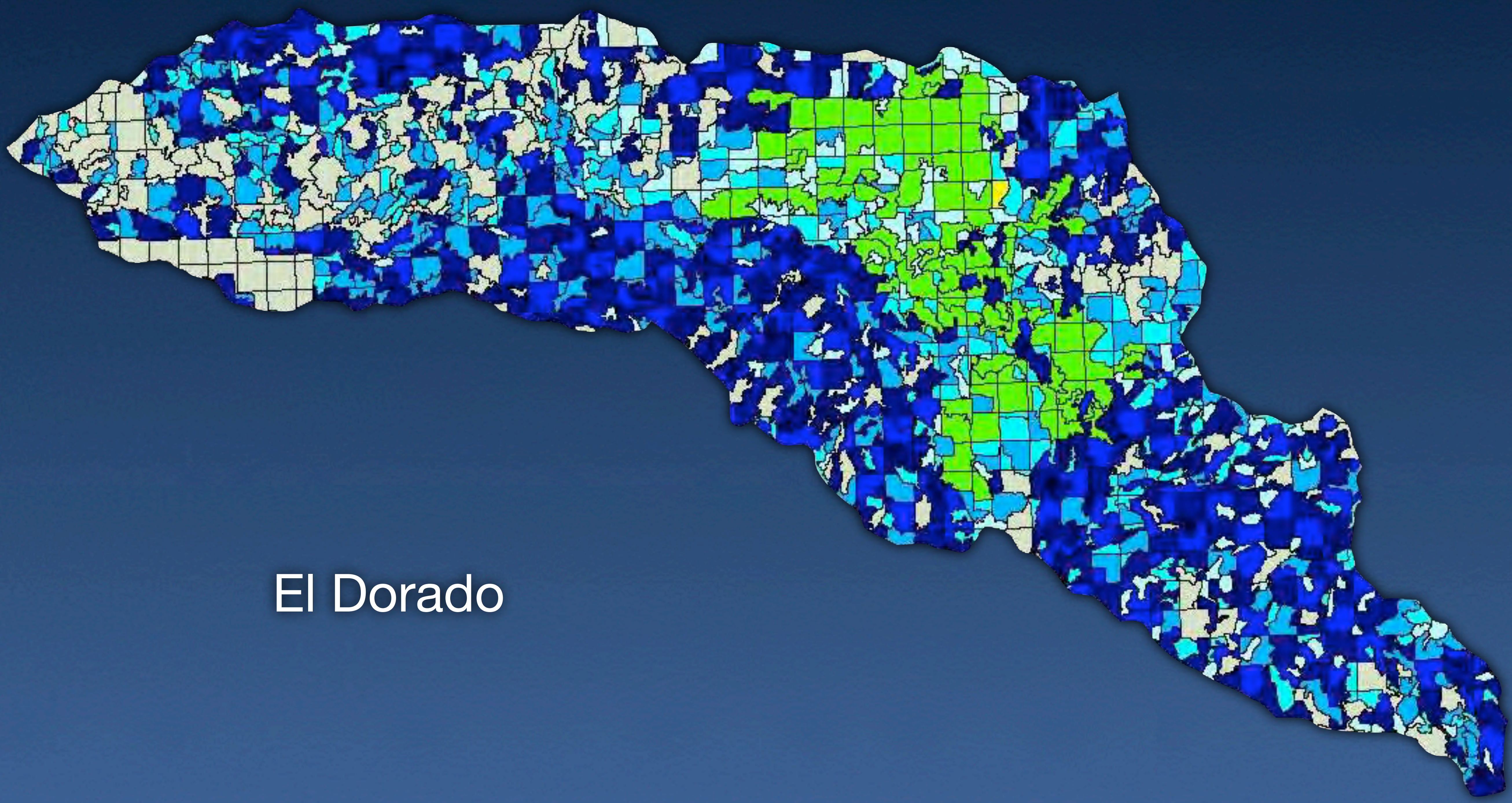
1. ARM:
   - Directly solved by CPLEX
   - 3 optimal in <400s, 1 reaches 0.03% GAP
2. ARM+old-growth
   - CPLEX based branch-and-cut: need heuristics, use of rooted formulations, “ring” cuts, etc.
   - 3 with <1% GAP, 1 with 2.2% GAP

Economic Effect

- ARM: 2-5% loss in NPV
- ARM+old-growth: additional loss of:



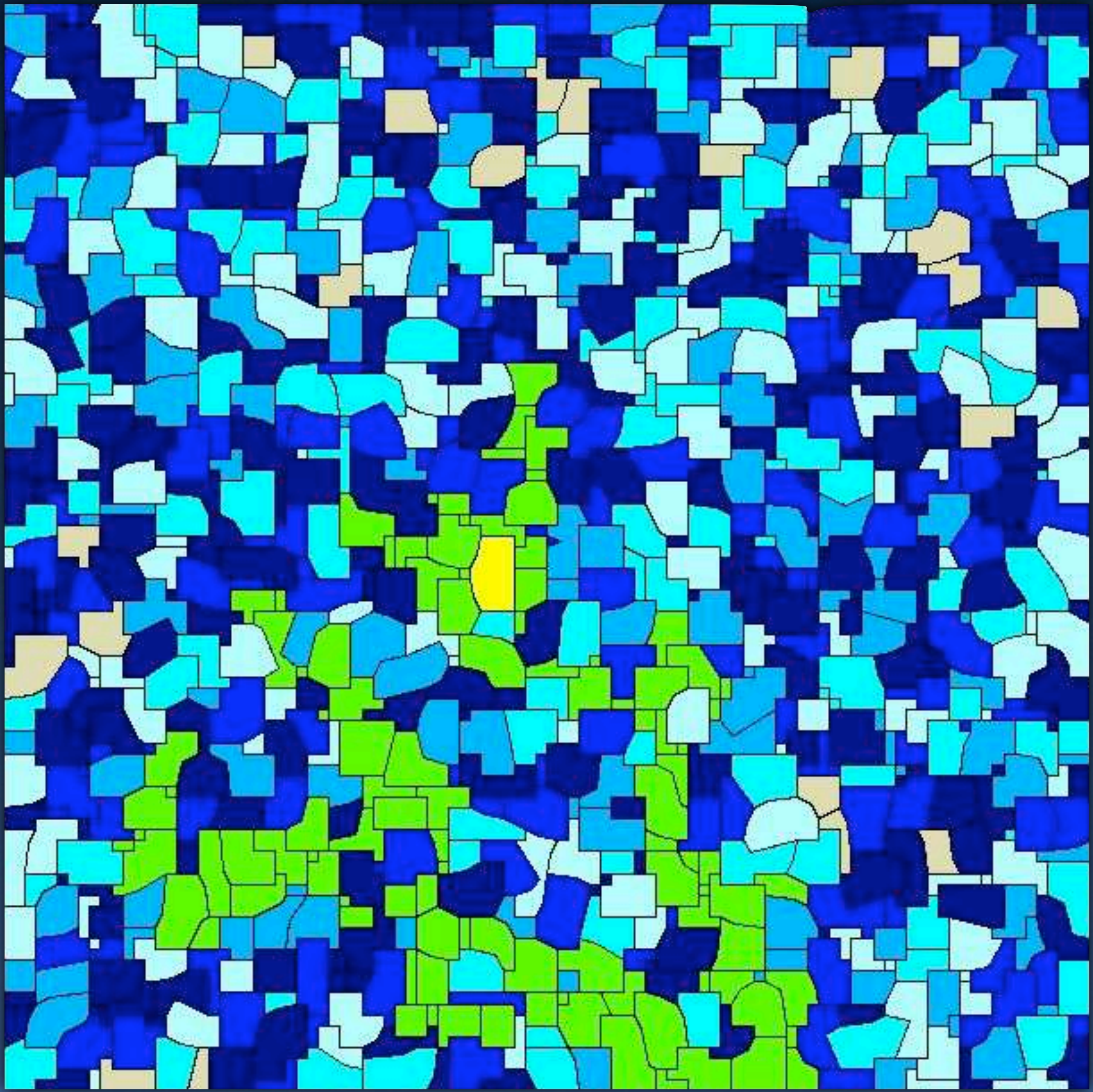
Solutions Sometime Look Good



El Dorado

Solutions Sometime Don’t Look Good

FLG9A



Conclusions and Future Work

- Done:
  - Connectivity for environmental protection
  - Can obtain good solutions for old-growth
  - Optimization: Cost is moderate
- To do:
  - Optimization too “clever”: snake like patches
  - Some challenges in branch-and-cut