Optimization and Modeling at UW: Fish, Cows, Sanctions and Energy

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- Hire (and/or engage) people with breadth of, and complementary expertise - theory, algorithms, computation, applications

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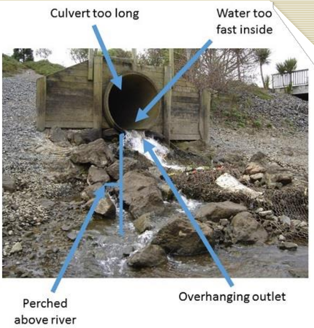
- Hire (and/or engage) people with breadth of, and complementary expertise - theory, algorithms, computation, applications
- Key impact area: decision making in (environmentally) resource constrained problems
- Feature: shared resource that interacts with complex multi-user systems
- Enhance understanding of decision space, facilitate policy design and operational improvement
- Build appropriate models, fast enough solution for expert interaction, visualize results

Overview

- Anadromous fish migrate from the sea upstream into freshwater to spawn.
- Natural & man-made barriers break stream connectivity and prevent fish from penetrating deep into inland lakes and rivers



- There are over 235,000 identified barriers to migration in the Great Lakes Basin
  - Lake Michigan: >83% of tributaries inaccessible
  - Lake Huron: >86% of tributaries inaccessible
  - Lake Erie: >50% reduction of population size

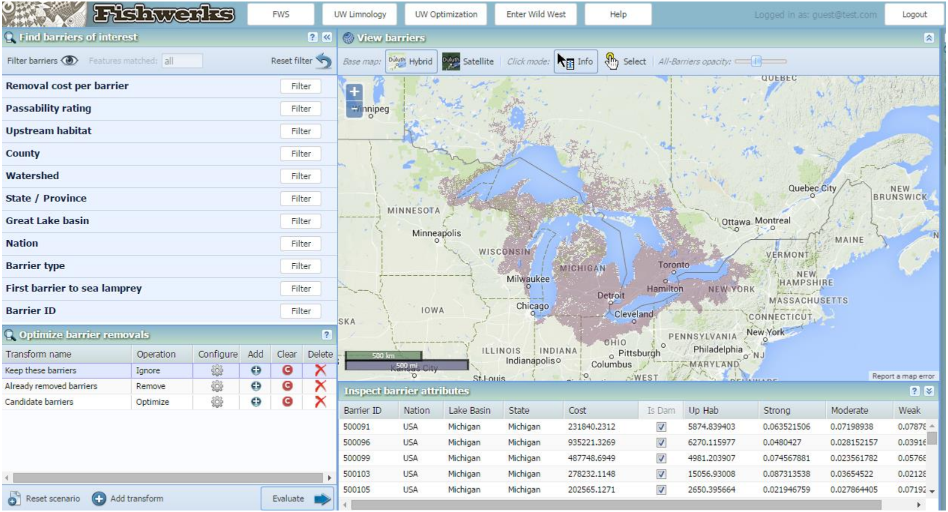
Cont'd

- Barriers can be mitigated to allow for fish passage:
  - Removal of dams, improved road crossings, fish passageways
- However, they are very expensive – Average costs for fixes:
  - Dams: $100,000 - $650,000 each
  - Others: $30,000 - $150,000 per project
- Limited funds necessitate ideal selection of projects
  - Difficult to assess where funds should be used
  - Country/State/County lines make appropriation difficult
- Increasing passability increases risk for the spread of invasive aquatic species (e.g. Sea Lamprey)

The Goal (Customer #1)

1. Provide an interactive tool to consolidate big-data sets across multiple departments (DNR, FWS, NFPP, etc) and visually display in a meaningful way.
2. *Utilize optimization to maximize efficiency in policy decisions and funds appropriations.
3. *Allow any user to dynamically solve a large range of models and scenarios without requiring background knowledge of optimization.
4. Provide means for certified users to update/validate data sets.

Data Visualization: http://www.greatlakesconnectivity.org/



The Data

For every Barrier [J]: 236,264

- Barrier ID – A unique string identifier
- Geographical Info – Nation, State, County, Lake Basin, Watershed
- Barrier Type – Dam or Road Passage
- Cost – Estimated cost to mitigate the barrier
- Root – If the barrier is the first in the stream (no downstream barriers)
- Downstream ID – Identifier of the downstream barrier

For every Fish Guild [S]: 36

- Invasive – If it is an invasive species or not

For every [$J \times S$]: 8,505,504

- Passability Rating – % Chance species can pass this barrier
- Upstream Habitat – Amount of usable habitat upstream of barrier

The Model

Objective:

$$\max \sum_{j \in J} \sum_{s \in S \setminus \text{Inv}} v_{js} * z_{js}$$

Subject To:

$$\sum_{j \in J} x_j * c_j \leq B$$

$$z_{js} = \left(\bar{p}_{js} + \pi_{js} \cdot x_j\right) * z_{ds}, \qquad \forall j \in J, d \in D(j), s \in S$$

$$x_j \in \{0,1\}$$

Where:

- v_{js} := Upstream Habitat, $\bar{p}_{js}$:= Passability Rating, π_{js} := Probability Increase (if mitigated)
- c_j := Cost of mitigation, B := Total Available Budget
- z_{js} := Cumulative passability rating, D(j) := Set of nodes downstream of j. Note: $|D(j)| \leq 1$.
- x_j := Decision to Remove barrier 'j'

Smart Modelling - Linearization

$$z_{js} = (\bar{p}_{js} + \pi_{js} \cdot x_j) * z_{ds}, \qquad \forall j \in J, \forall d \in D(j)$$

Use set of roots ($R \subset J$):

$$z_{rs} = \bar{p}_{rs} + \pi_{rs} \cdot x_r, \qquad \forall r \in R, s \in S$$

Introduce new variable $y_{js} = x_{js} * z_{ds}$:

$$z_{js} = \bar{p}_{js} \cdot z_{ds} + \pi_{js} \cdot y_{js}, \qquad \forall j \in J \backslash R, s \in S$$

Add additional constraints:

$$y_{js} \leq x_j, \qquad \forall j \in J \backslash R, s \in S$$

$$y_{js} \leq z_{ds}, \qquad \forall j \in J \backslash R, s \in S$$

Basic {0,1} LP Model:

$$\max \sum_{j \in J} \sum_{s \in S \setminus \mathrm{Inv}} v_{js} * z_{js}$$

Subject To:

$$\sum_{j \in J} x_j * c_j \leq B$$

$$z_{rs} = \bar{p}_{rs} + \pi_{rs} \cdot x_r, \qquad \forall r \in R, s \in S$$

$$z_{js} = \bar{p}_{js} \cdot z_{ds} + \pi_{js} \cdot y_{js}, \qquad \forall j \in J \setminus \mathrm{R}, s \in S$$

$$y_{js} \leq x_j, \qquad \forall j \in J \setminus \mathrm{R}, s \in S$$

$$y_{js} \leq z_{ds}, \qquad \forall j \in J \setminus \mathrm{R}, s \in S$$

$$x_j \in \{0,1\} \qquad \forall j \in J$$

Interactive Modelling

Allow user to:

- Select their range of influence (i.e. State, County, etc)
- Select mitigatable barriers using a broad range of criteria
- Manipulate Constraints
- Visualize Results

Let's check it out! ($B = 10^7$)

- Minnesota : 3,458 – 6s.
- Wisconsin: 19,854 – Timed Out!?

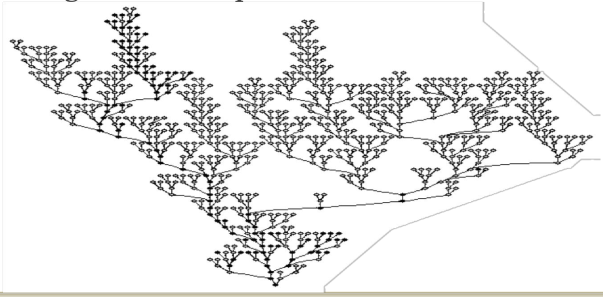
Problem!

{0,1} Linear Programming is $\mathcal{NP} - Complete$!

- Solution time quickly becomes unpractical as problem size grows!
- Web tool requires fast processing to inform user.

Need to find methods to speed up solution time!

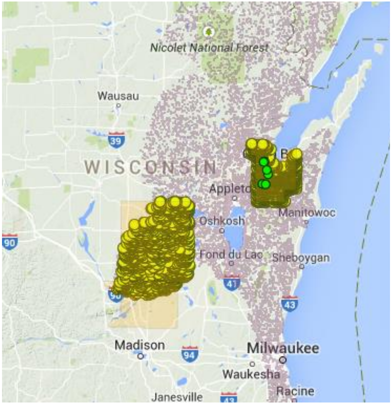
Could we take advantage of the unique structure of our data?



Pre-Processing

Disjoint Counties: Data Compression

- May desire collaboration between counties
- Downstream barriers effected by upstream decisions
  - Barriers in-between are irrelevant
  - Can be removed by smartly incorporating their data into other nodes!



Representative Species

- 36 total fish guilds – Many have very similar parameter data!
- Use QAP to separate guilds into ‘representative groups’
  - Smaller overall data set – improves speed of (relaxed) master solution

$$\min\left\{\sum_{g\in G}\sum_{i\in S}\sum_{j\in S}(d_{ij} * z_{ijg})\right\}$$

Subject to:

$$\sum_{g\in G} x_{sg} = 1, \qquad \forall s \in S$$

$$z_{ijg} \leq x_{ig}, \qquad \forall i,j \in S, g \in G$$

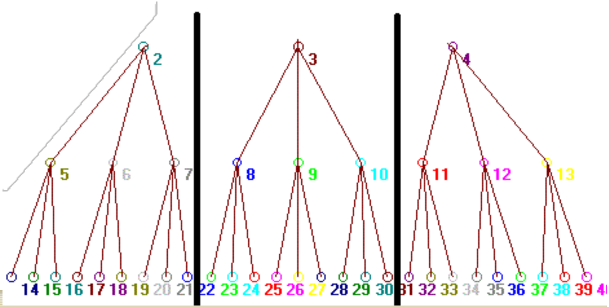
$$z_{ijg} + 1 \geq x_{ig} + x_{jg}, \qquad \forall i,j \in S, g \in G$$

Independent Streams?

Each root node corresponds to a completely independent tree!

Can solve separate, smaller MIP on each tree.

- However, budget constraint is global!
- *How do determine budget in each tree?*



The Goal (Customer #2)

Quickly and accurately create return-on-investment (ROI) curves for a wide-breadth of project scenarios.

- Each curve requires > 20 data points to cover all range of possible budgets!

Supplement base model with additional constraints:

- Ensure that available habitat for ALL species increases by specific amount
  - While still maximizing total habitat
- Prevent invasive species from gaining too much habitat.

Test Data Set: Lake Huron Basin

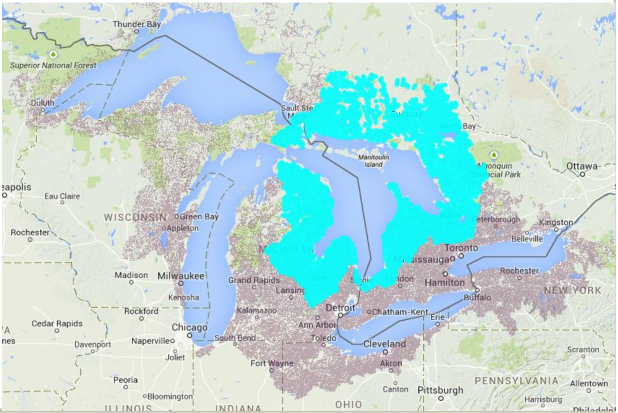
51,149 Barriers

36 Species

- 2 Invasive Species

Model Size:

- 1,934,421 rows
- 1,274,454 columns
  - 753 discrete-columns
- 4,896,386 non-zeroes



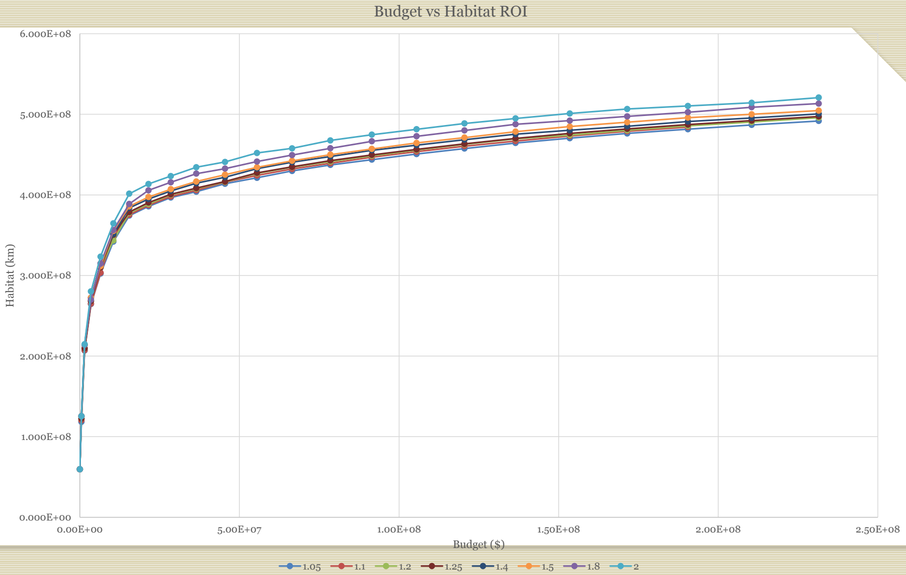
The Problem:

- {0,1} Linear Programming is $\mathcal{NP} - Complete$!
- Our Data Set is extremely large.
- Solution times grow exponentially with budget [CPLEX, WID Clusters]:
  - $B = 10^6$: 8211 s (Gap = 0%)
  - $B = 10^7$: 2132 s (Gap = 0%)
  - $B = 10^8$: >4 days (Gap = 1%)
  - $B = 5 * 10^8$: >4 days (Gap = 10%)
- Customer desires ROI Curve generation, requiring data points over the entire range of budgets and different scenarios!
- Solution time is unpractical for dynamic web-app modelling!

Performance:

Budget ($)	Sol Time (s)	Gap (%)	Sol Time for Best (s)	% Speedup
10^6	573	0.53	8211	1,333 %
10^7	668	0.88	2132	219 %
10^8	2431	1.31	> 4 days	14,116 %

As we can see, we are able to obtain reasonable solutions for most budgets in less than 10 minutes!

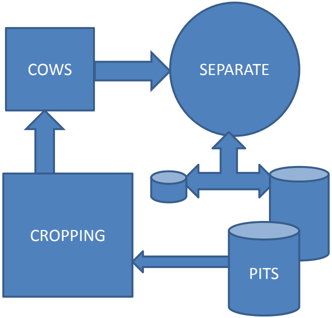


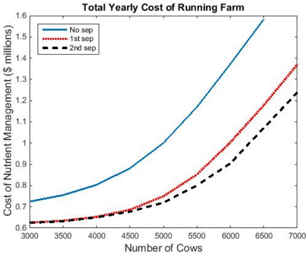
Budget vs Habitat ROI
6.000E+08
5.000E+08
4.000E+08
3.000E+08
2.000E+08
1.000E+08
0.000E+00
Habitat (km)
0.00E+00
5.00E+07
1.00E+08
1.50E+08
2.00E+08
2.50E+08
Budget ($)
1.05
1.1
1.2
1.25
1.4
1.5
1.8
2

Already Impactful!

- Researchers at UW Limnology believe(d) that invasives constraint is vital to amount of attainable habitat.
  - Large amounts of research conducted to identify spread threats
  - Investing research $ into improving mitigation/treatment techniques
    - Pheromones, lampricide, traps, low-head barriers, etc
- ROI Curves show otherwise!
- Either…
  - We've discovered a flaw in current theories on invasive species spreading
  - Or… (More Likely), a flaw in the data set.

Biomass Research and Development Initiative (BRDI)

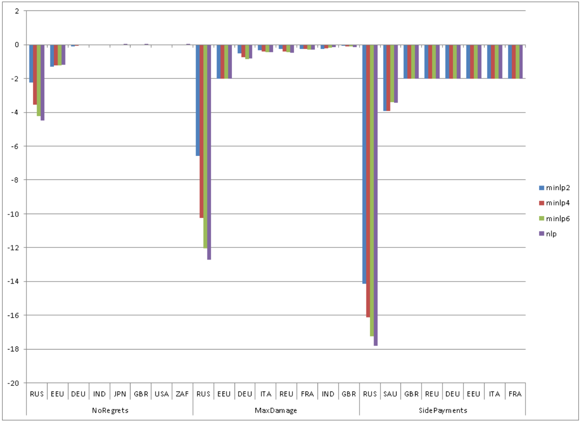




- Whole farm (complex interacting) mathematical model
- Long term sustainable (environment and financial)
- Economic/Logistic Optimization, taking into account phosphorus runoff, other environmental restrictions
- Incorporates data analytics (e.g. SNAP+)
- New insights to operate system efficiently, how to enforce much stricter environmental constraints using blend of rotations, NMP and separations
- Large (mixed integer) optimization

Optimal Sanctions (Boehringer/F./Rutherford)

- GTAP global production/trade database: 113 countries, 57 goods, 5 factors
- Coalition members strategically choose trade taxes to *minimize* Russian welfare
- Russia chooses trade taxes to *maximize* Russian welfare in response
- Nash equilibrium



Resulting equilibrium with no regrets (coalition), maximize damage, side payments

Security-constrained Economic Dispatch (SCED)

$$\min_{u, x_0, \ldots, x_k} \quad c^T u + \rho(u) \qquad \triangleright \text{ Total cost}$$

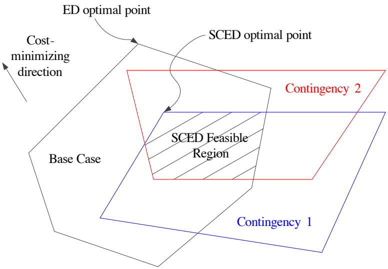
$$\text{s.t.} \quad 0 \le u \le \bar{u} \qquad \triangleright \text{ GEN capacity const.}$$

$$g_0(x_0, u) = 0 \qquad \triangleright \text{Base-case network eqn.}$$

$$-\bar{x} \le x_0 \le \bar{x} \qquad \triangleright \text{Base-case flow limit}$$

$$g_k(x_k, u) = 0, \quad k = 1, \ldots, K \qquad \triangleright \text{Ctgcy network eqn.}$$

$$-\bar{x} \le x_k \le \bar{x}, \quad k = 1, \ldots, K \qquad \triangleright \text{Ctgcy flow limit}$$



- Base-case topology g_0 and line flow x_0
- If k-th line fails, line flow jumps to x_k : $g_k = 0$
- Ensure x_k in bounds $\forall k$

Model structure

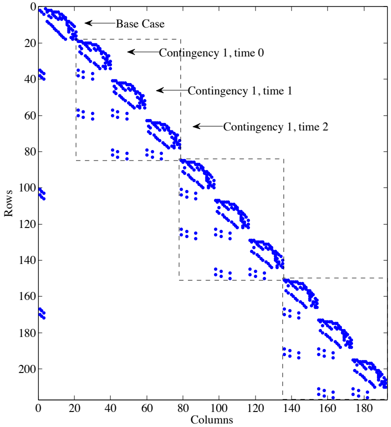


Figure : Sparsity structure of the Jacobian matrix of a 6-bus case, considering 3 contingencies and 3 post-contingency checkpoints.

- Corrective actions are not modeled in ISO's dispatch software (deemed unsolvable!)
- We **model** the *multi-period* corrective rescheduling in SCED; solutions much better quality
- **Enhance** the Benders' **algorithm** to solve the problem faster
- **Achieve** about 50× **speedup** compared to traditional approaches

Conclusions

- Optimization guides the development of complex interaction processes within application domains
- Combination of models provides effective decision tool at multiple scales
- Policy implications addressable using MOPEC
- Problems solved by combination of domain expertise, modeling prowess, good theory/algorithms and efficient implementations all facets needed
- Many new settings available for deployment; need for more theoretic and algorithmic enhancements