Cows, Fish, Fields of Fuel and Optimization

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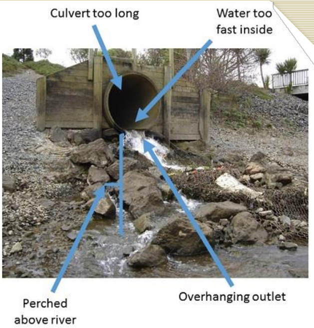
How to enhance the impact of optimization in applications?

- 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

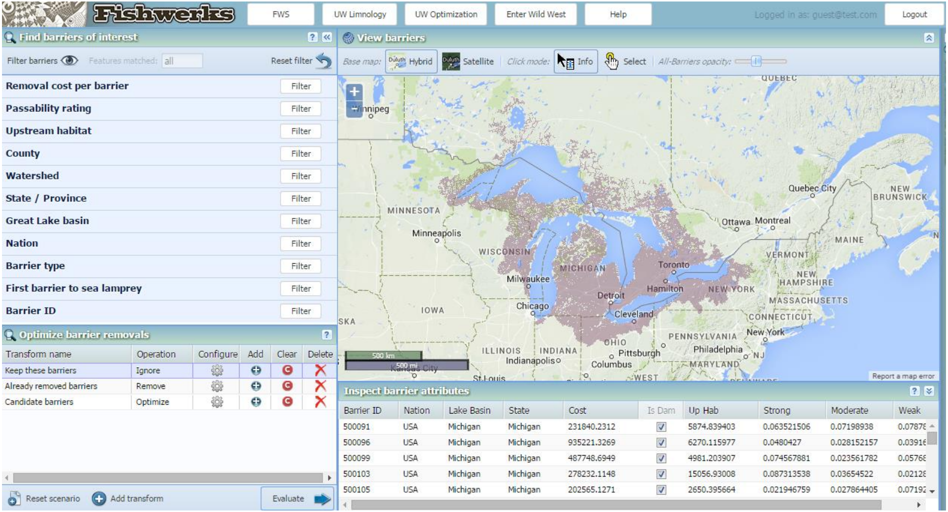
Cont'd

- 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

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

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 $y_{js} = x_{js} * z_{ds}$:

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

Add additional constraints:

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

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

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!?

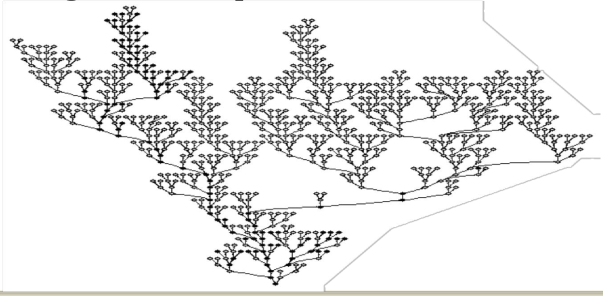
Problem!

{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!

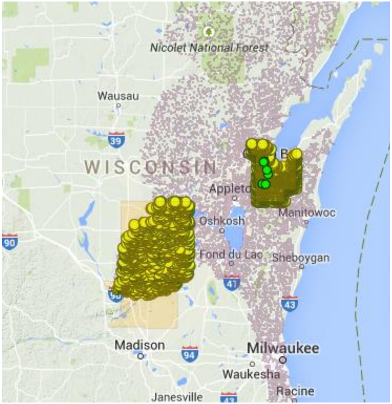
Could we take advantage of the unique structure of our data?



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:

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

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

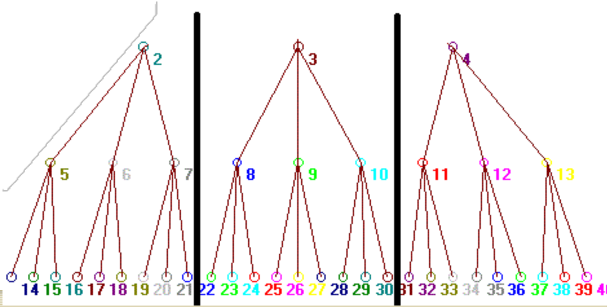
$$z_{ijg} + 1 \geq x_{ig} + x_{jg}, \qquad \forall i, j \in S, g \in G$$

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.

Additional Constraints

- Ensure all (non-invasive) species improve:

$$\sum_{j \in J} (v_{js} * z_{js}) \geq v_{0s} * U_s, \qquad \forall s \in S \backslash \text{Inv}$$

where v_{0s} is the starting habitat for each species and U_s is the percentage increase for each species.

- Prevent over-proliferation of invasive species:

$$\sum_{j \in J} (v_{ji} * z_{ji}) \leq v_{0s} * U_i, \qquad \forall i \in \text{Inv}$$

$$y_{ji} \geq z_{di} + (x_j - 1), \qquad \forall j \in J, i \in Inv, d \in D(j)$$

Full Model:

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

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

$$\sum_{j\in J} \left(v_{js} * z_{js}\right) \ge v_{0s} * U_s, \qquad \forall s \in S\setminus \text{Inv}$$

$$\sum_{j\in J} \left(v_{ji} * z_{ji}\right) \le v_{0s} * U_i, \qquad \forall i \in \text{Inv}$$

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

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

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

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

$$y_{ji} \ge z_{di} + \left(x_j - 1\right), \qquad \forall j \in J, i \in Inv, d \in D(j)$$

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

Test Data Set: Lake Huron Basin

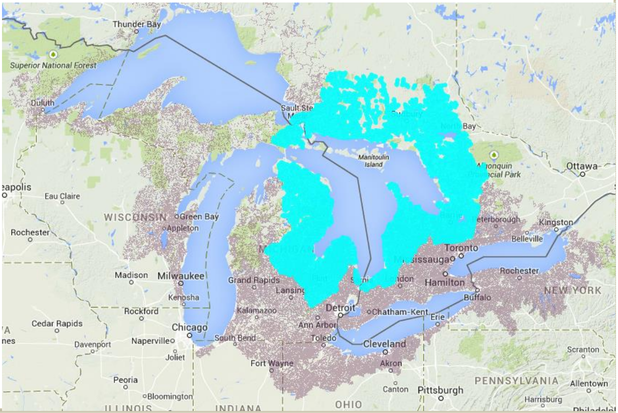
51,149 Barriers

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!

Back to Decomposition

- Entire ‘Forest’ is made up of independent trees (starting at each root)
- But… we have three *Global* constraints that cannot be decomposed

Idea: Use a heuristic to estimate necessary budget within each independent tree.

  - Solve relaxed-MIP over entire data set.
  - Determine amount of total budget spent in each tree.
  - Re-enforce binary constraint on each tree with portion of total budget.

'Master Problem':

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

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

$$\sum_{j \in J} (v_{js} * z_{js}) \ge v_{0s} * U_s, \qquad \forall s \in S \setminus \text{Inv}$$

$$\sum_{j \in J} (v_{ji} * z_{ji}) \le v_{0s} * U_i, \qquad \forall i \in \text{Inv}$$

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

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

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

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

$$y_{ji} \ge z_{di} + (x_j - 1), \qquad \forall j \in J, i \in Inv, d \in D(j)$$

$$0 \le x_j \le 1 \qquad \forall j \in J$$

Decomposing Habitat Constraints

Minimum increase constraint:

- Typical value used: $U = 5\%$
- Bound is never tight – species generally see increases of $100 - 1000\%$!
- **Removed constraints** from decomposition model.

Maximum invasives constraint:

- Relaxed-MIP provides an upper bound on obtainable habitat.
- Therefore, treat invasives habitat exactly like a 'budget'
  - Apportion % of total invasive 'budget' to each tree based on amount allowed in master!
- Upperbound on rMIP guarantees feasible solutions in decomposed trees.

Results:

Budget ($)	Gap (%)
$1 \cdot 10^8$	0.9752
$2 \cdot 10^8$	1.7424
$3 \cdot 10^8$	0.8031
$4 \cdot 10^8$	1.4213
$5 \cdot 10^8$	10.536

- Each scenario still took >2 hours to solve (LP itself can take nearly an hour).
- 11/12 of decomposed trees solve to optimality
  - One tree was too large and exceeded set resource limit (45 min per tree)
- Despite optimal solve in each sub-tree, still did not obtain optimal solutions!
  - What went wrong?!

Problems Identified

Time:

- Not all trees are of equal size!
  - Most are very small (< 1000 *barriers*), solve optimally < 1 minute.
  - Some trees ($1000 < T < 5000$) in size, can take $1 - 30$ minutes to solve
  - One tree $> 11{,}500$ barriers, cannot be solved optimally!
- Thus, even the sub-problems are too large for reasonable solution times

Optimality Gap:

- The rMIP does NOT provide an optimal distribution of the budget!
- 'Partial' removal of barriers allows operations within a tree that are infeasible when constrained to binary programming (violation of invasive constraints).

Solution #1: Time

In order to facilitate faster solution times, sub-problems need to be further decomposed into now-dependent 'Networks'.

Algorithm idea:

- Combine all small trees into larger network.
- Continuously breakdown trees that are too large into smaller subtrees
  - Recursively divide subtrees until they fit into a network.
  - In order to track network dependence, all divided subtree roots are excluded from networks, and instead tracked in a set of 'LeftOut' barriers.
    - Every 'LeftOut' barrier has an association to all networks containing upstream barriers.

How to fix dependency?

Solution #2: Network Dependency

- Many networks are now dependent on the decisions made on their 'LeftOut' set of roots (and subtree roots).
- Therefore, force binary solutions on 'LeftOut' barriers during relaxed Master solve (relax all others).
- For each network:
  - Fix associated 'LeftOut' barriers to values from rMIP.
  - Allocated $ and invasives 'budgets' to each network based on amount used in rMIP.

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!

Why This Works

Though we approached this as a decomposition... It's not!

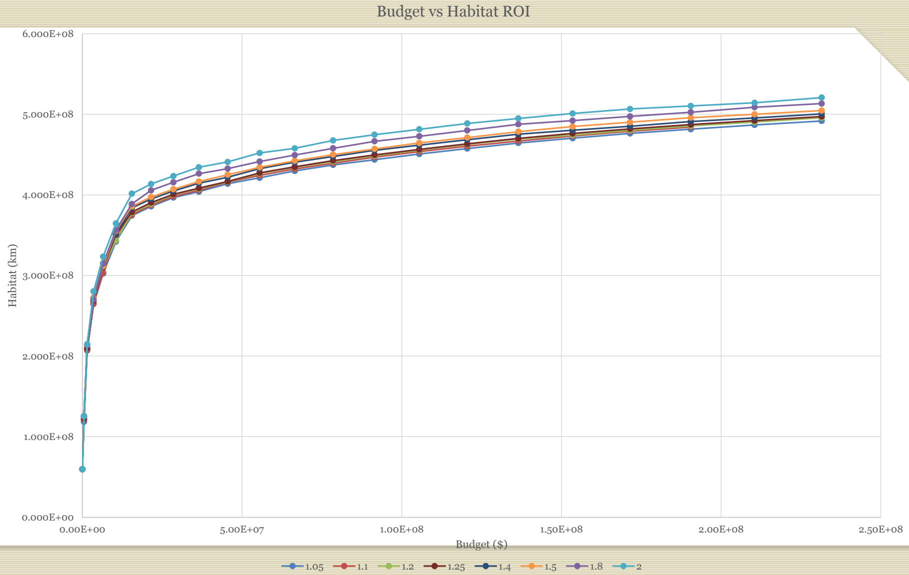
Our network splitting technique is actually a **selection heuristic**!

- 'Leftout' nodes are the barriers 'rooted' at the largest subtrees...
- Thus, they impact the most number of other barriers!
- **Most likely to be significant.**

With smaller budgets, most if not all $ is spent on these barriers!

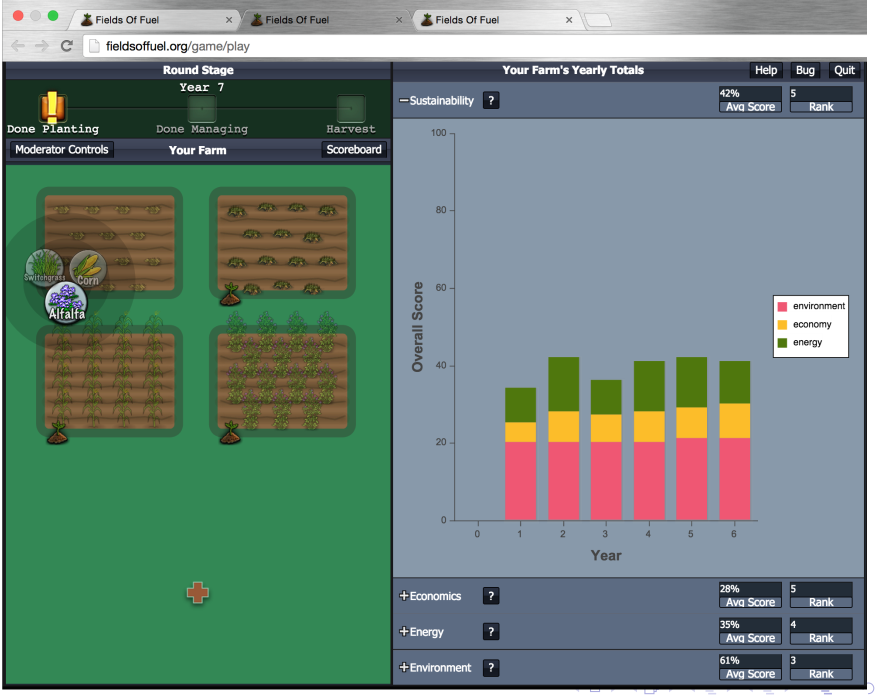
Importance of Fast Algorithm

1.05		1.1		1.2		1.25		1.4		1.5		1.8		2	
Budget	Habitat	Budget	Habitat	Budget	Habitat	Budget	Habitat	Budget	Habitat	Budget	Habitat	Budget	Habitat	Budget	Habitat
0.00E+00	5.945E+07	0.00E+00	5.945E+07	0.00E+00	5.945E+07	0.00E+00	5.945E+07	0.00E+00	5.945E+07	0.00E+00	5.94E+07	0.00E+00	5.945E+07	0.00E+00	5.94E+07
5.00E+05	1.183E+08	5.00E+05	1.203E+08	5.00E+05	1.224E+08	5.00E+05	1.224E+08	5.00E+05	1.254E+08	5.00E+05	1.25E+08	5.00E+05	1.254E+08	5.00E+05	1.25E+08
1.50E+06	2.068E+08	1.50E+06	2.074E+08	1.50E+06	2.096E+08	1.50E+06	2.096E+08	1.50E+06	2.139E+08	1.50E+06	2.14E+08	1.50E+06	2.139E+08	1.50E+06	2.15E+08
3.50E+06	2.645E+08	3.50E+06	2.650E+08	3.50E+06	2.683E+08	3.50E+06	2.683E+08	3.50E+06	2.724E+08	3.50E+06	2.72E+08	3.50E+06	2.699E+08	3.50E+06	2.80E+08
6.50E+06	3.023E+08	6.50E+06	3.033E+08	6.50E+06	3.101E+08	6.50E+06	3.101E+08	6.50E+06	3.148E+08	6.50E+06	3.12E+08	6.50E+06	3.146E+08	6.50E+06	3.23E+08
1.05E+07	3.421E+08	1.05E+07	3.485E+08	1.05E+07	3.435E+08	1.05E+07	3.506E+08	1.05E+07	3.515E+08	1.05E+07	3.55E+08	1.05E+07	3.564E+08	1.05E+07	3.65E+08
1.55E+07	3.743E+08	1.55E+07	3.753E+08	1.55E+07	3.777E+08	1.55E+07	3.788E+08	1.55E+07	3.839E+08	1.55E+07	3.86E+08	1.55E+07	3.888E+08	1.55E+07	4.01E+08
2.15E+07	3.857E+08	2.15E+07	3.872E+08	2.15E+07	3.887E+08	2.15E+07	3.905E+08	2.15E+07	3.949E+08	2.15E+07	3.97E+08	2.15E+07	4.057E+08	2.15E+07	4.14E+08
2.85E+07	3.967E+08	2.85E+07	3.980E+08	2.85E+07	4.002E+08	2.85E+07	4.008E+08	2.85E+07	4.049E+08	2.85E+07	4.07E+08	2.85E+07	4.157E+08	2.85E+07	4.23E+08
3.65E+07	4.040E+08	3.65E+07	4.057E+08	3.65E+07	4.076E+08	3.65E+07	4.084E+08	3.65E+07	4.145E+08	3.65E+07	4.17E+08	3.65E+07	4.264E+08	3.65E+07	4.34E+08
4.55E+07	4.138E+08	4.55E+07	4.158E+08	4.55E+07	4.162E+08	4.55E+07	4.166E+08	4.55E+07	4.219E+08	4.55E+07	4.25E+08	4.55E+07	4.326E+08	4.55E+07	4.41E+08
5.55E+07	4.212E+08	5.55E+07	4.242E+08	5.55E+07	4.266E+08	5.55E+07	4.274E+08	5.55E+07	4.326E+08	5.55E+07	4.34E+08	5.55E+07	4.414E+08	5.55E+07	4.52E+08
6.65E+07	4.297E+08	6.65E+07	4.322E+08	6.65E+07	4.344E+08	6.65E+07	4.348E+08	6.65E+07	4.405E+08	6.65E+07	4.42E+08	6.65E+07	4.494E+08	6.65E+07	4.58E+08
7.85E+07	4.37E+08	7.85E+07	4.393E+08	7.85E+07	4.414E+08	7.85E+07	4.426E+08	7.85E+07	4.476E+08	7.85E+07	4.50E+08	7.85E+07	4.579E+08	7.85E+07	4.68E+08
9.15E+07	4.44E+08	9.15E+07	4.469E+08	9.15E+07	4.485E+08	9.15E+07	4.497E+08	9.15E+07	4.554E+08	9.15E+07	4.57E+08	9.15E+07	4.665E+08	9.15E+07	4.75E+08
1.05E+08	4.51E+08	1.05E+08	4.537E+08	1.05E+08	4.557E+08	1.05E+08	4.564E+08	1.05E+08	4.617E+08	1.05E+08	4.64E+08	1.05E+08	4.728E+08	1.05E+08	4.81E+08
1.20E+08	4.58E+08	1.20E+08	4.604E+08	1.20E+08	4.627E+08	1.20E+08	4.633E+08	1.20E+08	4.685E+08	1.20E+08	4.71E+08	1.20E+08	4.800E+08	1.20E+08	4.89E+08
1.36E+08	4.64E+08	1.36E+08	4.669E+08	1.36E+08	4.695E+08	1.36E+08	4.701E+08	1.36E+08	4.753E+08	1.36E+08	4.79E+08	1.36E+08	4.877E+08	1.36E+08	4.95E+08
1.53E+08	4.70E+08	1.53E+08	4.731E+08	1.53E+08	4.742E+08	1.53E+08	4.762E+08	1.53E+08	4.802E+08	1.53E+08	4.85E+08	1.53E+08	4.92E+08	1.53E+08	5.01E+08
1.71E+08	4.76E+08	1.71E+08	4.790E+08	1.71E+08	4.802E+08	1.71E+08	4.819E+08	1.71E+08	4.852E+08	1.71E+08	4.90E+08	1.71E+08	4.97E+08	1.71E+08	5.07E+08
1.90E+08	4.81E+08	1.90E+08	4.842E+08	1.90E+08	4.856E+08	1.90E+08	4.872E+08	1.90E+08	4.910E+08	1.90E+08	4.96E+08	1.90E+08	5.03E+08	1.90E+08	5.10E+08
2.10E+08	4.87E+08	Total time:	12638	2.10E+08	4.903E+08	2.10E+08	4.921E+08	2.10E+08	4.956E+08	2.10E+08	5.00E+08	2.10E+08	5.09E+08	2.10E+08	5.14E+08
2.31E+08	4.92E+08		3.510556	2.31E+08	4.958E+08	2.31E+08	4.973E+08	2.31E+08	5.006E+08	2.31E+08	5.05E+08	2.31E+08	5.13E+08	2.31E+08	5.21E+08
Total time (s):	11555			Total time:	15851	Total time:	13468	Total time:	27284	Total time:	45020	Total time:	48595	Total time:	44324
Hours:)	3.209722				4.403056		3.741111		7.578889		12.5056		13.49861		12.3122


Budget vs Habitat ROI
Habitat (km)
0.000E+00
1.000E+08
2.000E+08
3.000E+08
4.000E+08
5.000E+08
6.000E+08
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!

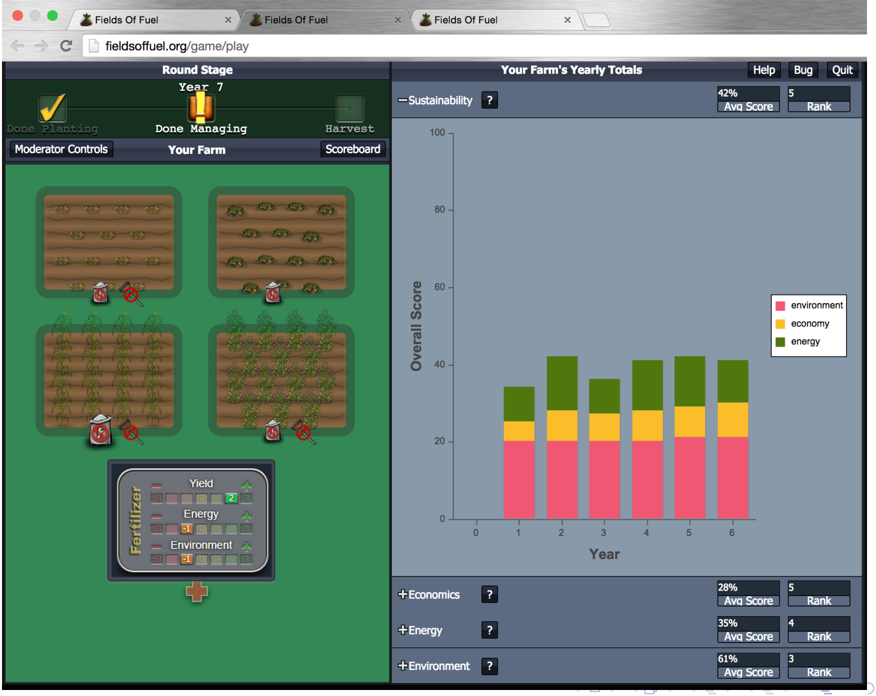
- Researchers at UW Limnology believe(d) that invasives constraint is vital to amount of attainable habitat.
  - Large amounts of research conducted to identify spread threats
  - Investing research $ into improving mitigation/treatment techniques
    - Pheromones, lampricide, traps, low-head barriers, 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.

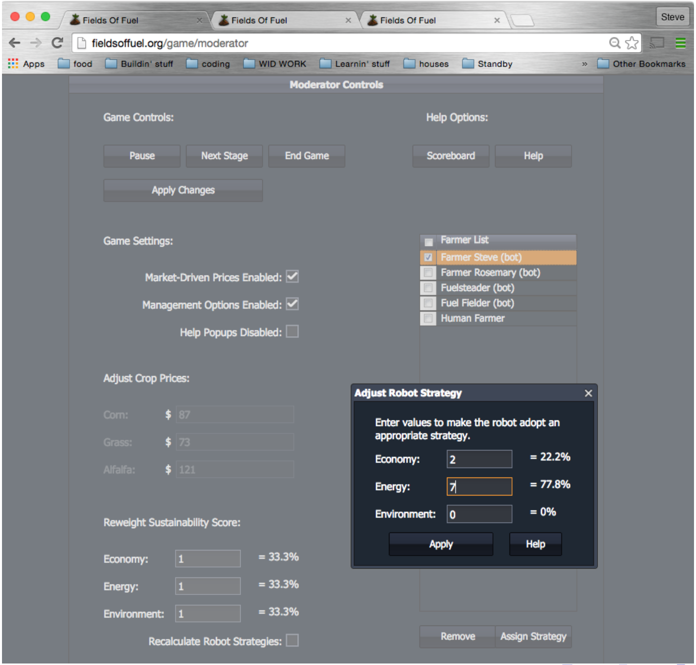

Fields Of Fuel
Fields Of Fuel
Fields Of Fuel
fieldsoffuel.org/game/play
Round Stage
Year 7
Done Planting
Done Managing
Harvest
Moderator Controls
Your Farm
Scoreboard
Switchgrass
Corn
Alfalfa
Your Farm's Yearly Totals
Help
Bug
Quit
Sustainability
?
42%
Avg Score
5
Rank
Overall Score
100
80
60
40
20
0
0
1
2
3
4
5
6
Year
environment
economy
energy
Economics
28%
Avg Score
5
Rank
Energy
35%
Avg Score
4
Rank
Environment
61%
Avg Score
3
Rank


Fields Of Fuel
fieldsoffuel.org/game/play
Round Stage
Year 7
Done Planting
Done Managing
Harvest
Moderator Controls
Your Farm
Scoreboard
$77 (Crop Price)
$14280 (Revenue)
-$7286 (Costs)
=$6994 (Net Income)
$77 (Crop Price)
$12283 (Revenue)
-$7286 (Costs)
=$4997 (Net Income)
$158 (Crop Price)
$43676 (Revenue)
-$18953 (Costs)
=$24722 (Net Income)
$158 (Crop Price)
$51527 (Revenue)
-$18953 (Costs)
=$32574 (Net Income)
Field Changes Over Time
Economy
Energy
Environment
< Previous Year
6
Next Year >
Your Farm's Yearly Totals
Help
Bug
Quit
Sustainability
42% Avg Score
5 Rank
Overall Score
Year
environment
economy
energy
Economics
28% Avg Score
5 Rank
Prices
Revenue
Feed Market
Fuel Market
Price ($ / Ton)
Year
grass
corn
alfalfa
Energy
35% Avg Score
4 Rank
Environment
61% Avg Score
3 Rank


fieldsoffuel.org
Fields Of Fuel
Round Stage
Year 7
Done Planting
Harvest
Moderator Controls
Your Farm
Scoreboard
Corn
21.9 tons/acre
147.7 GJ/acre (Out)
-18.9 GJ/acre (In)
=128.8 GJ/acre (Net)
Corn
21.31 tons/acre
143.7 GJ/acre (Out)
-18.6 GJ/acre (In)
=125.1 GJ/acre (Net)
Switchgrass
6.63 tons/acre
57.6 GJ/acre (Out)
-10.7 GJ/acre (In)
=46.9 GJ/acre (Net)
Switchgrass
7.17 tons/acre
62.3 GJ/acre (Out)
-11.4 GJ/acre (In)
=50.9 GJ/acre (Net)
Field Changes Over Time
Economy
Energy
Environment
< Previous Year
6
Next Year >
Your Farm's Yearly Totals
Help
Bug
Quit
Sustainability
67%
Avg Score
1
Rank
Overall Score
Year
environment
economy
energy
Economics
81%
Avg Score
3
Rank
Energy
70%
Avg Score
1
Rank
Yield
Energy
Energy (GJ)
Year
grass
corn
alfalfa
Environment
45%
Avg Score
3
Rank


Fields Of Fuel
fieldsoffuel.org/game/play
Round Stage
Year 7
Done Planting
Done Managing
Harvest
Moderator Controls
Your Farm
Scoreboard
Switchgrass
1590 Soil Fert (N)
61% Beneficial Bugs
560 tons CO2 eq
98% Water Quality
Switchgrass
1070 Soil Fert (N)
61% Beneficial Bugs
569 tons CO2 eq
98% Water Quality
Corn
575 Soil Fert (N)
53% Beneficial Bugs
3041 tons CO2 eq
88% Water Quality
Corn
2146 Soil Fert (N)
43% Beneficial Bugs
3227 tons CO2 eq
85% Water Quality
Field Changes Over Time
Economy
Energy
Environment
< Previous Year
6
Next Year >
Your Farm's Yearly Totals
Help
Bug
Quit
Sustainability
42% Avg Score
5 Rank
Overall Score
Year
environment
economy
energy
Economics
28% Avg Score
5 Rank
Energy
35% Avg Score
4 Rank
Environment
61% Avg Score
3 Rank
Overall
Water
Emissions
Score
Year
soil health
water quality
beneficial bugs
emissions


Fields Of Fuel
fieldsoffuel.org/game/play
Round Stage
Year 7
Done Planting
Done Managing
Harvest
Moderator Controls
Your Farm
Scoreboard
Fertilizer
Yield
Energy
Environment
Your Farm's Yearly Totals
Help
Bug
Quit
Sustainability
42%
Avg Score
5
Rank
Overall Score
Year
environment
economy
energy
Economics
28%
Avg Score
5
Rank
Energy
35%
Avg Score
4
Rank
Environment
61%
Avg Score
3
Rank


Fields Of Fuel
Fields Of Fuel
Fields Of Fuel
Steve
fieldsoffuel.org/game/moderator
Apps
food
Buildin' stuff
coding
WID WORK
Learnin' stuff
houses
Standby
Other Bookmarks
Moderator Controls
Game Controls:
Help Options:
Pause
Next Stage
End Game
Scoreboard
Help
Apply Changes
Game Settings:
Market-Driven Prices Enabled:
Management Options Enabled:
Help Popups Disabled:
Farmer List
Farmer Steve (bot)
Farmer Rosemary (bot)
Fuelsteader (bot)
Fuel Fielder (bot)
Human Farmer
Adjust Crop Prices:
Corn: $ 87
Grass: $ 73
Alfalfa: $ 121
Adjust Robot Strategy
Enter values to make the robot adopt an appropriate strategy.
Economy: 2 = 22.2%
Energy: 7 = 77.8%
Environment: 0 = 0%
Apply
Help
Reweight Sustainability Score:
Economy: 1 = 33.3%
Energy: 1 = 33.3%
Environment: 1 = 33.3%
Recalculate Robot Strategies:
Remove
Assign Strategy

Idea and implementation

- Multiple agents interacting independently, along with shared resource
- Farmers (planting and management, leeching, CO2)
- Economy (supply, demand, money), Environment (bug index), Energy
- Use in schools, undergraduate classes and group of Ag/Econ experts

Idea and implementation

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- Repeated game
- Single player not interesting - introduce bots
- Implement bots using GAMS
  - Information in: same as a human player
  - Key step: approximate other players actions/response function
  - Different objectives
  - Information out: planting and management decisions

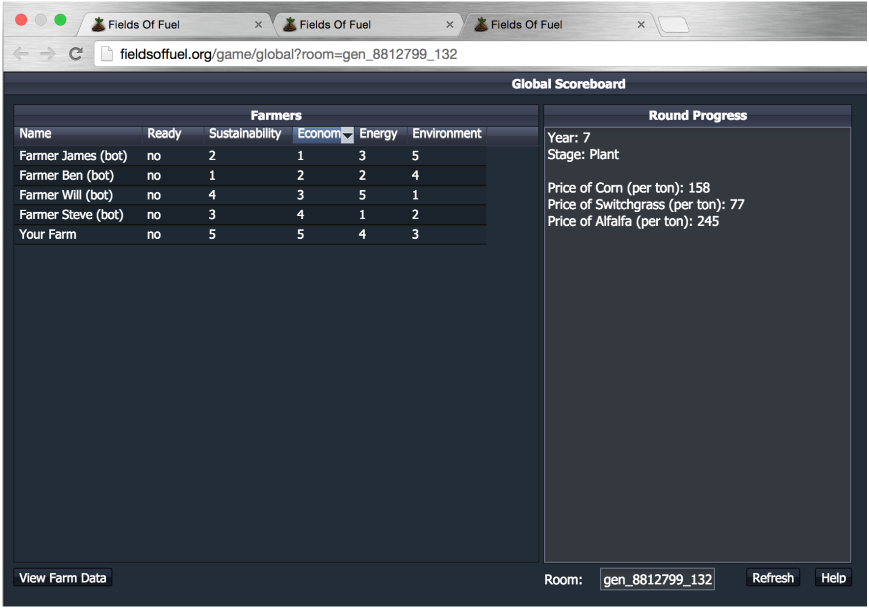
- Point your google chrome browser at: fieldsoffuel.org

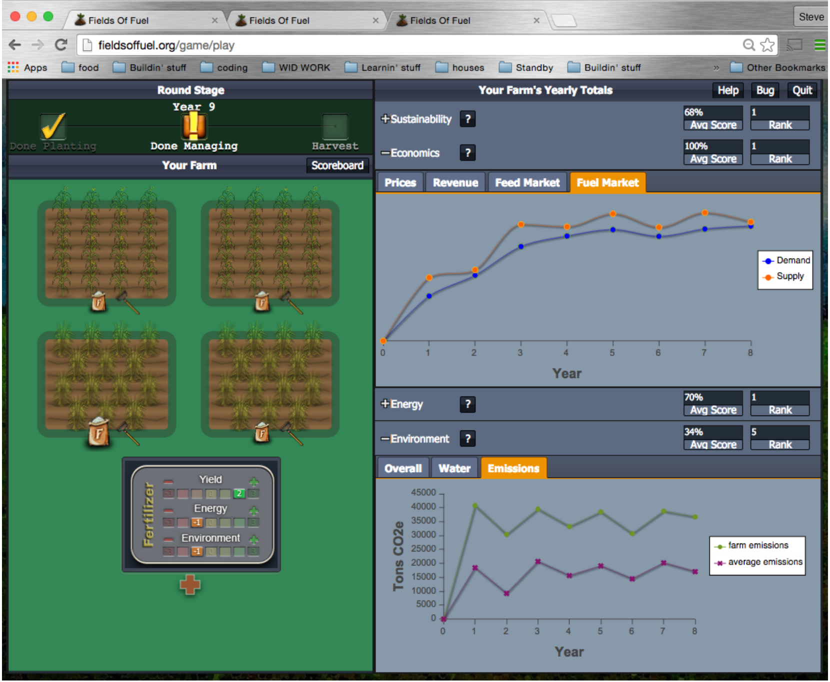
Aside: designing bots

- Bots receive same information as human players (see graphs and help)
- Only know own strategy
- Different objectives (economy, energy, environment, combination)

Aside: designing bots

- Bots receive same information as human players (see graphs and help)
- Only know own strategy
- Different objectives (economy, energy, environment, combination)
- Perennials: need history/look-ahead
- Runoff and bug index: need neighbors strategies
- Understand the economy/prices
- Prediction model for next 5 periods
- Solve multistage look-ahead MIP model (in real time)
- Distributed solution, each bot can use multiple cores


Fields Of Fuel
Fields Of Fuel
Fields Of Fuel
fieldsoffuel.org/game/global?room=gen_8812799_132
Global Scoreboard
Farmers
Name Ready Sustainability Econom Energy Environment
Farmer James (bot) no 2 1 3 5
Farmer Ben (bot) no 1 2 2 4
Farmer Will (bot) no 4 3 5 1
Farmer Steve (bot) no 3 4 1 2
Your Farm no 5 5 4 3
Round Progress
Year: 7
Stage: Plant
Price of Corn (per ton): 158
Price of Switchgrass (per ton): 77
Price of Alfalfa (per ton): 245
View Farm Data
Room: gen_8812799_132
Refresh
Help


Fields Of Fuel
fieldsoffuel.org/game/play
Round Stage
Year 9
Done Planting
Done Managing
Harvest
Your Farm
Scoreboard
Your Farm's Yearly Totals
Help
Bug
Quit
+Sustainability
68%
Avg Score
1
Rank
−Economics
100%
Avg Score
1
Rank
Prices
Revenue
Feed Market
Fuel Market
Demand
Supply
Year
+Energy
70%
Avg Score
1
Rank
−Environment
34%
Avg Score
5
Rank
Overall
Water
Emissions
Tons CO2e
farm emissions
average emissions
Year
Fertilizer
Yield
Energy
Environment

(M)OPEC

$$\min_{x} \theta(x, p) \text{ s.t. } g(x, p) \leq 0$$

$$0 \leq p \perp h(x, p) \geq 0$$

```
equilibrium
min theta x g
vi h p
```

- Solved concurrently

(M)OPEC

$$\frac{\min_{x} \theta(x,p) \text{ s.t. } g(x,p) \le 0}{0 \le p \perp h(x,p) \ge 0}$$

$$\begin{aligned} x \perp \nabla_x \theta(x,p) + \lambda^T \nabla_x g(x,p) \\ 0 \le \lambda \perp -g(x,p) \ge 0 \\ 0 \le p \perp h(x,p) \ge 0 \end{aligned}$$

```
equilibrium
min theta x g
vi h p
```

- Solved concurrently
- Requires global solutions of agents problems (or theory to guarantee KKT are equivalent)
- Theory of existence, uniqueness and stability based in variational analysis

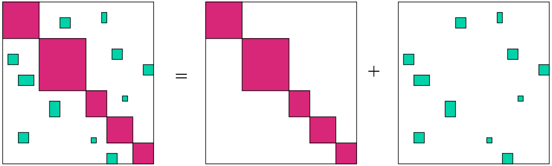
MOPEC

$$\min_{x_i} \theta_i(x_i, x_{-i}, p) \text{ s.t. } g_i(x_i, x_{-i}, p) \leq 0, \forall i$$

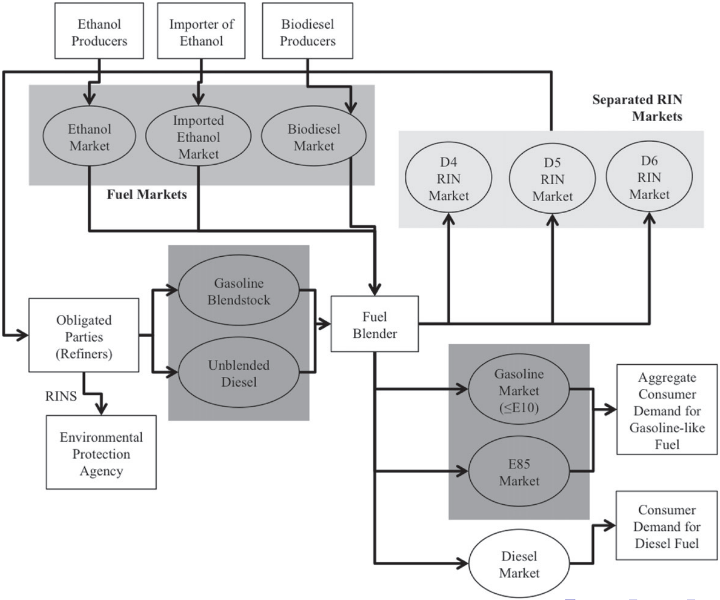
$$p \text{ solves } \mathrm{VI}(h(x, \cdot), C)$$

```
equilibrium
min theta(1) x(1) g(1)
...
min theta(m) x(m) g(m)
vi h p cons
```

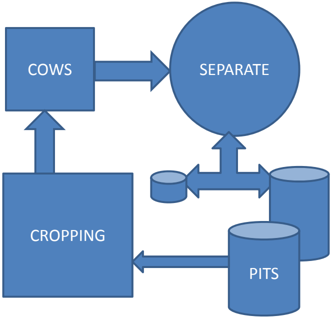
- (Generalized) Nash
- Reformulate optimization problem as first order conditions (complementarity)
- Use nonsmooth Newton methods to solve
- Solve overall problem using "individual optimizations"?

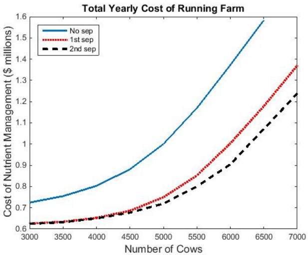


US Biofuel Market



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

Conclusions

- Combination of models provides effective decision tool at multiple scales
- MOPEC problems capture complex interactions between optimizing agents
- Policy implications addressable using MOPEC
- MOPEC available to use within the GAMS modeling system
- Approximation and aggregation improve solution times
- Optimization guides the development of complex interaction processes within application domains
- Many new settings available for deployment; need for more theoretic and algorithmic enhancements