NEXT GENERATION OF MATHEMATICAL PROGRAMMING MODELING AND SOLVING TOOLS

NEW YORK INFORMS METRO CHAPTER
UPDATED FEBRUARY 12 2013
Agenda

- Optimization Problems (OP)
- How do we solve OP?
- Can we Graph and Solve?
- Case Studies
Our Mission Statement

- To provide advanced modeling and solving tools for developing industrial applications in the decision-making and data-mining areas.

- Our targets are:
  - Operating companies in the process industries.
  - Application software providers.
  - Consulting service providers.
Our Industrial Modeling Frameworks

- Process industry business problems can be complex hence an Industrial Modeling Framework provides a pre-project or pre-problem advantage.
- An IMF embeds Intellectual Property related to the process’s flowsheet modeling as well as its problem-solving methodology.
Our Business Model

- What do we license: IMPRESS, IMF, Solvers.
- What is our pricing scheme: License Fee, Support & Maintenance Fee.
- What are our license terms: Based on Customer’s Needs i.e., Rental for a specified period (months to years) or Perpetual.
IA Services

- Application Support
  - Free prototyping to get you started (for a reasonable number of consulting hours).
  - Full modeling and solving support.

- Consulting Services
Academic Collaboration & Partnership

- Carnegie Mellon University
- University of Wisconsin
- Cornell
- Stevens Institute Of Tech
- Fairleigh Dickinson University
Solving a Business Problem with Optimization****

Business Problem

oric Specialist

Mathematical Model

\[ \begin{align*}
\text{min} & \quad c^T x \\
\text{s.t.} & \quad Ax \leq b \\
& \quad x \text{ integer}
\end{align*} \]

OR Specialist

Solver

Solution to
Mathematical Model

\[ x_1 = 3, x_2 = 0, \ldots \]

Business Results

**What are the key decisions?**
**What are the constraints?**
**What are the goals?**

From: Jean-François Puget, IBM Distinguished Engineer, “recent presentation, IBM: Lessons Learned When Selling Optimization To Business Users
Business users

- They don’t care about the technology
- They care about their problem
  - Eg schedule next day plant operations, next month roster for bus drivers, etc
- They want
  - Return on investment
  - Help to solve their problem
  - To be in charge

From: Jean-François Puget, IBM Distinguished Engineer, recent presentation, IBM: Lessons Learned When Selling Optimization To Business Users
Return on investment for optimization is great

Grand Total Benefits Exceed $170 Billion from Edelman Finalist Projects, 1972 through 2010

(Conservatively quantified benefits, realized plus at most 2 years anticipated, in 2011 dollars)

From: Jean-François Puget, IBM Distinguished Engineer, recent presentation, IBM: Lessons Learned When Selling Optimization To Business Users
What are common solving optimization technologies?

- Linear Programming
- Mixed Integer Programming
- Nonlinear Programming
- Constrained Programming
- Meta-Heuristics
Access the solver: Use the Libraries

**Example**
The example above is converted into the following augmented form:

Maximize: $S_1 x_1 + S_2 x_2$  (objective function)
Subject to: $x_1 + x_2 + x_3 = L$  (augmented constraint)

$F_1 x_1 + F_2 x_2 + x_4 = F$  (augmented constraint)
$P_1 x_1 + P_2 x_2 + x_5 = P$  (augmented constraint)

$x_1, x_2, x_3, x_4, x_5 \geq 0$.

where $x_3, x_4, x_5$ are (non-negative) slack variables, representing in this example the unused area, the amount of unused fertilizer, and the amount of unused insecticide.

In matrix form this becomes:

Maximize $Z$:

$$
\begin{bmatrix}
1 & -S_1 & -S_2 & 0 & 0 & 0 \\
0 & 1 & 1 & 0 & 1 & 0 \\
0 & F_1 & F_2 & 0 & 1 & 0 \\
0 & P_1 & P_2 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
Z \\
x_1 \\
x_2 \\
x_3 \\
x_4 \\
x_5
\end{bmatrix}
= 
\begin{bmatrix}
0 \\
L \\
F \\
P
\end{bmatrix},
\begin{bmatrix}
x_1 \\
x_2 \\
x_3 \\
x_4 \\
x_5
\end{bmatrix} \geq 0.
$$

- Load the matrix Using
  - C
  - Visual Basic
  - Python
  - other
Access the solver: Use a modeling language

- Mathematical Programming language (basically they do the same thing):
  - GAMS,
  - AMPL
  - AIMMS
  - MOSEL
  - MPL
  - OPL
  - LINDO
set PERIOD ordered;

param sales_period;
param production_cost {PERIOD};
param production_capacity {PERIOD};
param demand {PERIOD};
param sale_price {PERIOD};
param storage_capacity;
param holding_cost;
param initial_stock;
param final_stock;

var Production {PERIOD} >= 0;
var Storage {PERIOD} >= 0;

maximize Profit:
sum {i in PERIOD} demand[i] * sale_price[i]
  - sum {i in PERIOD} Production[i] * production_cost[i]
  - sum {i in PERIOD: ord(i) < sales_period} Storage[i] * holding_cost;

subject to Storage_Capacity{i in PERIOD}:
Storage[i] <= storage_capacity;

subject to Production_Capacity{i in PERIOD}:
Production[i] <= production_capacity[i];

subject to Balance{i in PERIOD: ord(i)> 1}:
Production[i] + Storage[prev(i)] - demand[i] - Storage[i] = 0;

subject to Initial_Balance:
Production[first(PERIOD)]+ initial_stock-demand[first(PERIOD)]
- Storage[first(PERIOD)] = 0;

subject to Final_Balance:
Storage[last(PERIOD)] = final_stock;
Question #1

- Can we automate the model formulation?
Our Goal: Automate the process of matrix generation

- Literature
  - EMOSL (Dash Optimization)
  - CONCERT (ILOG)
  - Semantic/Structured Modeling (Professor A. Geoffrion)
  - OPTEX – DecisionWare
  - UOPSS (Jeff Kelly)
Our Modeling Environment: IMPRESS

- IMPRESS: Industrial Modeling & Presolving System is our proprietary modeling platform.
- You can model, solve, interface and interact with any supply-chain, production-chain, demand-chain and/or value-chain optimization problem.
- IMPRESS so far has been applied in:
  - Production Planning
  - Plant Scheduling
  - Pipeline & Marine Shipping
  - Energy Management
Why are we unique?

- IMPRESS is **flowsheet-based** (i.e., a figurative language).
  
  This means that the modeling is inherently **network or superstructure “aware”** with equipment-to-equipment, resource-to-resource, activity-to-activity, etc. as explicit language constructs or objects.

  It also means that all of the effort of generating the sparse A matrix in the LP, MILP and NLP is done automatically by automatically creating all of the **sets, parameters, variables and constraints** when the model is configured using our proprietary and comprehensive library of sub-models.
Jet Fuel Supply Chain IMF - Example

- One oil-refinery producing different grades of jet fuel and one airport terminal storing Jet-A, Jet-A1 and Jet-B with a railroad in between.

- Logistics details such as the input-output or yield modeling of the refinery and the round-trip times of the tank-cars (similar to batch-processes with cycle-time) are modeled & solved as a MILP.
Jet Fuel Supply Chain IMF - Flowsheet

Oil-Refinery

Tank Cars

ROUND-TRIP TIMES

Airport Jet Tanks

Simple Structure of the Oil Refinery
Jet Fuel Supply Chain IMF - Flowsheet

Tank Cars and Airport Jet Tanks
Jet Fuel Supply Chain IMF - Flowsheet
Question #2

- What type of Units can I represent in the flowsheet?
Jet Fuel Example - UNITS

- Tank, Pool
- Crude Oil distillation Unit
- Supply Point
- Outlet port – flow interface
- Vacuum Distillation Unit
- Demand Point
Question #3

- How can you add a Unit in IMPRESS?
- What about a general purpose modeling language?
Easy to add or insert Units

Add another tank in parallel

Add a jet fuel parcel (movable inventory)
set PERIOD ordered;

param sales_period;
param production_cost {PERIOD};
param production_capacity {PERIOD};
param demand {PERIOD};
param sale_price {PERIOD};
param storage_capacity;
param holding_cost;
param initial_stock;
param final_stock;

var Production {PERIOD} >= 0;
var Storage {PERIOD} >= 0;

maximize Profit:
sum {i in PERIOD} demand[i] * sale_price[i]
- sum {i in PERIOD} Production[i] * production_cost[i]
- sum {i in PERIOD: ord(i) < sales_period} Storage[i] * holding_cost;

subject to Storage_Capacity{i in PERIOD}:
Storage[i] <= storage_capacity;

subject to Production_Capacity{i in PERIOD}:
Production[i] <= production_capacity[i];

subject to Balance{i in PERIOD: ord(i) > 1}:
Production[i] + Storage[prev(i)] - demand[i] - Storage[i] = 0;

subject to Initial_Balance:
Production[first(PERIOD)] + initial_stock - demand[first(PERIOD)]
- Storage[first(PERIOD)] = 0;

subject to Final_Balance:
Storage[last(PERIOD)] = final_stock;

What about adding in the modeling Language?
You need to add both the node set and arc set in the modeling structures

Variables
Index sets
Data
Constraints
Objective function
## Comparison

<table>
<thead>
<tr>
<th></th>
<th>MODELING Languages</th>
<th>IMPRESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Can you model this problem?</td>
<td>Probably</td>
<td>YES</td>
</tr>
<tr>
<td>How Long it will take? Cost?</td>
<td>6 months</td>
<td>days</td>
</tr>
<tr>
<td></td>
<td>1-2 consultants</td>
<td></td>
</tr>
<tr>
<td>What type of consultant?</td>
<td>OR Specialist</td>
<td>Engineer or OR Specialist</td>
</tr>
<tr>
<td>What about Nonlinear Constraints?</td>
<td>A few modeling Languages</td>
<td>YES</td>
</tr>
<tr>
<td>Multi-Period</td>
<td>You have to do this yourself</td>
<td>Standard</td>
</tr>
<tr>
<td>What happens if I want to delete or add a unit?</td>
<td>Remodel and Reprogram</td>
<td>Add or Delete</td>
</tr>
</tbody>
</table>
How do you draw a chart?
How do we draw the chart

- Use DIA Python, Open Source [Microsoft Visio]
- IML, Data File
- IPL, API
DIA Chart
Question #5: Why this technology now?

- No recent innovation in Modeling Languages
- Mixed Integer Programming Codes are Very Fast (Gurobi, CPLEX, Xpress)
- Engineering Disciplines use optimization, but they are not OR Specialists (they have little modeling expertise and MP expertise)
Question #5: Why this technology now?

- Most of the difficult Planning and Scheduling problems have Special Structures (Electrical Eng. and Chemical Eng.: Power flow network, Process flowsheet, OR specialist have limited experience in modeling them).

- Engineers know about the modeling structure but have limited MP algorithmic experience.
Power Flow Network
Process Flow Network
Planuling = Planning + Scheduling

- **Logistics (Quantity*Logic (proy’d-quality), MILP):**
  - “discrete-time” where each time-period has the same duration.
  - Time-periods may be “small-buckets” (un-ary) or “big-buckets” (N-ary):
    - If un-ary then only one activity per time-period (scheduling) but if N-ary then multiple activities per time-period where a “time-portion” variable for each operation is applied (planning).

- **Quality (Quantity*quality (fixed-logic), NLP):**
  - “distributed-time” where each time-period may have a different duration (global/common time-grid).
  - Same as logistics.

- All input data is entered in “continuous-time” (begin, end-times) and digitized i.e., discretized or distributed accordingly.
Scheduling

without the blender scheduling details

Planning

Solution: duration of each blender grade with time-period

Scheduling only for the blender:

Including setup, startup, switchover, shutdown
Crude Recipe
Crude Scheduling
Including setup, startup, switchover, shutdown

Refining Units
Operational Modes

Products Recipes
Products Planning
resulting targets to blender Scheduling/RTO

1st Planning (big-buckets)  2nd Scheduling (small-buckets)
Supply Chain Optimisation Programme
RASA Benefit Realisation Weekly Summary
-35
-25
-15
-5
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35
2008 Jan*
Feb*
Mar*
Apr*
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w 52
Contribution Relative to Apr08 QS61 Baseline (£k)
Realised Benefit ≠ Missed Opportunity Actual ≠ QS61 or Optimal
A Planning and Scheduling Example: Fast Moving Consumer Goods IMF

- Two materials produced in bulk-unit produces eighteen different packaged materials in pack-unit.
- Sequence-dependent switchovers with setup/setdown times & “repetitive” maintenance cleanouts on bulk-unit with material families.
- Due to the slow & fast nature of the bulk & pack-units we perform “novel” hybrid planning & scheduling i.e., bulk-unit is scheduled & pack-unit is planned to reduce solve time (“planuling”).
Fast Moving Consumer Goods IMF

Setup Times

Sequence-Dependent Switchovers

Forecasted & Firm Future Demand Orders

Plan fast units (A model)
And then with separate model schedule them (B model)

Schedule slow units (A model)
Fast Moving Consumer Goods IMF

- Time Horizon: 60 time-periods w/ day periods.
- Continuous Variables = 10,000
- Binary Variables = 5,000
- Constraints = 20,000
- Time to First Good Solution = 10 to 30-seconds
- Time to Provably Optimal = 1 to 10-hours due to sequence-dependent switchovers.
Cogeneration (Steam/Power) IMF

- Two multi-fuel steam boilers with three modes for different operating regions and standby.
- One steam turbogenerator to produce electrical power from high-pressure steam.
- One electrical power header with import & export of power to plant.
Cogeneration (Steam/Power) IMF

Fuel Header

Boiler1 w/ 3 Modes

Water Pump

Boiler2 w/ 3 Modes

HP Steam Header

Pressure Reducing Valve

Steam Turbogenerator

MP Steam Header

Power Header

Multiple Modes on Boilers
Cogeneration (Steam/Power) IMF

- Time Horizon: 168 time-periods w/ hour periods.
- Continuous Variables = 5,000
- Binary Variables = 1,000
- Constraints = 7,500
- Time to First Good Solution = 5 to 30-seconds
- Time to Provably Optimal = 5 to 15-minutes
Three thermal-plants and two hydro-plants with and without water storage.

Three nodes or buses with voltage phase angle inputs where each bus obeys Kirchhoff’s current and voltage laws.

One time-varying demand load located on bus #3.
Power Generation IMF

Thermal & Hydro Plants

Three Buses/Nodes

Voltage Phase Angles

1st & 2nd Kirchhoff Laws

Electrical Engineering

Varying Demand Load
Capital Investment/Facilities Location Problem
Strategic, Long Range, Fixed-Charge, Economies of Scale, Capacity Expansion, Design Synthesis Problem

Capital, Budgetary, Cash-Flow, Expenditure Constraint

Demand of D, E

Supply of A, B, C

Expansion?
Installation?
Maritime Industrial Shipping IMF

Maritime Transportation with Three Multi-Cargo Ships

*Maritime Inventory Routing Problem* (MIRP, Inventory Management & Ship Routing)

Production of C, D, E from A, B

Supply of A, B

Storage of C, D, E

Each Ship has Two Possible Routes with Different and Variable Cargoes

-**Perimeter**
-**Batch Process**
-**Continuous Process**
-**Pool**
-**Panel**
-**In-Port**
-**Out-Port**

Supply, Demand Points

Holdup When Processing

No Holdup When Processing

Tanks, Warehouses, Reservoirs

Ships, Tankers, Trucks

Materials, Resources, States
What is next?

- Risk Management in the Supply-Chain
- Supply-Chain Strategic Problem
- Marketing Optimization
- Wealth Management Optimization
- On-Line Optimization (RTO)