Supply Chain Optimisation 2.0 for the Process Industries

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inSIGHT 2013 EU, Wiesbaden, Germany, 10 October 2013
About UCL

- Founded in 1826
- The first to admit students regardless of class, race or religion
- The first to admit women students on equal terms with men
- The first to offer the systematic teaching of Medicine, Law and Engineering in England
- UCL is **ranked 4th in the world** in the 2013 QS World University Rankings
First Chemical Engineering Department in UK

1895-1900
Sir William Ramsay
UCL Chemistry
discovers the noble gases

1904
Wins Nobel Prize for Chemistry

1916
Memorial fund for Chemical Engineering at UCL established

1923
First UK Chair and Department of Chemical Engineering
Overview

• Process industry supply chains

• Healthcare - Capacity planning for pharmaceuticals

• Agrochemicals – Global supply chain planning

• Chemicals – Incorporation of sustainability

• Energy - Bioethanol production

• Concluding remarks
The process industries

- The process sector, excluding pharmaceuticals, globally represents almost 2750bn Euro in annual revenues (www.cefic.org)
  - approximately 20% from the European Union

- Chemical and pharmaceutical manufacturing is at the heart of the UK economy (www.cia.org.uk)
  - Annual sales of £60bn
  - 600,000 people depend on the chemical and pharmaceutical industry
  - 12% of total manufacturing, more than twice that of aerospace
Process Supply Chains

- Global, growing industry
- Inter-regional trade flows
- New investments

Increased need/scope for **supply chain optimisation**
- design/infrastructure
- planning/scheduling

Source: [www.cefic.org](http://www.cefic.org), 2012
Supply chain: “The network of facilities and distribution options that performs the functions of procurement of materials, transformation of these materials into intermediate and finished products, and distribution of these products to customers” (Ganeshan and Harrison, 1995)
Key issues in Supply Chain management

1. Supply chain design/infrastructure

- Where to locate new facilities (production, storage, logistics, etc.)
- Significant changes to existing facilities, e.g. expansion, contraction or closure
- Sourcing decisions – what suppliers and supply base to use for each facility
- Allocation decisions
  - what products should be produced at each production facility;
  - which markets should be served by which warehouses, etc.
Key issues in Supply Chain management

1. Supply chain design/infrastructure

2. Supply chain planning and scheduling

• Production planning
  – What should be made where & how

• Distribution
  – How best to distribute material

• Daily production scheduling at each site
  – minimise cost/waste/changeovers
  – meet targets set by higher level planning

• Daily vehicle routing
  – minimise distance
  – maximise capacity utilisation
Key issues in Supply Chain management

1. Supply chain design/infrastructure

2. Supply chain planning and scheduling

3. Supply chain control: real-time management

• How do we get the right product in the right place at the right time?
  – Replenishment strategy
  – Rescheduling
  – E-commerce and data sharing/visibility
  – …
Methodologies for Supply Chain management

- **Mathematical Programming**
  - High-level decisions
    - strategic/tactical
  - Fixed/unknown configuration
  - Aggregate view of dynamics

- **Simulation-based**
  - Fixed configuration
  - Detailed dynamic operation
  - Evaluation of performance measures

- Usually mixed-integer optimisation
- Models vary in:
  - Network representation (how many “echelons”)
  - Steady-state or multiperiod
  - Deterministic or stochastic
  - Single/multiple-objective
  - Degree of “financial” modelling (taxes, duties etc)
  - Detail of process representation
    - Plant level or major equipment level
Supply chain optimisation: trade-offs

- Differences in regional production costs
- Distribution costs of raw materials, intermediates and products
- Differences in regional taxation and duty structures, exchange rate variations
- Manufacturing complexity and efficiency
  - related to the number of different products being produced at any one site
- Network complexity
  - related to the number of different possible pathways from raw materials to ultimate consumers
Four focus areas

1. Healthcare – Pharmaceutical planning
2. Agrochemicals – Global supply chain planning
3. Chemicals – Sustainability
4. Energy – Biomass supply chains
Pharmaceutical supply chains

- Discovery generates candidate molecules
- Variety of trials evaluates efficacy and safety
- Complex regulation process

- Manufacturing
  - Primary manufacture of active ingredient
  - Secondary manufacture – production of actual doses
  - Often geographically separate for taxation, political etc reasons

- Distribution
  - Complex logistics; often global

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Research &amp; development</td>
<td>15%</td>
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<tr>
<td>Primary manufacturing</td>
<td>5-10%</td>
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<tr>
<td>Secondary mfg/packaging</td>
<td>15-20%</td>
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<tr>
<td>Marketing/distribution</td>
<td>30-35%</td>
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<tr>
<td>General administration</td>
<td>5%</td>
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<tr>
<td>Profit</td>
<td>20%</td>
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Global network planning for pharmaceuticals

- Each primary site may supply any of the secondary sites
- Final product market is divided in 5 geographical areas. Each geographical area has its own product portfolio, demand profile, secondary sites and markets
- Secondary products flow between geographical areas is not allowed
- Key decisions:
  - Product (re)allocation
  - Production/inventory profiles
  - Logistics plans

Large models $\rightarrow$ Decomposition algorithms

• Spatial
  – Step 1: Aggregate market; Relax secondary binary variables; Solve reduced MILP to determine primary binary variables
  – Step 2: Fix primary decisions; Disaggregate markets; Solve each of the secondary geographical areas separately to determine secondary binary variables
  – Step 3: Fix secondary binary variables; Solve reduced MILP to reallocate primary products and adjust the production rates/flows

• Temporal
  – Step 1: Forward rolling horizon to determine primary and secondary binary variables
  – Step 2: Fix binaries; Solve reduced problem to determine production rates/flows (LP)

Illustrative case

- 10 active ingredients
- 10 primary sites
- 100 final products
- 5 secondary geographical areas
- 70 secondary sites
- 10 market areas
- 12 time periods (4 months each)

- 136,200 continuous and 84,100 binary variables

<table>
<thead>
<tr>
<th>Method</th>
<th>$Z_{opt}$</th>
<th>Gap (%)</th>
<th>CPU (s)</th>
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<tbody>
<tr>
<td>Relaxed Linear Programming</td>
<td>1,008,827</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Full space</td>
<td>944,593</td>
<td>6.4</td>
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<td>Spatial decomposition</td>
<td>969,660</td>
<td>3.9</td>
<td>2,513</td>
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<tr>
<td>Temporal decomposition</td>
<td>960,577</td>
<td>4.8</td>
<td>48</td>
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</table>
Typical solution

Primary Product Allocation

Flows of primary products
Four focus areas

1. Healthcare – Pharmaceutical planning
2. Agrochemicals – Global supply chain planning
3. Chemicals – Sustainability
4. Energy – Biomass supply chains
Agrochemicals supply chain optimisation

- Global supply chain network
  - AI production
  - Formulation plants
  - Markets

- Production and distribution planning

- Capacity planning

- Objectives:
  - Cost
  - Responsiveness
  - Customer service level

- Multi-objective MILP model

Liu and Papageorgiou, Omega, 41, 369 – 382 (2013)
Case Study

- Supply chain network
  - 32 products, 8 plants, 10 markets

- Planning horizon
  - 1 year / 52 weeks

- Discrete lost sales levels:
  - 1%, 3%, 5%

- $\epsilon$-constraint method
  - Pareto-optimal solutions
Capacities for different scenarios

- **Minimum cost**
  - PCE: F2
  - CCE: F4

- **Minimum flow time**
  - PCE: F2
  - CCE: F6

- **F2 under PCE**: higher capacity at flow-time minimisation
Material Flows

- Fewer long-distance flows for minimum flow-time scenario
Four focus areas

1. Healthcare – Pharmaceutical planning
2. Agrochemicals – supply chain optimisation
3. Chemicals – Sustainability
4. Energy – Biomass supply chains
Incorporation of sustainability indicators into supply chain optimisation

• **Supply Chain Characteristics:**
  - 11 major raw materials
  - 17 raw material suppliers
  - 7 production plants
  - 270 products
  - 268 customer regions

• **Given:** Network structure, customer demands, reactor, plant, and transportation capacities

• **Objective:** Optimise tactical planning for one year

• **Data Sources:** Dow plant production, waste, emissions, & energy use; CEFIC transportation emissions

Zhang et al., LCA XIII conference (2013)
Product allocations for the different objectives

What if no capacity constraints?
Cost & GHG emission: Pareto Curve
Clear trade-offs between economic, environmental, and responsiveness performance.

Considerable decrease in GHG emission or lead time can be achieved by small increase in cost.
Four focus areas

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3. Chemicals – Sustainability
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Bioenergy supply chains

Main challenges the globe is facing today:

- Global climate change
- Security of energy supply
- Rising oil prices and depleting natural resources

Transportation sector is one of the main contributors to global CO₂ emissions

**Bioenergy**: most promising option to tackle these challenges

Bioethanol production – rapidly increasing
Optimisation of biofuel supply chains

- Biofuel supply chain
- Spatially-explicit representation
- "Neighbourhood flow" approach

Multi-objective MILP

Minimise $TDC$

$TEI \leq \lambda \ TEI^{\max}$

- Production constraints
- Demand constraints
- Sustainability constraints
- Transportation constraints

$(0 \leq \lambda \leq 1)$

Case study: UK bioethanol supply chain

Bioethanol production in the UK from **wheat** as first generation feedstock and **wheat straw**, **miscanthus** and **SRC** as second generation feedstocks.

2020 demand scenario with an EU biofuel target of 10% (by energy) has been studied.

Set-aside land in the UK (570.2 kha) is used for the cultivation of dedicated energy crops (miscanthus and SRC).

Total demand: 7,899 t ethanol/d

Case study – 2020 demand scenario

2020A: Minimum cost

2020B: Minimum Environmental Impact
Case study - Optimal UK bioethanol supply chain

<table>
<thead>
<tr>
<th>Biofuel production (% of the overall)</th>
<th>Domestic wheat</th>
<th>Imported wheat</th>
<th>Wheat straw</th>
<th>Miscanthus</th>
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</thead>
<tbody>
<tr>
<td>Minimum cost configuration</td>
<td>24%</td>
<td>10%</td>
<td>13%</td>
<td>53%</td>
</tr>
<tr>
<td>Minimum environmental impact configuration</td>
<td>14%</td>
<td>0%</td>
<td>8%</td>
<td>78%</td>
</tr>
</tbody>
</table>

- 62% GHG savings
- 100% domestic wheat use
- 70% set-aside land use
- 58% domestic wheat use
- 100% set-aside land use
- 69% GHG savings
Concluding remarks

• Optimisation-based methodologies are increasingly used for deterministic supply chain planning and design

• Challenges
  – Detail of process representation
  – Integration across length and time scales
  – Dealing with complex uncertainties/robustness
  – Multiple performance measures
  – Efficient solution algorithms
  – Designing supply chains of the future
    • Low carbon energy supply chain systems
    • Water
    • Customised and affordable healthcare
    • Biomass driven: Bioenergy/biomaterials and biorefineries
    • Waste-to-value and reverse production systems (closed loop supply chains)
  • …
Acknowledgements

- UK Engineering and Physical Sciences Research Council
- Centre for Process Systems Engineering

- Prof Nilay Shah
- Dr Songsong Liu, Ms Ozlem Akgul, Dr Rui Sousa