Agent-based systems for supply chain management

Fernando D. Mele, Gonzalo Guillén-Gosálbez, Antonio Espuna and Luis Puigjaner

Department of Chemical Engineering
Polytechnic University of Catalonia, Barcelona, Spain

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Outline

• Introduction
• Simulation models for SCM
• Multi-agent system for SCM
• Simulation-based optimization (Sim-Opt)
• Multi-objective Sim-Opt
• Mathematical programming vs Sim-Opt
• Conclusions
Supply Chain
A SC can be defined as a network of business entities who work together in an effort to acquire raw materials, transform these raw materials into intermediate and finished products, and distribute these final products to retailers (Simchi-Levi et al., 2000)
SCM: Trends and challenges

Dynamic considerations:
• Dynamic simulation, simulation/optimization approaches

Integrated approaches
• Horizontal integration (manufacturing, distribution, etc.)
• Vertical integration (different decision-making levels: strategic, tactical and operational)

Multi-objective optimization
• Different conflictive criteria (economic, environmental issues, etc.)
• Rigorous approaches (weighted-sum method, $\epsilon$-constraint method, goal-programming method)
• Heuristic approaches (GA-based, SA-based, etc.)
Approaches for SCM

SCM models and tools

Transactional
- Enterprise resource planning systems (ERP)
- Material resource planning systems (MRP)
- Customer relationship management systems (CRM)
- ...

Analytical

Normative or optimization approaches
- Deterministic math. prog.
- Stochastic math. prog.
  (LP, MILP, NLP, MINLP)

Descriptive approaches
- Forecasting models
- Simulation models
- ...

Introduction
Analytical approaches for SCM

Planning-based approaches

- Operations research optimization models
  - LP, MILP, NLP, MINLP Deterministic / stochastic math. programming

- Centralized approaches with global information sharing

Demand-driven approaches

- Discrete event-based simulation
  - Deterministic / stochastic simulation

- Centralized or decentralized approaches, variable degree of information sharing
Deterministic simulation

Simulation models for SCM

Performance indexes

Index calculator

Simulation model

Equations or other relationships describing how the state variables change over time as a function of the decisions and external events

Parameters

Decision variables

Simulation outputs
Stochastic simulation

Simulation models for SCM
Modeling principles: generic modeling unit for SCM

Generic modeling unit

ORDER input \( (OR_{in}) \)

ORDER output \( (OR_{out}) \)

MATERIAL input \( (MAT_{in}) \)

MATERIAL output \( (MAT_{out}) \)
Demand model: orders placed by customers

ORDER input (OR_in)

Quantities:
- Normal distribution

Times:
- Poisson distribution

Simulation models for SCM
The state **order reception**

**States and transitions**

ORDER input *(OR_in)*

- **Idle**
  - {
    - Event that wakes up the system
    - Inv1:
      - entry:
        - Inv1_c=t; exit:
        - IF-=0.6*a; IG-=0.4*a; H+=a; on ORin: O+=b; on INV1:
          - O<=5
            - [O<5]/O=a
          - O>5
            - [O>5]/O=a
    - [t>=Inv1_c+5]/a=b
  
- Event that wakes up the system
- Checking availability of products F and G
- Updating inventories of F and G

**Logic conditions**

- [O<=5]/O=a
- [t>=Inv1_c+5]/a=b
- [IF<10]/[IG<10]/O+=a
- [IF>=10]/[IG>=10]/O+=a
- [O>5]/O=a
- [O<5]/O=a

**Simulation models for SCM**
Inventory model (state ordering)

Inventory control policies

- Continuous
  - (s, k) System
  - (s, Q) System
  - (R, S) System

- Periodic
  - (R, S) System
  - (R, s, S) System
  - (R, s, k) System

\[ u = k(s - \text{Inv}) \]

ORDER output

(\text{OR\_out})

Simulation models for SCM
Discrete event-based simulation

Performance measures: Key Performance Indicators (KPIs)

\[ \mathcal{F}(\eta) = E[f(\eta, \omega)] \]

- **Economic:** Total SC profit
  \[ \text{Profit} = R - C \]
  \[ R = \sum_t \sum_{j \in \text{Prod}} \sum_i Q_{ijt} \cdot \text{price}_{ij} \]
  \[ C = \text{Trn}C + \text{Inv}C + \text{Prd}C \]

- **Social:** Customer satisfaction
  \[ MD_{Sat} \leq \frac{\sum_{pkt} \text{Sales}_{pkts}}{\sum_{pkt} \text{Dem}_{pkts}} \quad \forall t > 1, s \]

- **Environmental:** Greenhouse effect impact
  \[ GHE = \sum_e \text{GWP}_e \cdot m_e \]

Simulation models for SCM
An **agent** is an encapsulated computer system that is situated in some environment, and that is capable of flexible, autonomous action in that environment in order to meet its design objectives.

*Wooldridge and Jennings, 1995*

**Autonomy:** it should have some control over its actions and should work without human intervention.

**Social ability:** it should be able to communicate with other agents and/or with human operators.

**Reactivity:** it should be able to react to changes in its environment.

**Pro-activeness:** it should also be able to take initiative based on pre-specified goals.
Agent-based simulation model

Implementation of a multi-agent system

Real supply chain

Simulation model
(multi-agent system)

Central agent
- Exchanges messages
- Provides access to modules
Sub-agents

Implementation of a multi-agent system

Tasks
- Storage of raw materials
- Production
- Storage of final products

Sub-agents
- Sales
- Inventory
- Purchases
- Transport
Storage agent

Plants (storage), warehouses, distribution centers and retailers

Storage agent

Subagents: Sales, Inventory, Purchasing and Transport

Messages

- external customer
- manufacturing plant
- distribution center
- . . .

States and transitions

- external supplier
- manufacturing plant
- distribution center
- . . .
Stochastic simulation

- Probabilistic index calculator
- Sampling tool
- Simulation model
- Environmental Financial (modules)
- Multi-agent system for SCM

Probabilistic performance indexes
Performance indexes
Uncertain parameters
Decision variables
Simulation outputs
Index calculator
Probabilistic index calculator
Sampling tool
Simulation model
Multi-agent system

Environmental Financial (modules)
Decision variables
Simulation outputs
Index calculator
Probabilistic index calculator
Sampling tool
Simulation model
Multi-agent system

Multi-agent system for SCM
Software implementation

Retailers, warehouses and plants

- C#, .NET of Microsoft ®
- SC model: XML files
Simulation outcome

Multi-agent system for SCM
Agent-based simulator

Framework for dynamic simulation of SCs

• Centralized or decentralized decision-making
• Different production, storage and transportation policies
• Connection with different modules:
  • Demand forecast
  • Planning, scheduling, etc.
• Flexibility

Lack of optimization capabilities!!
Simulation-based optimization

Decision-making under uncertainty

Sim-Opt architecture
Sim-Opt architecture

Simulation model

Probabilistic index calculator

Performance indexes

Environmental Financial...

Sampling tool

Uncertain parameters

Meta-heuristic algorithms (SA, GAs…)

Initial values

Optimization tools

Improved values

Decision variables

Multi-agent system

Sim-Opt architecture

Index calculator

Simulation outputs

Meta-heuristic algorithms (SA, GAs…)

Initial values

Optimization tools

Improved values

Decision variables

Multi-agent system

Sim-Opt architecture
Case study Sim-Opt

SC design problem

- Strategic-Tactical levels (capacities and inventory control policies)
- Uncertain demand (time and amount)
- System ($R$, $s$, $S$) for distribution centers
- System ($s$, $S$) for retailers
- Maximize expected profit
Case study Sim-Opt

Results

<table>
<thead>
<tr>
<th>Entity</th>
<th>Distribution center D1</th>
<th>Distribution center D2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Design I</td>
<td>8,000</td>
<td>8,000</td>
</tr>
<tr>
<td>Design II</td>
<td>8,000</td>
<td>0</td>
</tr>
<tr>
<td>Design III</td>
<td>8,000</td>
<td>0</td>
</tr>
<tr>
<td>Design IV</td>
<td>2,000</td>
<td>2,000</td>
</tr>
<tr>
<td>Design V</td>
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Sim-Opt architecture
Case study Sim-Opt

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Large CPU times!!

Tuning parameters

Sim-Opt architecture
Sim-Opt architecture

IF $f(x_k) > E[f(x_k^*)] + \zeta$, $\zeta = 2\sigma_f(x_k)$, THEN DISCARD $x_k$
Sim-Opt architecture

**Tuning parameters**

**Genetic algorithm parameters**

- $MaxGen$: Maximum number of generations
- $N$: Population size
- $Ns$: Number of Monte Carlo samples
- $Px$: Probability of cross-over
- $Pm$: Probability of mutation

**Metamodel**

- $\zeta$: Maximum tolerance
- $\phi$: Frequency of metamodel training

**Maximum number of simulations**

$$N = Ns \cdot N \cdot (Rep \cdot MaxGen + 1)$$
Case study

SC with embedded multi-product plants

Control policies

Loonkar and Robinson, 1970

- Integration of tactical-operational levels
- Uncertain demand (quantity and amount)
- System \((R, s, S)\) for distribution centers and \((s, S)\) for retailers
- Maximize expected profit

Sim-Opt architecture
Case study

Outer loop optimization

- $\text{MaxGen}$: 100 generations
- $N_s$: 50 samples (scenarios)
- $\text{Time}$: 10 s/run (total time 28 hours)
- $N$: $2 \cdot 10^4$ simulation runs

Inner optimization

- 0.1-1 seconds
- GAMS-CPLEX

Sim-Opt architecture
Multi-objective Sim-Opt

- Optimization outcomes
  - Approximation to the Pareto set
  - Improved values of the decision variables

- Objective function and constraints
  \[ E[f_p(\eta, \omega)] \]

- Financial module
  - Evaluate financial impact

- Environmental module
  - Evaluate impact based on LCA principles

- Meta-heuristic algorithms
  - NSGA, NSGAII, PSA, etc.

- Sampling tool
  - Monte Carlo

- Index calculation
  - \( f_p(\eta, \omega) \)

- Simulation model
  - Simulation outcomes

- Simulation outcomes

- Meta-heuristic algorithms
  - NSGA, NSGAII, PSA, etc.

- Initial solution
  - Initial values
  - \( \eta^0 \)

- Decision variables

- Monte Carlo
Environmental issues in SCM

Environmental concerns

Total impact (entire SC)
Life Cycle Assessment (LCA)

LCA
(ISO 14040 series on LCA)

Objective strategy to evaluate the environmental loads associated with a product, process or activity

by quantifying energy and materials used and waste released

to evaluate opportunities to do improvements

It includes the ENTIRE LIFE CYCLE of the product

Main drawback: a systematic procedure to search alternatives for environmental improvements is lacking

Combine LCA with optimization tools
(Azapagic et al., 1999, Hugo and Pistikopoulos, 2005)
Case study

Multi-objective tactical-operational SCM problem

- Uncertain demand (quantity and amount)
- System \((R, s, S)\) for distribution centers and \((s, S)\) for retailers
- Maximize expected profit
- Minimize expected contribution to global warming

\[
\min_{\eta} U = \begin{cases} 
-F_1(\eta) &= -E[Profit(\eta, \omega)] \\
-F_2(\eta) &= E[EnvIndex(\eta, \omega)] \\
&\vdots 
\end{cases}
\]

\[
GHE = \sum_e GWP_e \cdot m_e
\]

\[
m_e = \varphi_e^P \cdot t^P + \varphi_e^I \cdot t^I + \varphi_e^T \cdot t^T
\]
Case study

Approximation to the Pareto set

*MaxGen* 100 generations
*Ns* 90 samples
*Time* 10 s/simulation
*N* \(1 \cdot 10^5\) simulations
Total time 100 hours (NSGAII)

Inventory profiles of product B in distribution center *D1*
Case study

GA parameters

Graphical user interface of the Life Cycle Assessment module (LCA)

Graphical results

Multi-objective Sim-Opt
Mathematical Programming vs Sim-Opt approach

- Based on algebraic equations
- Steady state models
- Centralized system
- Simplifications
- Well established theory
- Available software (GAMS, AIMMS, etc.)
- Optimal solutions

- Based on logic rules (states and transitions).
- Captures the dynamics of the system
- Centralized/decentralized system
- Realistic SC representation
- Need to develop efficient optimization strategies
- Customized solution (generic programming languages: C++, C#, Java, Visual Basic, etc.)
- Optimality is not guaranteed
Mathematical Programming vs Sim-Opt approach

- Push systems (make-to-stock)
- Centralized system (global information sharing)
- Strategic/Tactical/Operational
- Solve well defined design/planning/scheduling problems
- Optimization skills (math. prog.)
- Available decomposition strategies
- Optimal or near-optimal solutions

- Pull systems (make-to-order)
- Decentralized system (partial sharing of information)
- Strategic/Tactical
- Provides insights: capture dynamics and delays in information flows
- Software development skills (C++, Java, etc.)
- Cannot avoid large CPU times
- Optimality is not guaranteed
Conclusions

- Multi-agent system for SCM
  - Decentralized SCs
  - Dynamics
  - Realistic industrial practices

- Sim-Opt framework to improve the SCM

- Use of meta-models to decrease CPU time

- Multi-objective optimization