Building Models of Global Supply Chains
Basic Principles and Requirements

Nr.135 (WIP)

Barbara Krenn*, Corinna Engelhardt-Nowitzki*, Christian Savu-Krohn, Helmut Zsifkovits***

* Chair of Industrial Logistics, University of Leoben, A-8700 Leoben, Austria, E-mail: barbara.krenn@wbw.unileoben.ac.at, Tel: +43 (0) 3842 402 6024; Fax: +43 (0) 3842 402 6022

** Chair of Information Technology, University of Leoben, A-8700 Leoben, Austria, E-mail: christian.savu-krohn@mu-leoben.at, Tel: : +43 (0) 3842 402 1504; Fax: +43 (0) 3842 402 1502

ABSTRACT

In a market environment of increasing complexity, managing the entire supply chain becomes a critical factor for success in logistics. The requirements on simulation are as ambitious as wide-spread. Simulation models are implemented to evaluate concepts and system designs, analyse, modify and optimise existing systems and control material flows.

This work covers two main topics. First, we analyse the properties of existing concepts for simulation models, so as to consolidate present knowledge on the modelling of a supply chain. Therefore, theoretical developments from the field of supply chain optimisation by simulation are revisited. Secondly, we describe and analyse the different key terms and concepts of discrete-event simulation. We characterise and distinguish the key terms for a supply chain simulation model, like objects, states, timeframes and flows and the specific requirements on different kinds of supply chains. Generally, the reasons for modelling a supply chain are quite divergent. Models are often case-based or focus on selected aspects or subsystems of a global network. Finally, we summarise potentials and shortcomings of supply chain simulation and delineate issues for further research.

Key Words: Supply Chain, Supply Chain Simulation, Literature Review, Discrete-Event Simulation, Simulation, Modeling Techniques

1. INTRODUCTION

The global market is subject to conditions that are difficult to control within a supply chain (SC) environment. The increasing demands on the flexibility of a supply chain are driven by ongoing globalization, the application of mass customization principles, like customized products at reasonably low costs, the pace of scientific research and shorter life cycles of many goods. Particularly, the effective coordination of supply chain processes is an important requirement.

Therefore, in the early 1990's the term Supply Chain Management (SCM) came into use. "SCM is the management of upstream and downstream relationships with suppliers and customers to deliver superior customer value at less cost to the supply chain as a whole" (Christopher, 2005, p.5).

The performance of a supply chain depends on numerous factors of the processes within the chain. For example, one of the most difficult is uncertainty which often affects many areas up and down the chain. For example, this leads to dynamic effects in the supply chain like the bullwhip effect. Although numerous approaches have been reported (Lee et al, 1997, Dejonckheere et al. 2003, Geary et al. 2006), this phenomenon could not be fully eliminated. Obviously, we are forced to deal with a specific amount of uncertainty in the supply chain and therefore, need effective tools that help us to evaluate and reduce it. Simulation is a very powerful way to support the analysis, modification and optimization of existing systems as well as evaluation of new concepts for the supply chain.

This paper investigates currently available supply chain simulation models regarding their applicability for supply chain management matters. Furthermore we are evaluating the usability of discrete event simulation (DES) in supply chain modeling within a challenging SC environment as discussed above.

The paper is organized as follows. The first part is devoted to the discrete-event simulation, its basic principles and model requirements. At second, we categorize state-of-the art concepts for supply chain simulation using a set of typical features. From these we analyze three approaches dealing with the topic of modularity and reusability in more detail. The third part analyzes the application fields of DES and its possible obstacles for the specific requirements in unpredictable and volatile SC settings. Finally we address the general shortcomings and potentials of supply chain simulation (SCS) and discuss possible fields of further research in supply chain simulation.

2. Discrete Event Simulation

Law and Kelton (2000, p.6) define discrete-event simulation "as the modeling of a system as it evolves over time by a representation in which the state variables change instantaneously at separate points in time. These points in time are the ones at which an event occurs, where an event is defined as an instantaneous occurrence that may change the state of the system".

Furthermore, we use the following systematization throughout the paper (Table 2.1):

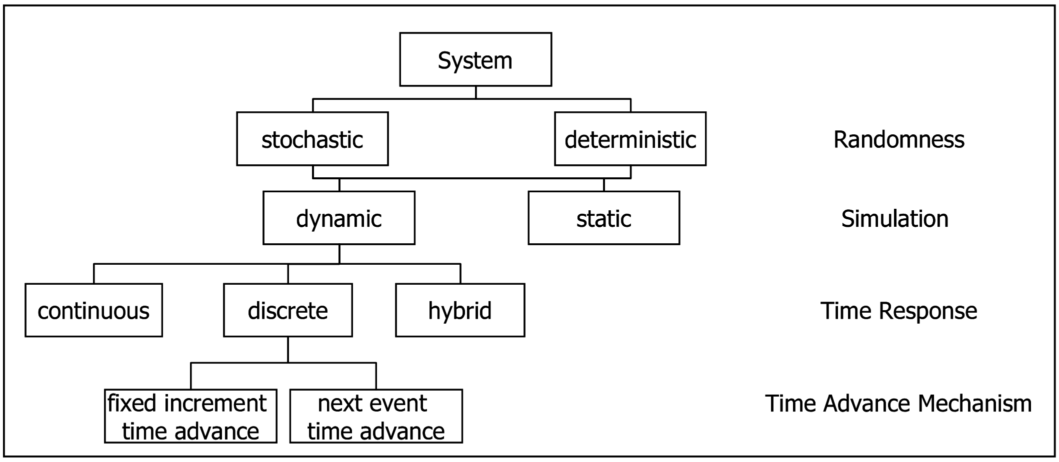

Figure 2.1 A classification of the important properties of a simulation model

2.1. Modeling Concepts of DES

2.1.1. Key Terms and Time Advance Mechanisms

A simulation model uses interacting entities with individual attributes to map real world components, and state variables (e.g. work in progress).

An entity is either dynamic and flows through the system, i.e. it models products to be manufactured, or static, not moving in the system and serves other entities as e.g. people or equipment.

The set of system state variables contain all information needed to express what is happening within the system at a given point in time. System state variables in a discrete-event model remain constant over intervals of time and change their values only at certain well-defined moments called events, whereas the state of continuous models is represented by dependant variables that change continuously over time, as typically defined through difference equations (Banks, 2000).

Besides, events also change the state of the system by manipulating the attributes of entities. We distinguish between external and internal events by observing whether their occurrence is from inside the system like machine scheduling or from outside the system, like the start of production orders.

For DES there are three common ways in modeling to synchronize a model's state change with the passage of simulation time (Banks, 2000):

- Event scheduling: The time is to advance to the moment of the next scheduled event
- Process interaction: The entity moves as far as possible in the system until it is delayed, enters an activity or exits the system. When its movement is halted, the clock advances to the time of the next movement of any entity.
- Activity scanning: It produces a simulation program composed of independent modules waiting to be executed. First, a fixed amount of time is advanced, or scanned. Secondly, the system is updated if an event occurs.

According to Law and Kelton (2000, p.9) "the following components will be found in most DES models using the next event time advance approach […]:

- System state: The collection of state variables necessary to describe the system at a particular time
- Simulation clock: A variable giving the current value of the simulated time
- Event list: A list containing
- Statistical counters: Variables used for storing statistical information about the system performance
- Initialization routine: A subprogram to initialize the simulation model at time 0
- Timing routine: A subprogram that determines the next event from the event list and then advances the simulation clock to the time when that event is to occur
- Event routing: A subprogram that updates the system state when a particular type of event occurs (there is one event routine for each event type)
- Library routines: A set of subprograms used to generate random observations from probability distributions that were determined as part of the simulation model
- Report generator: A subprogram that computes estimates (from statistical counters) of desired measures of performance and produces a report when the simulation ends
- Main program: A subprogram that invokes the timing routine to determine the next event and then transfers control to the corresponding event routine to update the system state appropriately. The main program may also check for termination and invoke the report generator when the simulation is over".

The logical relationships among these components are shown in figure 2.2.

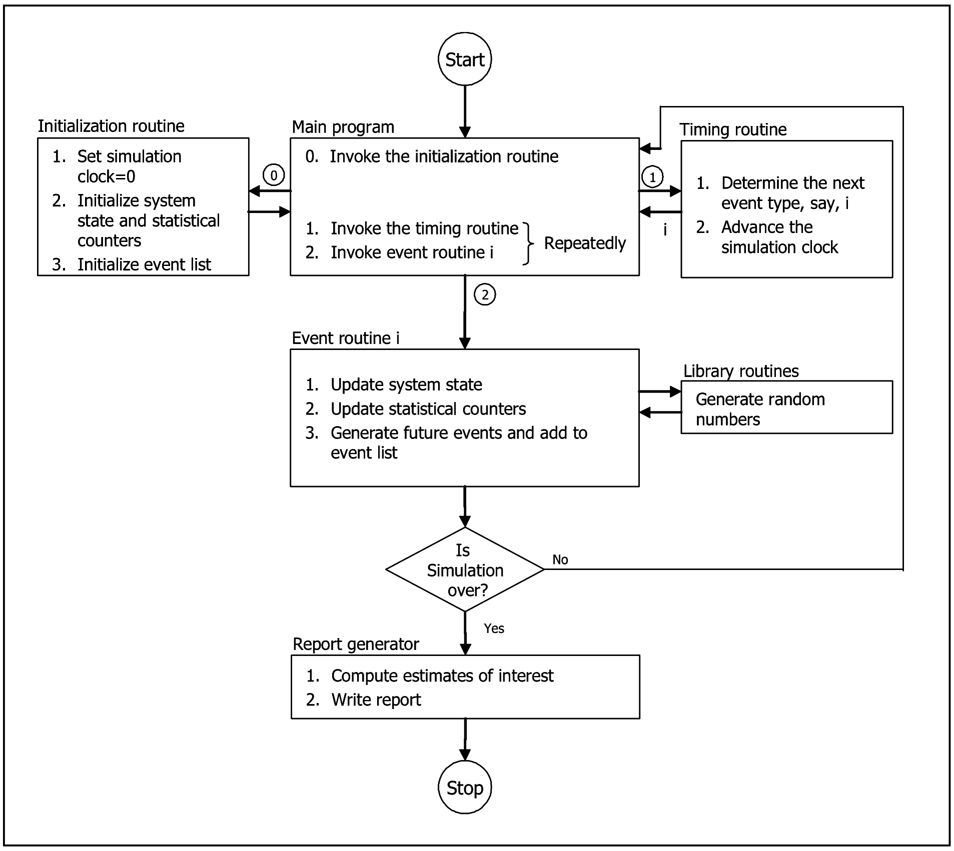

Figure 2.2 Flow of control for the next event time advance (Law and Kelton, 2000)

2.1.2. Distributed Simulation

Distributed simulation tries to reduce run time, integrate distributed services and use different sources in order to achieve the simulation target. The simulation is executed on several processors. We distinguish three kinds of distributed simulation (Page and Kreutzer, 2005):

- Parallel simulation: parallel executions of independent experiments within a single model
- Component-based simulation: individual model components are executed on separate processors
- Web-based simulation: execution of simulation models in a web-based environment

For further reading, refer to Fujimoto (2000).

For general processes and specifically for supply chains, behavior can be modeled by the mechanisms described above. It is obvious that the capability of a certain model to validly investigate complex SC depends on its specific features like the time advance mechanism, the defined entities and their attributes, the state variables and the programmed interactions of these objects.

3. LITERATURE REVIEW

This review ascertains the applicability of the surveyed model's on common supply chain tasks. For example, one can distinguish the featured planning horizons which determine the decision level addressed, i.e. operational, tactical or strategic decisions in supply chain management.

Furthermore, many efforts have been made to capture the dynamics of supply chains by using different modeling techniques. The available publications on SCS indicate throughout the last years, features like distributed simulation, usability on every planning horizon in the chain and reusability of supply chain models have influenced the design process of simulation models.

The literature review will present and reflect some recent approaches in the area of supply chain simulation. A number of papers have been investigated and relevant approaches of the last years have been analyzed. First an overview of supply chain simulation models is given. Subsequently, three specific simulation model approaches dealing with the topic of reusability and modularity are explored in detail.

3.1. SCS Model's Overview - Classification Criteria

The following section categorizes 14 current supply chain modeling approaches using four main criteria:

- **Model Scope**
  The model scope covers two features - the planning horizon (strategic, tactical or operational level) and the focused planning fields of activity, like production planning and scheduling or inventory planning.
- **Supply Chain Features**
  The SC model is characterized by key data and management ratios focused on, like costs, performance, taxes, inventory, coordination, info sharing and social,

environmental criteria, its global scope and its tiers. If there are any features in the model facilitating the simulation of cross-county relationships between supply chain members this will be marked as a global scope. Often this possibility couldn't be specified (ns.). Furthermore, if the models tiers can be configured arbitrary, this category will be evaluated as configurable (c.).

- **Modeling Techniques**
  This category addresses the underlying technologies and used programming languages. Advanced Planning and Scheduling (APS) procedures and Discrete Event Simulation (DES) are typical state-of-the-art technologies for planning and controlling. The numerous demands on a SCS model led to the development of hybrid approaches, like DES and continuous simulation, DES + analytic approaches, DES + High Level Architecture (HLA) based simulation and DES + Monte Carlo Simulation are distinguished. Furthermore we characterize approaches by their use of Genetic Algorithms, fuzzy set theory and object-oriented model constructions.
- **Developmental Stage**
  The developmental stage distinguishes models at the conceptual level from those implemented in a real world scenario.

Table 3.1 lists the papers and models that are analyzed.

Table 3.1 Reference table

	author (year) & title		author (year) & title
[1]	Chatfield et al. (2001) "Sisco: A supply chain simulation tool utilizing SILK^{TM} and XML"	[8]	Liu et al. (2004) "Easy-SC: A supply chain simulation tool"
[2]	Lendermann et al. (2001) "Distributed simulation with incorporated APS procedures for high-fidelity supply chain optimization"	[9]	Umeda and Lee (2004) "Design specifications of a generic supply chain simulator"
[3]	Petrovic (2001) "Simulation of supply chain behaviour and performance in an uncertain environment"	[10]	Vieira and Júnior (2005) "A conceptual model for the creation of supply chain simulation models"
[4]	Lee and Kim (2002) "Production-distribution planning in supply chain considering capacity constraints"	[11]	Wang and Shu (2005) "Fuzzy decision modeling for supply chain management"
[5]	Lee et al. (2002) "Supply Chain Simulation with discrete-continuous combined modelling"	[12]	Hung et al. (2006) "Object-oriented dynamic supply chain modeling incorporated with production scheduling"
[6]	Nagurney and Toyasaki, (2003) "Supply chain supernetworks and environmental criteria"	[13]	Rossetti et al. (2006) "An object-oriented framework for simulating multi-echelon inventory systems"
[7]	Ding et al. (2004) "ONE a new tool for supply chain network optimization and simulation"	[14]	Wang and Takakuwa (2006) "Module-based modelling of production-distribution systems considering shipment consolidation"

Table 3.2 shows the results of the models analysis as an overview.

Table 3.2 Literature overview

Reference	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Model Scope														
Planning horizon														
• Strategic	x	x	x	x	x	x	x	x		x	x	x		x
• Tactical	x	x	x	x	x	x	x	x	x	x	x	x	x	x
• Operational	x	x		x				x	x			x	x	x
Planning fields of activity														
• Procurement planning	x	x	x			x		x	x	x		x		x
• Inventory planning	x	x	x		x			x	x	x	x	x	x	x
• SC planning + optimization	x	x	x	x	x	x	x	x	x	x	x	x		x
• Production scheduling	x			x				x	x			x		x
• Demand planning	x	x	x	x	x		x	x	x	x	x		x	
• Distribution planning	x	x	x	x		x		x	x	x				x
Supply Chain Features														
Number of SC tiers reported	c.	5	c.	c.	5	3	c.	c.	c.	4	4	c.	3	c.
Global scope	x	x	ns.	ns.	ns.	x	x	ns.	ns	x	ns.	x	x	ns.
Investigated parameters														
• Costs	x	ns.	x	x		x	x	x	x	x	x	ns.	x	x
• Performance	x	x	x	x	x	ns.	x	x	x	x	x	x	x	x
• Taxes, exchange rate	x					x	x							
• Inventory	x	x	x	x	x			x	x	x	x		x	x
• SC coordination	x	x					x			x	x			
• Information sharing	x	x							x					
• Social, environmental criteria							x							
Modeling Techniques														
APS procedures		x												
DES	x					x	x	x	x	x			x	x
Object-oriented programming	x		x					x				x	x	
Hybrid approach:														
• DES + continuous simulation					x									
• DES + analytic approach			x	x										
• DES + Monte Carlo simulation												x		
• DES + HLA-based distributed simulation		x												
Genetic algorithms							x				x			
Fuzzy set theory			x								x			
Programming language	Java,XML Silk™	ns.	C++	Arena, C++	ns.	Fortran	ns.	Java	ns.	Arena	ns.	C++	Java (JSL)	Arena, VBA
Developmental Stage														
Implemented model		x					x					x		x

Most of these models are applicable for strategic and tactical planning issues but lack of operational matters. The majority of the models focus only on typical strategic and tactical issues like inventory planning, demand planning and SC planning + optimization. Capacity planning and production scheduling are only considered in six of the papers. An important contribution to the applicability of supply chain models for real world scenario is the capability to create arbitrary SC tiers. Most of the reviewed approaches have this possibility. Cross-county relationships between supply chain members are considered in some models but often this property couldn't be identified. Surprisingly in this context only a few models account for taxes, exchange rates and social and environmental criteria. Therefore the others are probably limited to socially and economically closely related countries. All but one are built using DES or a hybrid approach involving DES. Only four model approaches have been applied on real world scenarios to evaluate their validity.

3.2. Model Analysis

There are two issues that show high relevance for the focus of SC simulation dealing with uncertain/complex requirements. First there is the issue of reusability leading to a reduction of designing, construction, verification and validation effort and the associated costs. Models or model components that have already been validated might be reused. Secondly, modularity permits an arbitrary combination of the individual SC modules and therefore enables an easy way to built complex supply chain structures and flexible applications. In many cases in module based simulation tools numerous parameters have to be set but nevertheless the construction effort is low compared to non-modular approaches. These issues of reusability and modularity led to a more detailed analysis of the following papers [10], [12] and [14] dealing with these topics. The model approaches are presented in the following way. First the model is described then the controlling principles and measures of performance are given. Finally shortcomings, potentials and the underlying technology are mentioned briefly.

Vieira and Júnior (2005) present a software independent conceptual model. It suggests three hierarchical levels differing in detail. The first level maps the interaction between the supply chain tiers like suppliers, manufacturers, retailers and consumer market and the flows in the chain (material and information flow). Within the second level each of those is refined to its main processes and procedures. The third level details some of the manufacturer's functions like the ordering and the fabrication procedure or sales & demand processes. The announced development of a fourth level will lead to more simulation parameters for the supplier, manufacturer and retailer.

The proposed simulation structure follows the principles of a pull production. Different operation philosophies like make-to-stock, make-to order or make-to-assembly can be implemented. The suggested inventory control policy is kept simple and assumes the demand to be constant over periods, but other more sophisticated control policies can be included.

Performance is measured by the cycle time between retailer and manufacturer, variations in the production or order levels at the supplier's site and by considering variations in the total average inventory within the supply chain.

This model doesn't take any lead times between demand occurrence and the transmission to its supplier into account. Moreover it doesn't consider minimal purchase lots and production lot sizes. Instead, orders are placed independently of size and cost and lot quantities are produced independent of their costs. Furthermore, this model doesn't include features like forecasting, shop-floor scheduling/planning and capacity planning.

On the other hand it seems useful for testing collaboration strategies among the supply chain members or visualizing material flow effects like the bullwhip effect. The application field is the strategic and partially the tactical level, and will be expanded to the operational.

The conceptual model is built with ARENA, simulation software based upon discrete event simulation. The modular character is advantageous in term of reusable, user-friendly easily adaptable models.

The second approach investigated uses object-orientation to realize so called “generic supply chain nodes” (Hung et al., 2005). In order to reflect different physical characteristics of business processes such a generic node can be instantiated as a composition of the following three main components: Inbound Material Management (IMM) which controls the stock levels of inbound materials groups (there is an individual replenishment control policy for each material), the Material Conversion (MC) which plans or schedules production and determines when the orders can be fulfilled considering constraints and manufacturing logic, and the Outbound Material Management (OMM) which controls the stock levels of outbound materials groups. Additionally, each node allows for specific parameters to each of the three generic parts. Finally these nodes can be linked together arbitrary to form a complex supply chains.

The model supports several replenishment policies, like Re-order Point (ROP) techniques, Material/Distribution Requirements Planning (MRP/DRP) or Just-In-Time concepts. The generic node model can also be linked to external software like a scheduling program. Monte Carlo simulation is used to evaluate performance under uncertainty. Performance can be measured by the customer service level, the probability of stock out and the average inventory. Furthermore, to assess the inventory policy adopted, the mean stock level over a certain number of simulations is taken at each time step.

It is possible to describe many different supply chains with this approach because there are few fixed guidelines. It is not a drag and drop simulation modeling software and there is no graphic user interface. The user has to write C++ code to parameterize the generic nodes for his supply chain. The running time of the object-oriented architecture combining DES and the Monte Carlo simulation is assumedly high. The simulation concept is currently extended to include transportation dynamics and optimization. On one hand user-friendliness is limited by the programming effort, on the other hand many properties of one’s supply chain can be considered. The approach is an important contribution to build global, reusable and generic models applicable on all decision levels within the supply chain.

Wang and Takakuwa (2006) developed a module-based simulation model consisting of arbitrary supply chain tiers configurable in a convergent, divergent, conjoined or general supply chain structure. There is a retailer module to perform the functions of a retailer, a distributor module to perform the functions of a distribution center, a warehouse module, similar to the distributor module but only serving one downstream customer, the factory module for the manufacturing processes and the products module to characterize the products.

Similar to Vieira and Júnior the supply chain is controlled by a pull mechanism. ROP techniques are used in the inventory policy and multi-stage multi-product inventory management is applicable. For the modules different shipment consolidation policies are available, e.g. the distribution center consolidates the orders from all downstream retailers and delivers them in a milk run fashion.

The performance is measured by calculating inventory holding costs, shortages costs, transportation costs, inventory level, backorder fraction and lead time.

The model is based upon discrete event simulation and is implemented using ARENA combined with Excel VBA. Data can be imported or exported from or to Excel. The modular system allows for a rather easy investigation of strategic, tactical and operational questions in production-distribution SC systems. The configuration is straight-forward through a graphic-user interface. Complex systems requirements not covered can be added via VBA programming

Vieira and Júnior (2005) and Wang and Takakuwa (2006) provide a user-friendly graphic interface to support an easy SC configuration process of complex SC structures. The individual modules can easily be linked together to create supply chains of arbitrary tiers and structures. Many fixed guidelines in the individual modules of these approaches provide less all-round applicability and modification possibilities than the model of Hung et al. (2005). Their generic node model focuses on applicability on all planning horizons and high reusability. Therefore he created object-oriented model components that can be reused or expanded for tasks involving other operational, tactical and strategic planning issues. The disadvantage of this model compared to the two others is the effort in programming the needed settings for individual supply chains. Concerning Vieira's model, reusability can be justified by the abstraction levels of the hierarchical approach.

For a further survey of current supply chain simulation models the interested reader may refer to Duarte et al. (2002), Liu et al. ((2006), Vergara et al. (2002), Barnett and Miller (2000), Qiao and Riddick (2004), Kaihara (2003), Röder and Tibken (2006), Kerbache and Smith (2004), Biswas and Narahari (2004). There are also a number of comprehensive reviews on this topic as of Beamon (1998) and Terzi and Cavalieri (2004). Commercial software tools like IBM's Supply Chain Simulator (SCA) by Chen et al. (1999) or the Compaq Supply Chain Analysis Tool CSCAT by Ingalls and Kasales, 1999 are also often cited.

4. Applicability of DES in Supply Chain Simulation

In this section we investigate the applicability of DES for supply chain simulation and eventually arising obstacles. In this context sufficient model fidelity is a critical factor (Lendermann et al., 2001). The preconditions for applying DES can be described as follows:

- Time-discrete system behavior (discrete processes or processes that can be discretized)
- A finite number of system elements and state changes within the system
- System component dependencies can be mathematically described
- Complex dependencies within the system are quantifiable

Since the complexity of material flow systems is usually high, this is already a critical issue within an enterprise or a smaller enterprise section, but even more difficult from a cross-company perspective or looking at an entire supply chain. As the example in figure 4.1 shows, supply chains may involve networks of many sub-suppliers, suppliers, producers, wholesalers, retailers and customers:

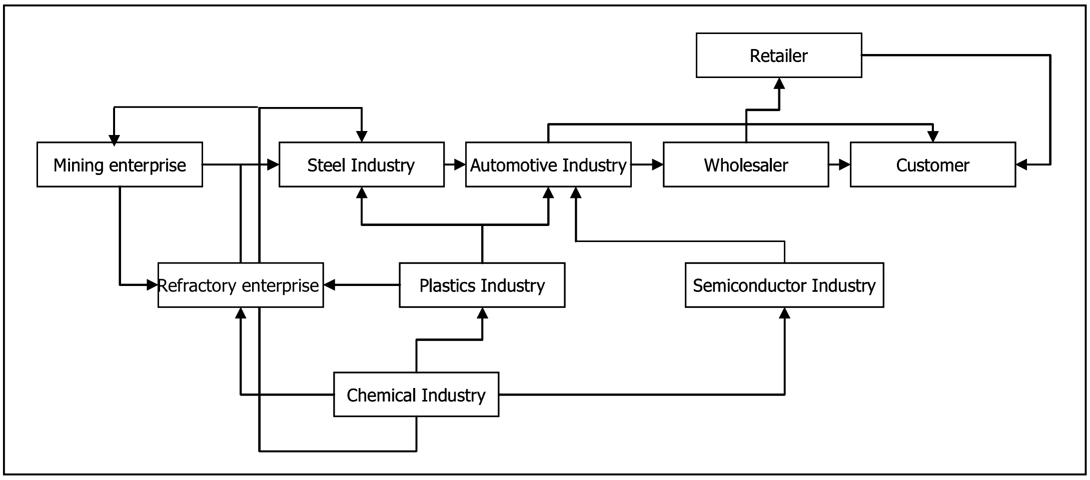

Figure 4.1 An example for a complex value chain modification in the process industry

If the probable system's behavior shall be tested under certain circumstances within a "what-if analysis", model fidelity has to be acquired within different preconditions:

- Known relations can be constituted using real data (e.g. historical data, proven logistic laws) or appropriate statistic probability distributions (e.g. an exponential function for the representation of time-intervals between lot arrivals). At best a distribution is derivated from real measurement data.
- Risks mostly can be represented using statistic methods (e.g. probability distributions and expectancy values). Herewith it is important to apply a broad risk definition in the sense of any deviation from the expected or planned system state – be it positive or negative (Blitz, 2000, Hinterhuber et al., 1998).
- By contrast with risk, uncertainties (in a narrow sense considered as random) can merely be represented validly via statistical assumptions, because there is no assured probability distribution or expectancy value. The uncertainty of a system depends on its boundaries (uncertain input values and open boundaries) and its dynamics (instability). This may influence the model fidelity tremendously, depending on the degree of concurrence between the real system and the researcher's estimation.

The more a real supply chain is characterized by non-linearity, complex feedback relationships between entities, time-delays between cause and effect of a change, uncertainty and measurement data insufficiency (faults, inconsistency, incompleteness), the more difficult and important it becomes to appropriately assess the extend of validity losses regarding the forecast of the system behavior towards internal or external impulses (e.g. customer-, market-, supplier-, technology- or management-driven). A further problem is the applied level of detail: If chosen too generic, the model will not be capable to represent specific supply chain effects. If defined too particularized, first feasibility will be endangered due to the high effort necessary and second the model loses maintainability.

On the other hand similar problems apply even more impetuously on alternative methods for the analysis and optimization of supply chain systems (Banks et. al., 2002). In this sense simulation is – even though definitely delivering the more miss-fitting results, the less accurate the implied assumptions are – a useful approach. Though, this applies only if a thorough fault probability and sensitivity analysis regarding the elasticity of imprecise model parameters and components towards simulation results is done. Having this in mind we agree with Banks et al. (2002), who state that DES appears to be particularly feasible for supply chain management in industries that are subject to the following characteristics:

- A mass production environment characterized by high variability and stochastic uncertainties throughout the supply chain
- Numerous complex operational interdependencies between suppliers and customers provide significant potential for optimization and therefore call for collaborative performance improvement.
- Optimization of sequence and capacity utilization in manufacturing is required and therefore the flexibility regarding capacity adaptations (e.g. because of high capital costs) is limited.
- Value-added operations are strongly driven by logistics.
- Value added operations comprise a high share of repetitive tasks.

In addition to the previous discussion SC systems can be regarded as complex adaptive systems (Kirchhof, 2003) that apply principles and mechanisms of self-similarity and that have the ability to learn. This high degree of adaptability leads to a good resilience towards perturbations that result from volatile, uncertain or unpredictable environments. A promising way to model such systems is provided by Multi-Agent-Systems (Lidokhofer, 2007). Those systems use a decentralized and therefore very robust approach that mainly consists of local interactions between autonomous agents, inducing the global system behavior according to the phenomena of emergence and self-organization. Though, such systems are not yet wide-spread in practice and therefore have disadvantages regarding the existence of best practice solutions and the broad availability of expert knowledge or benchmarking applications.

Summarized it can be stated that DES is a very useful tool in supply chain modeling. Since still some obstacles are to be considered, the real supply chain has to be looked at carefully, whether the best solution can be derived from "classical" DES-use or from innovative alternative approaches (e.g. if uncertainty is to high and doesn't allow for sufficient model fidelity). Also hybrid approaches can be a beneficial way (e.g. Bossel, 1994). In practice projects the question will arise, whether a certain modeling technology, tool or expertise is accessible at all. It may happen, that the theoretically best solution (e.g. in case of high uncertainty within the supply chain section to be analyzed this could be Multi-Agent based simulation) is not applicable. In such cases the inaccuracies of an eventually available (and well-known) "classical" DES-approach may be compensated by carrying out intensive scenario experiments and a careful sensitivity analysis that not only indicate the assumed supply chain system behavior but that also identify those parameters whose even small fluctuations have a disproportionate influence on the simulation results (e.g. within production environments utilization variability).

5. Conclusions regarding Potentials and Shortcomings of Supply Chain Simulation

The following overview summarizes relevant potentials and shortcomings of DES or mainly DES-based supply chain simulation. Advantageous potentials are in particular:

- Complex systems are often liable to uncertainty, and simulation is an effective tool to explore possible alternative parameter settings and supply chain scenarios within a

variety of timeframes (form e.g. operative process planning and control up to the evaluation of the strategic evolution of supplier or customer networks).
- Simulation broadens the user's horizon about complex relationships and intransparent dependencies within the system under deterministic as well as under stochastic operating conditions. E.g. bottlenecks or other unfavorable conditions can be detected and possible solutions developed. During system reengineering alternative settings can be evaluated, even though neither real experiments are feasible, nor algebraic optimization methods can be (efficiently) applied.
- Innovations and alternative strategies for the supply chain can be easily investigated.

As the above discussion has shown, the following shortcomings have to be taken into account:

- Accurate and complete data is required (or has to be compensated via workarounds).
- The level of detail needed for the model is sometimes difficult to estimate within the target conflict between usability and transparency versus accuracy and model fidelity.
- Designing and building a simulation model is still a time-consuming task. A huge amount of practical projects show kind of a "complexity explosion", because users tend to implement all specific characteristics of a flow system instead of concentrating their efforts on the efficacious factors (e.g. by means of sensitivity considerations or factor analysis).
- Simulation simplifies real world systems and is liable to errors caused by the intrinsic complexity in all phases of the modeling process and by the extrinsic complexity of the issues to be explored, demanding a careful fault analysis during model verification and validation.
- The formal modeling methods used (e.g. for process visualization or entity definition) and the software tools require education, on-the-job training and experience so as to create valid and robust simulation models
- The user must be able to interpret the output data in an appropriate way. At this point, statistical analysis tools may help.

6. Further research

Further research needs for supply chain simulation lie in various topics that shall be shortly assorted within the following paragraphs.

Although a very useful method, within the enterprise environment the effort of developing, verifying and validating a simulation model is often avoided due to time-pressure. Module-based supply chain simulation approaches promise to be a remedy, but are currently still too complex, too undeveloped in their capabilities, too undistributed and therefore merely proven and finally too generic to apply on "real-world-scenarios". Therefore, IBM has focused on operational supply chain simulation in the last years to tackle tasks in process control, decision support and proactive planning (Banks et al., 2002, cp. also Lin et al. (2002). The development of modular supply chain simulation software should be directed towards highly customizable, fast and robust applicability. There are some papers proposing generic supply chain simulation models, applicable and reusable for all sorts of problems in different businesses (Chatfield et al., 2001, Petrovic, 2001, Swaminathan et al., 1998, Vieira and Júnior, 2005, Wang and Takakuwa, 2006, Lee and Kim, 2002, Umeda and Lee (2004) and Duarte et al., 2002), an optimal trade-off between universality at one hand and huge specialization abilities at the same time.

Additionally, distributed simulation also gains importance. The development of robust, high-performance distributed simulation tackles the issues of geographical distribution, data shielding, local maintenance and scalability using common principles e.g. of the object-oriented paradigms, such as encapsulation (Banks et al. 2002). For further reading, refer to Fujimoto (2000) and Page and Kreutzer (2005). One possible development is the integration of classical (DES) approaches in innovative methods such as Multi-Agent-Systems. The development of a neighbored field – database design and programming – has shown a similar evolution that might be a pattern also for simulation applications.

Furthermore methods for finding the appropriate level of detail, as well as models that can combine varying level of details. Alternatively, on can think of scalable models that enclose the ability of drill-downs and roll-ups as currently available e.g. within data warehouse technologies are desirable. There are only few proposals addressing this matter (Zülch et al., 2002, Persson, 2002, Jain et al., 2001 and Law and Kelton, 2000).

While many developments have been made in supporting the model coding, there are few tools available to assist the conceptual modeling phase. Heavey and Ryan (2006) present an overview of general process modeling tools and refer to their support for simulation.

The accuracy of the results obtained depends primarily on the accuracy and validation of the data provided. The required data are often difficult to collect and to export to usable formats. Technical advances in integration with ERP-Systems such as SAP and automating model data maintenance increase the manageability of data. For further reading, refer to Everton and Stafford (2005).

7. Conclusions

We presented and analyzed current developments in supply chain simulation. We gave a general survey of discrete event simulation and its applicability in industrial scenarios. The utility and applicability of discrete event simulation is undisputable but there are still obstacles. The continuous nature of processes is not possible to handle and consequently, the interactions between the continuous components are also not considered in DES models. Furthermore, the complexity of modeling design and finding a suitable level of detail is complicating the supply chain simulation process, too.

There are still many issues to be addressed in different research topics concerning the supply chain simulation which were presented in the last chapter. Reviewing literature, a comprehensive benchmark problem for supply chain simulation models could not be found, whereas in other research fields like Machine Learning, it is common practice to evaluate a new method on standard benchmark problems.

REFERENCES

Banks, J. (2000), Getting started with AutoMod, AutoSimulations Inc., Utah.

Banks, J., Jain, S., Buckley, S., Lendermann, P. and Manivannan, M. “Opportunities for simulation in supply chain management”, Proceedings of the 2002 Winter Simulation Conference, pp. 1652-1658

Barnett, M. and Miller, C. (2000) “Analysis of the virtual enterprise using distributed supply chain modeling and simulation: an application of e-SCOR”, Proceedings of the 2000 Winter Simulation Conference, pp. 352-355

Beamon, B. (1998) “Supply chain design and analysis: Models and methods”, Int. J. Production Economics, Vol 55, pp. 281-294

Blitz, H. (2000), Risikomanagement nach KonTrsG, Schäffer-Poeschel, Stuttgart.

Biswas, S. and Narahari, Y. (2004) “Object oriented modeling and decision support for supply chains”, European Journal of Operational Research, Vol 153, pp. 704-726

Bossel, H. (1994), Modeling and Simulation, A. K. Peters, Wellesley MA and Vieweg, Braunschweig/Wiesbaden.

Chatfield, D., Harrison, T. and Hayya, J. (2001) “Sisco: A supply chain simulation tool utilizing SILKTM and XML”, Proceedings of the 2001 Winter Simulation Conference, pp. 614-622

Chen, B., Bimber, O., Chhatre, C., Poole, E. and Buckley, S. (1999) “eSCA: a thin-client/server/web-enabled system for distributed supply chain simulation”, Proceedings of the 1999 Winter Simulation Conference, pp. 1371-1377

Christopher, M. (2005), Logistics and Supply Chain Management, Prentice Hall, Harlow.

Dejonckheere, J., Disney, S.M., Lambrecht, M.R and Towill, D.R. (2003) “Measuring and avoiding the bullwhip effect: A control theoretical approach”, European Journal of Operational Research, Vol 147, pp.567-590

Ding, H., Benyoucef, L., Xie, X., Hans, C. and Schumacher, J. (2004) “ONE a new tool for supply chain network optimization and simulation”, Proceedings of the 2004 Winter Simulation Conference, pp. 1404-1411

Duarte, B., Fowler, J., Knutson, K., Gel, E. and Shunk, D. (2002) “Parameterization of fast and accurate simulations for complex supply networks”, Proceedings of the 2002 Winter Simulation Conference, pp. 1327-1336

Everton, J. and Stafford, R. (2005) “Using workflow business process tools in simulation modelling”, Proceedings of the 2005 Winter Simulation Conference, pp. 2063-2067

Fujimoto, R. (2002), Parallel and Distributed Simulation Systems, Wiley, New York.

Geary, S., Disney, S.M. and Towill, D.R. (2006) “On bullwhip in supply chains – historical review, present practice and expected future impact”, Int. J. Production Economics, Vol 101, pp. 2-18

Heavey, C. and Ryan, J. (2006) “Process modelling support for the conceptual modelling phase of a simulation project”, Proceedings of the 2006 Winter Simulation Conference, pp. 801-808

Hinterhuber, H., Fohler-Norek, Ch. and Sauerwein, E. (1998), Betriebliches Risiko-management, Verlag Österreich, Wien.

Hung, W., Samsatli, N. and Shah, N. (2006) “Object-oriented dynamic supply chain modeling incorporated with production scheduling”, European Journal of Operational Research, Vol 169, pp.1064-1076

Ingalls, R. and Kasales, C. (1999) “CSCAT: The Compaq supply chain analysis tool”, Proceedings of the 1999 Winter Simulation Conference, pp. 1202-1206

Jain, S., Workman, R., Collins, L., Ervin, E. and Lathrop, A. (2001) “Development of a high-level-supply chain simulation model”, Proceedings of the 2001 Winter Simulation Conference, pp. 1129-1137

Kaihara, T. (2003) “Multi-agent based supply chain modelling with dynamic environment”, Int. J. Production Economics, Vol 85, pp. 263-269

Kerbache, L. and Smith, J. (2004) “Queueing networks and the topological design of supply chain systems”, Int. J. Production Economics, Vol 91, pp. 251-272

Kirchhof, R. (2003), Ganzheitliches Komplexitätsmanagement : Grundlagen und Methodik des Umgangs mit Komplexität im Unternehmen, Dt. Univ.-Verl., Wiesbaden

Law, A. and Kelton, W. (2000), Simulation Modeling and Analysis, McGraw Hill, Boston.

Lee, H.L., Padmanabhan, V., Whang, S. (1997) “The Bullwhip Effect in supply chains”, Sloan Management Review/Spring, pp.93-102

Lee, Y. and Kim, S. (2002) “Production-distribution planning in supply chain considering capacity constraints”, Computers & Industrial Engineering, Vol 43, pp. 169-190

Lee, Y., Cho, M., Kim, S. and Kim, Y. (2002) “Supply Chain Simulation with discrete-continuous combined modelling, Computers & Industrial Engineering, Vol 43, pp. 375-392

Lendermann, P., Gan, B. and McGinnis, L. (2001) “Distributed simulation with incorporated APS procedures for high-fidelity supply chain optimization”, Proceedings of the 2001 Winter Simulation Conference, pp. 1138-1145

Lidokhover, A. (2007), Multi-Agenten-Systeme. Grundlagen, Konzepte, Methoden, Vdm Verlag Dr. Müller, Saarbrücken.

Liu, J., Wang, W., Chai, Y. and Liu, Y. (2004) “Easy SC: A supply chain simulation tool”, Proceedings of the 2004 Winter Simulation Conference, pp. 1373-1378

Liu, R., Kumar, A. and Stenger, A. (2006) “Simulation results for supply chain configurations based on information sharing”, Proceedings of the 2006 Winter Simulation Conference, pp. 627-635

Nagurney, A. and Toyasaki, F. (2003) “Supply chain supernetworks and environmental criteria”, Transportation Research, Part D Vol 8, pp. 185-213

Page, B. (1991), Diskrete Simulation – Eine Einführung mit Modula-2, Springer, Berlin.

Page, B. and Kreutzer, W. (2005), The Java Simulation Handbook, Shaker, Aachen.

Persson, J. (2002) “The impact of different levels of detail in manufacturing systems simulation models”, Robotics and Computer Integrated Manufacturing, Vol 18, pp.319-325

Petrovic, D. (2001) “Simulation of supply chain behaviour and performance in an uncertain environment”, Int. Journal of Production Economies, Vol 71, pp. 429-438

Qiao, G. and Riddick, F. (2004) “Modeling information for manufacturing-oriented supply chain simulations”, Proceedings of the 2004 Winter Simulation Conference, pp. 1184-1188

Röder, A. and Tibken, B. (2006) “A methodology for modelling inter-company supply chains and for evaluating a method of integrated product and process documentation”, European Journal of Operational Research, Vol 169, pp. 1010-1029

Rossetti, M., Miman, M., Varghese, V. and Xiang, Y. (2006) “An object-oriented framework for simulating multi-echelon inventory systems”, Proceedings of the 2006 Winter Simulation Conference, pp. 1452-1461

Swaminathan, J., Smith, S. and Sadeh, N. (1998) “Modeling supply chain dynamics: a multiagent approach”, Decision Sciences, Vol 29 No 3, pp. 607-632

Terzi, S. and Cavalieri, S (2004) “Simulation in the supply chain context: a survey”, Computers in Industry, Vol 53, pp. 3-16

Umeda, S. and Lee, Y. (2004) “Design specifications of a generic supply chain simulator”, Proceedings of the 2004 Winter Simulation Conference, pp. 1158-1166

Vergara, E., Khouja, M. and Michalewicz, Z. (2002) „An evolutionary algorithm for optimizing material flow in supply chains", Computers & Industrial Engineering, Vol 43, pp. 407-421

Vieira, G. and Júnior, O. (2005) "A conceptual model for the creation of supply chain simulation models", Proceedings of the 2005 Winter Simulation Conference, pp. 2619-2627

Wang, J. and Shu, Y.-F. (2005) "Fuzzy decision modeling for supply chain management", Fuzzy Sets and Systems, Vol 150, pp. 107-127

Wang, X. and Takakuwa, S. (2006) "Module-based modelling of production-distribution systems considering shipment consolidation", Proceedings of the 2006 Winter Simulation Conference, pp. 1477-1484

Zülch, G., Jonsson, U. and Fischer, J. (2002) "Hierarchical simulation of complex production systems by coupling of models, Int. Journal of Production Economies, Vol 77, pp. 39-51