MESOSCOPIC SUPPLY CHAIN SIMULATION

Til Hennies[(a)], Tobias Reggelin[(b)], Juri Tolujew[(c)]

[(a), (b), (c)] Fraunhofer Institute for Factory Operation and Automation IFF and Otto-von-Guericke University Magdeburg

[(a)]til.hennies@st.ovgu.de, [(b)]tobias.reggelin@iff.fraunhofer.de, [(c)]juri.tolujew@iff.fraunhofer.de

ABSTRACT

Supply Chain Management has become a highly strategic discipline that can make up a substantial competitive advantage for every organization in globalized, intertwined logistical networks. Due to the complexity of today's supply chains, simulation has become a powerful tool in order to increase the supply chain's resilience and robustness as the major objectives of supply chain management. This paper compares existing approaches for supply chain simulation and shows the advantageousness of a mesoscopic approach for supply chain simulation. Major benefits of the mesoscopic approach are its flexibility, speed of modeling and simulation and ease of use. Mesoscopic simulation models can be used both in the planning phase and during the operation of the supply chain. Combining elements of continuous simulation and discrete-event simulation, the mesoscopic approach facilitates modeling and simulation of many real world supply chain problems. Modeling efforts are balanced with the necessary level of detail of the output data that is needed for calculations of key performance indicators in order to evaluate the supply chain performance.

The paper applies the mesoscopic modeling and simulation approach using the simulation software MesoSim, an own development, in order to show its advantages.

Keywords: Supply Chain Management, Supply Chain Simulation, Mesoscopic Simulation

1. INTRODUCTION

Supply Chain Management is an increasingly complex discipline that includes operational, tactical and strategic decisions between different stakeholders regarding physical material flows as well as information and finance flows covering all organizational functions. (Keith and Webber 1982) Modeling these supply networks is a powerful way in order to (1) increase understanding of the system behavior, (2) develop a strategic solution to a specific organizational problem or (3) utilize models for planning purposes on an ongoing basis. These decisions always aim at the major objectives of supply chains that are resilience, the capability to respond to variations, and robustness, the capability to withstand environmental changes. (Chopra and Meindl 2008)

The benefits of supply chain modeling have been acknowledged in scientific and industrial environments and in consequence, during the last two decades there has emerged a variety of different modeling approaches including deterministic optimization models, stochastic simulation models (Jain and Leong 2005), hybrid simulation-optimizations (Hicks 1999) and information-technology driven models that are focused on real-time integration of organizational big data as classified in (Min and Zhou 2002). There has not yet emerged a dominant approach for supply chain modeling, however, and the existing variety makes the selection of the best modeling approach a non-trivial task. (Anderson and Morrice 1999) In general, there can be distinguished solution generation approaches that are rather mathematical optimizations and solution evaluation approaches that are simulations. Mathematical optimization models are not able to incorporate variations in time but only find stationary optimal solutions which in practice are less important within the area of supply chain management. (Kleijnen and Smits 2003) Simulation models are identified as the superior approach, because they allow for reproductions of highly complex systems, any desired level of detail or aggregation and replication of stochastic, dynamic behaviors.

Simulation techniques are manifold and the absence of an approach that fits every supply chain problem results in a proliferation of supply chain simulation methods that are tailored to certain problems of supply chain management such as supply chain design, production planning and scheduling, inventory control, transportation and logistics management, risk management and inter-organizational coordination, cooperation and integration. This paper compares and classifies these approaches, methods and tools in order to match supply chain questions with the most appropriate simulation that meets the user's objectives.

This paper will be structured as follows: Section 2 will provide a description and comparison of the major simulation approaches that are currently used for supply chain simulations. Section 3 will describe the mesoscopic simulation approach and will show the advantageousness of this approach for supply chain simulation. Section 4 will present the results of a simulation study that shows the flexibility, ease of use and speed of mesoscopic supply chain simulation.

2. SUPPLY CHAIN SIMULATION - REVIEW

The scope of supply chain management includes strategic, tactical and operational problems within and between organizations. Typical questions within the area of supply chain management are capacity planning, resource planning, lead time planning, production planning, inventory management, sourcing strategies and information sharing implementations. The variety of problems within this area has caused the emergence of many different simulation approaches. Simulation approaches can be distinguished based on characteristics such as scope (macro-, meso-, microscopic), time (continuous, discrete, hybrid), orientation (object-, process-, activity-oriented), input-data required and output data generated. This paper will compare major approaches that are subject to discussion within the field of supply chain simulation.

Discrete-Event Simulations are widespread in industrial and logistical environments and there is a broad spectrum of software for very specific purposes as well as general purpose software. Discrete-event simulations provide very detailed information, but are related to high input data quantities and requirements, high modeling efforts and high calculation times. (Scholz-Reiter, Beer et al.) In addition, the high level of detail of the data generated most often is not needed by the user. (Min, Zhou, 2002) Supply chain applications can be found in (Alizadeh, Eskandari et al. 2011) who test the impacts of stochastic lead times, demands and item life times on a simple inventory-system with a discrete-event Arena-model or in (Ingalls and Kasales 1999) who test and evaluate the service levels and profitability as major performance indicators for different supply chain configurations using a three-echelon Arena-simulation model.

System Dynamics was initially developed by Jay W. Forrester in 1961 and is based on causal loop diagrams, stock and flow diagrams and delays to model the behavior of complex systems. This approach has been utilized in many different disciplines like physics, biology, energetic or environmental issues and social systems, but has recently also been applied to supply chain modeling. Different supply chain models are described in (Angerhofer and Angelides 2000). (Ashayeri and Keij 1998) use system dynamics modeling for business process reengineering and (Campuzano and Mula 2011) discuss performance evaluation and improvement based on a simulation model. System Dynamics is a strategic long-term oriented approach and provides output data on aggregated levels only, but requires much less modeling efforts than discrete-event simulations. Dynamic feedback processes determine long-term system behaviors and system dynamics is a powerful tool to create understanding and initiate organizational change. Due to the high level of aggregation continuous simulation models are inappropriate for operational supply chain problems such as planning and scheduling, allocation or routing problems.

Simulation-Optimization is a young approach that is described in (Abo-Hamad and Arisha 2011; März, Krug et al. 2011). This approach suggests an iterative procedure of alternating simulation and optimization. Therewith, it removes the inherent weaknesses of optimizations to not incorporate variations in time and simulations of not generating optimal solutions. The combination supports supply chain decision making by generating optimal solutions that in addition are robust and resilient over time. This approach, however, requires high levels of skills and sophistication. Developing the interaction of these models is a logically and technically complex task. Modeling efforts as well as calculation times are very high and the necessity of the data generated needs to be assessed and evaluated in advance because it often goes beyond the necessities for supply chain problems. Supply chain applications can be found in (Better, Glover et al. 2007) dealing with the field of risk management and in (Hicks 1999) presenting a four-step procedure for supply chain design questions.

Pure spreadsheet based simulations as described in (Powell 1997; Plane 1997; Kleijnen and Smits 2003) are per se deterministic and static. Even though these attributes are contrary to the goal of modeling very complex dynamic behaviors of supply chains, spreadsheets have introduced simulation to the industrial environment as the required skills and scientific backgrounds for implementation are much lower and spreadsheets are very commonly used in industrial environments. Supply chain topics of inventory management and transportation and logistics can be addressed with spreadsheet simulations (Chwif, Pereira Barretto, and Saliby 2002) develop a spreadsheet based model to dynamically determine safety stocks in supply networks and therewith even incorporate dynamic behavior. Monte-Carlo simulations as add-ons to spreadsheet-based simulations introduce stochastic elements to the deterministic environment wherefore they are more appropriate for supply chain simulations. (Deleris and Erhun 2005) suggest Monte-Carlo simulation as a technique to improve risk-management within supply chain management as one specific aspect of the complex and comprehensive system. Spreadsheets based simulations and Monte Carlo simulations are both appropriate measures for certain aspects of supply chain problems, but they do not incorporate dynamic behavior which is essential in supply chain management.

3. MESOSCOPIC SIMULATION APPROACH

In order to overcome the described disadvantages of existing approaches to supply chain simulation (Reggelin 2011a) and (Reggelin and Tolujew 2011) have developed a mesoscopic approach to modeling and simulation of logistics networks and the mesoscopic simulation software MesoSim.

Mesoscopic models represent logistics flow processes on an aggregated level through piecewise constant flow rates instead of modeling individual flow objects. This assumption is valid since logistics flows do not change continuously over time because the control of resources is not carried out continuously but only at certain points of time like changes of shifts, falling below or exceeding inventory thresholds. (Reggelin 2011a) The resulting linearity of the cumulative flows facilitates event scheduling and the use of mathematical formulas for recalculating the system's state variables at every simulation time step. (Reggelin 2011b) The simulation time step is variable and the step size depends on the occurrence of scheduled events. This leads to a high computational performance. (Schenk, Tolujew et al. 2009)

In terms of level of detail, mesoscopic simulation models fall between object based discrete-event simulation models and flow based continuous simulation models. (Schenk, Tolujew et al. 2010)

The appropriateness of this approach for supply chain simulation is based on the inherent characteristics of supply chains.

- Supply chains deal with flows of materials and information on an aggregated level. Single logistics objects are of secondary interest.
- Supply chains include both continuous processes (e.g. continuous inventory reduction) and discrete impulse-like flows (e.g. event-based inventory replenishments).
- Supply chains include different products and product portions that must be representable in the simulation model. In mesoscopic models, different product types run in parallel through all nodes and edges of the supply chain.
- Supply chain complexity requires both simplification and efficient calculation algorithms as offered by the mesoscopic approach by using mathematical formulas to calculate the results as continuous quantities in every modeling time step.
- Supply chain performance evaluation occurs on a mesoscopic level. Neither aggregated results of a macroscopic simulation nor detailed primary data of a microscopic simulation can be utilized without being transformed into mesoscopic metrics (throughputs, cycle times, utilizations,..)
- Supply chain data is available on aggregated levels. For discrete-event simulation, detailed data needs to be deducted and for system dynamics, the level of detail is even reduced. Mesoscopic simulation directly utilizes available supply chain data.

4. MESOSCOPIC SUPPLY CHAIN SIMULATION IN PRACTICE

4.1. Supply Chain Description

The simulation study is based on a real-world supply chain of a company that designs, manufactures, markets and services consumer goods. The production of these products is outsourced and executed by suppliers that are located in Asia. Production times vary depending on the product with known fluctuations. Suppliers are grouped into strategic suppliers and others. Via distribution centers, products are transported to warehouses and locally sold and delivered to customers. Even though the sales prices for the products are the same for all customers, there are strategic customers accounting for 80% of sales and secondary customers purchasing the remaining 20%. Main supply routes pass distribution centers that are located in European countries. Three modes of transportation are used namely truck, railroad and sea transportation. The transportation is executed in accordance with minimum batch size constraints. The minimum lot size for transportation is one container that can contain different group packs of product types. The products are classified based on the desired service-levels. The warehouses are geographically distributed across Europe. The main objective of the company is an inventory level optimization at its warehouses and distribution centers under the condition of realizing as few goods movements as possible. The structure of the supply chain is illustrated in Figure 1. The mesoscopic simulation model aims at rebuilding the supply chain configuration in order to prepare a risk analysis of deterministically defined safety stock levels.

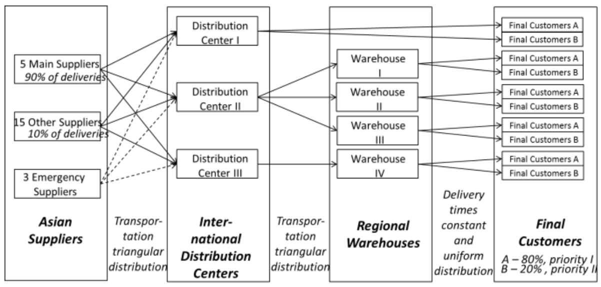

Figure 1: Supply Chain Structure

4.2. Modeling with MesoSim

Basic elements of the mesoscopic simulation model are source, sink, funnel, assembly, disassembly and delay. The mesoscopic approach supports modeling different product types and portions that can flow in parallel through the system because of multichannel funnels and delays. In addition to piece-wise constant flows, a mesoscopic model may employ impulse-like flows to represent the flow of logistics objects through a logistics system. These elements are utilized to replicate the structure and processes as described for the supply chain.

4.2.1. Structure

Funnels are main structural elements that represent suppliers, distribution centers, warehouses and customers within the model. Funnels are parameterized through output flow rates and impulse-like outputs for each product type, opening inventories, constraining performance limits and proportional distributions of outputs to successional elements. Delays are used to imitate transportation and delivery times. Parameters of delays are constant or variable lag times and output allocation to successors. Assembly and disassembly imitate material handling and (de-) composition of logistical units at distribution centers or warehouses. These elements are defined by parameters of funnels and in- and output percentages. The distribution network modeled comprises four vertical stages and up to four horizontal stages and is illustrated in Figure 2.

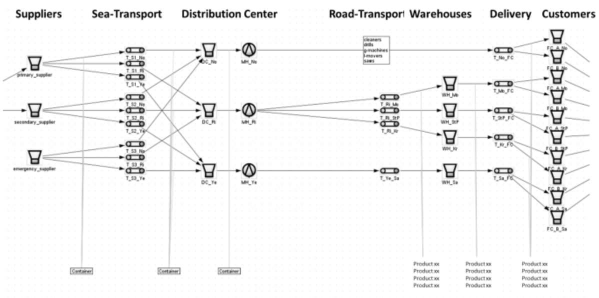

Figure 2: MesoSim Supply Chain Model

4.2.2. Processes

Processes in MesoSim are replicated through piece-wise continuous and impulse-like flows to represent the flow of logistics objects through a logistics system. Impulse-like flows allow representing bundled movement of logistics objects like bundled transports or the movement of production batches. The creation of the actual simulation model requires input data from the real system. The input data needed for mesoscopic simulation is aggregated and includes average production times and volumes for each product type with the respective fluctuations on a periodic level, shipment and production batch sizes, average processing performances of the structural elements, probabilities of risks and estimations of demand distributions. Information at this level of aggregation can directly be implemented in the MesoSim model.

Based on this information, the following supply chain processes are incorporated in the simulation model.

- Suppliers continuously produce different products and once a certain quantity is reached they ship them in containers to distribution centers.
- Production times for all products are normally distributed with defined average values and standard deviations.
- Sea-transportation lead times to distribution centers are based on triangular distributions.
- At the distribution centers, material handling of containers is imitated and product types can be newly combined for further distribution. Uniform distributions are assumed for material handling times.
- Transportation from distribution centers to warehouses is replicated using delay elements with triangular lead time distributions.
- At the warehouses, another material handling is imitated and product types are distinguished to allow for different demands. Constant material times are utilized.
- Demands are imitated by defining continuous output flow rates at each warehouse as well as impulse-like increases.

4.2.3. Scenarios

The development of inventory levels of all products at the final warehouses under certain conditions is of main interest for this simulation model. Major risks for supply chains can come from customer side as well as from supplier side wherefore both is imitated demand and supply uncertainty. Two scenarios are tested and inventory level developments observed.

1. The short fall of one supplier should be captured by others. Within the experiment, replenishment of one product type at a distribution center is halved compared to the regular situation and the impacts on inventories at final warehouses are assessed.
2. Impulse-like demand increases stress-test the supply chain at certain points of time. Imitating major contracts in form of large-scale orders illustrate impacts on overall inventory levels.

4.3. Results

This simulation was conducted in order to, firstly, show the applicability and advantages of mesoscopic simulation for supply chains and, secondly, realize the replication of a real-world supply chain for inventory development studies under demand and supply risks.

4.3.1. Supply Chain Simulation

The software MesoSim can be utilized for supply chain simulation and allows for modeling of main structures and processes and has certain advantages for supply chain modeling such as level of aggregation, speed and flexibility.

The utilized input data and generated output data for the simulation was on aggregated levels without the necessity of further aggregating or decomposing the data. The creation of modeling is straight-forward and can be quickly realized and calculation through the simulator is fast due to the calculation only at events concerning change of flow rates and the occurrence of impulses. Different scenarios could be imitated and tested and the model will be further adjusted to be used for planning purposes illustrating the flexibility and adjustability of the approach.

4.3.2. Scenarios

The created supply chain model is used to observe inventory developments at final warehouses under certain conditions.

The model is validated based on data derived from the real system. The exemplary inventory developments of two product types in one final warehouse are illustrated in the first diagram of Figure 3.

Based on this supply chain model, two scenarios have been tested in order to observe inventory developments and assess the impacts of uncertainties.

The impacts of a supply shortage of one product (red line) at the preceding distribution center on the final warehouse are shown in the second diagram. Safety stocks are almost depleted until the replenishment from other suppliers begins and stock levels increase.

Demand increases in the form of large scale orders for the second product (blue line) are visualized in the third diagram and show substantial safety stocks to cover these situations.

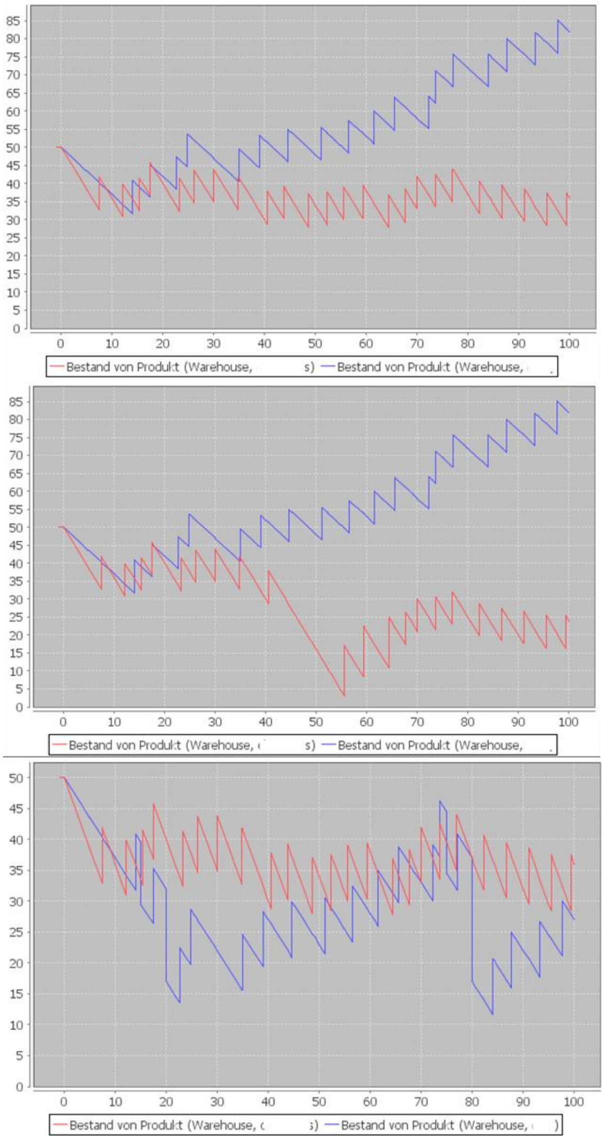

Figure 3: Inventory Developments at Final Warehouse given Supply and Demand Uncertainties

5. CONCLUSION AND OUTLOOK

This paper illustrates the application of the mesoscopic simulation approach to a real-world supply chain example utilizing the software MesoSim. The purpose of this study was to examine the advantages for supply chain simulation that have been expected from this approach. The mesoscopic simulation approach provides three major advantages for supply chain simulation:

- Level of detail: Supply chain simulation is used for key performance indicator calculations. KPIs aggregate data in order to assess and evaluate supply chain performance and identify system constraints. This purpose can be satisfied by mesoscopic simulation.
- Flexibility: Mesoscopic simulation is a generic approach that supports modeling of the majority of different supply chain problems. The adjustability of the aggregation level is essential for supply chain problems that by definition are very complex covering a broad spectrum.
- Speed: Mesoscopic simulation allows quick analysis of supply chains. Modeling effort is balanced with output data needed and calculation time required.

This paper provides both a review of modeling and simulation approaches for supply chain management and the first real-world example of a mesoscopic simulation model. The created model will be further developed to be used for planning purposes also.

More mesoscopic supply chain simulation models are needed to strengthen the results, further develop the software MesoSim and sustainably introduce mesoscopic simulation to supply chain management topics.

REFERENCES

Abo-Hamad, W., Arisha, A., 2011, Simulation-Optimisation Methods in Supply Chain Applications: A Review, *Irish Journal of Management*, pp. 95–123

Alizadeh, M., Eskandari, H., Sajadifar, S.M., Geiger, C.D., 2011, Analyzing a Stochastic Inventory System for Deteriorating Items with Stochastic Lead Time Using Simulation Modeling. In: Jain, S., Creasey, R.R, Himmelspach, J., White, K.P, Fu, M., *Proceedings of the 2011 Winter Simulation Conference*, 1pp.1650-1662, Dec. 11th – 14th2011, Phoenix, AZ

Anderson, E.G., Morrice, D.G., 1999, A Simulation Model to study the Dynamics in a service-oriented Supply Chain. In: Farrington, P. A., Nembhard, H. B., Sturrock, D. T. and Evans, G. W., eds. *Proceedings of the 1999 Winter Simulation Conference*, pp.1215-1220, Dec. 5th – 8th 1999, Phoenix, AZ

Angerhofer, B.J. and Angelides, M.C., 2000, System Dynamics Modelling in Supply Chain

Management: Research Review. In: Joines, J.A., Barton, R.R., Kang, K. Fishwick, P.A., eds. *Proceedings of the 2000 Winter Simulation Conference*, pp. 342-352, Dec. 10th -13th 2000, Orlando, FL

Ashayeri, J., Keij, R., 1998, Global business process re-engineering: a system dynamics-based approach, *International Journal of Operations and Production Management* 18 (9/10), pp. 817–831

Better, M., Glover, F., Kochenberger, G., Wang, H., 2011, Simulation Optimization: Applications in Risk Management, *International Journal of Information Technology & Decision Making* 7 (4), pp. 571-587

Campuzano, F., Mula, J., 2011, *Supply Chain Simulation: A System Dynamics Approach for Improving Performance*, London, Springer-Verlag.

Chopra, S., Meindl, P., 2008, *Supply Chain Management. Strategy, Planning and Operation*. New York, Prentice Hall International

Chwif, L., Pereira Barretto, M.R., Saliby, E., 2002, Supply Chain Analysis: Spreadsheet or Simulation?. In: Yuecesan, E., Chen, C.-H., Snowdon, J.L., Charnes, J.M., eds. *Proceedings of the 2002 Winter Simulation Conference*, pp.59- 66, Dec. 8th – 11th 2002, San Diego, CA

Deleris, L.A., Erhun, F., 2005, Risk Management in Supply Networks Using Monte-Carlo Simulation. In: Kuhl, M. E., Steiger, N. M., Armstrong, F. B. and Joines, J. A., eds. *Proceedings of the 2005 Winter Simulation Conference*, pp.1643-1649, Dec. 4th – 7th 2005, Orlando, FL

Hicks, D.A., 1999, A Four Step Methodology for using Simulation and Optimization Technologies in Strategic Supply Chain Planning. In: Farrington, P. A., Nembhard, H. B., Sturrock, D. T. and Evans, G. W., eds. *Proceedings of the 1999 Winter Simulation Conference*, pp.1215-1220, Dec. 5th – 8th 1999, Phoenix, AZ

Ingalls, R.G., Kasales, C., 1999, CSCAT: The Compaq Supply Chain Analysis Tool. In: Farrington, P. A., Nembhard, H. B., Sturrock, D. T. and Evans, G. W., eds. *Proceedings of the 1999 Winter Simulation Conference*, pp.1201-1206, Dec. 5th – 8th 1999, Phoenix, AZ

Jain, S., Leong, S., 2005, Stress Testing a Supply Chain Using Simulation. In: Kuhl, M.E., Steiger, N.M., Armstrong, F.B., Joines, J.A., *Proceedings of the 2005 Winter Simulation Conference*, 1pp.650-1657, Dec. 4th – 7th 2005, Orlando, FL

Keith, O.R., Webber, M.D., 1982, *Supply Chain Management. Logistics Catches Up with Strategy*, London, Chapman & Hall

Kleijnen, J. P. C., Smits, M. T., 2003, Performance metrics in supply chain management, *Journal of the Operations Research Society,* 54 (5), pp. 507–514

März, L., Krug, W., Rose, O., Weigert, G. 2011, *Simulation und Optimierung in Produktion und Logistik - Praxisorientierter Leitfaden mit Fallbeispielen*, Berlin, Springer-Verlag

Min, H., Zhou, G., 2002, Supply chain modeling: past, present and future, *Computers and Industrial Engineering,* 43, pp. 231–249

Plane, D.R., 1997, How to build spreadsheet models for production and operations management, *OR/MS Today*, 24, pp. 50-54

Powell, S.G., 1997, Leading the spreadsheet revolution, *OR/MS Today*, 24, pp. 8-10

Reggelin, T. 2011a, *Mesoskopische Modellierung und Simulation logistischer Flusssysteme*, Otto-von-Guericke-Universität Magdeburg

Reggelin, T., Tolujew, J., 2011, A Mesoscopic Approach to Modeling and Simulation of Logistics Processes. In: Jain, S., Creasey, R. R., Himmelspach, J., White, K. P., Fu, M. (Eds.) *Proceedings of the 2011 Winter Simulation Conference*,IEEE, Piscataway, pp. 1513-1523

Reggelin, T., 2011b, Mesoskopische Modellierung und Simulation logistischer Flusssysteme. In: Wimmer, T., Grosche, T., eds. *Flexibel-Sicher-Nachhaltig: Kongressband 28. Deutscher Logistik-Kongress*, Hamburg, DVV Media Group, pp. 287-290

Schenk, M., Tolujew, J., Reggelin, T., 2010, A Mesoscopic Approach to the Simulation of Logistics Systems. In: Dangelmaier, W., Blecken, A., Delius, R., Klöpfer, eds. *Advanced Manufacturing and Sustainable Logistics*, Berlin, Springer, pp. 15-25.

Schenk, M., Tolujew, J., Reggelin, T., 2009. Mesoscopic Modeling and Simulation of Logistics Networks, In: *Preprints of the 13th IFAC Symposium on Information Control Problems in Manufacturing*, Moskau, pp. 287-290

Scholz-Reiter, B., Beer, C. de, Freitag, M., Hamann, T., Rekersbrink, H., Tervo, J. T., 2008, Dynamik logistischer Systeme, In: Nyhuis, P., eds., *Beiträge zu einer Theorie der Logistik*, Berlin, Springer, pp. 109-138