Supply Chain Management Research Methodology Using Quantitative Models Based on Empirical Data

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Summary:
Various papers have been published that define requirements for theory development in operations management or try to connect the knowledge generated along the different research lines. Here, we define the scope of supply chain management research and its relationship with operations management research. We show how quantitative model-driven research - especially under consideration of empirical data and simulation models - can be conducted in supply chain management research because this research type holds great potential for advancing theory. Furthermore, we illustrate our ideas via some selected research examples.

Keywords:
Supply Chain Management, Quantitative Models, Empirical Data, Simulation Models
1 Introduction

One of the main difficulties in research methodology in the field of supply chain management research is that empirical theory building quantitative empirical research is still in its infancy. Therefore, opinions existing on what is “good” quantitative empirical research differ. In particular, the present paper will provide some ideas and concepts to overcome this problem and will describe how empirical quantitative model-driven research can be conducted as this type of research offers great opportunity for further advancing supply chain management theory.

First, in Section 2 the scope of supply chain management research and its relationship with operations management research will be defined. In Section 3, this paper will give an overview of quantitative model-driven research methodologies in supply chain management. In general, quantitative model-based research can be subdivided into empirical and axiomatic research as well as into descriptive and normative research. In particular, some reference papers of each research type will be mentioned.

Furthermore, the importance of discrete-event simulation models (Section 4) and aspects of mixed model research (Section 5) will be discussed. Section 6 will describe how to conduct “good” empirical quantitative model-driven research. Finally, Section 7 will summarize major findings and further ideas.

2 Supply Chain Management Research

In recent years, supply chain management was widely discussed in the management and scientific literature. However, it is not clear whether supply chain management itself can be established as a management concept with a long-term impact on theory and practice. Müller et al. (2003) summarized three supply chain management criteria that are used in literature, i.e.:

- Supply chain processes have to fulfill customer requirements.
- The focus of supply chain management is on the management of the flow and transformation of goods, the flow of information and that of funds from the raw material stage (extraction) to the end user (Handfield, 2002).
- Supply chain processes are company-spanning.

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The main objective of problem-solving methods in supply chain management is to reduce uncertainties. Sources of uncertainty are, e.g., the forecast horizon (i.e., uncertainty that is related to forecasting over a long period of time), input data (i.e., biases and errors of input data), administrative and decision processes, and inherent uncertainties (Van der Vorst et al., 1998). In the context of supply chain management, improvements to the communication and information exchange between the supply chain partners occupy a key position. Various management concepts such as, for example, Vendor-Managed Inventory (VMI), Continuous Replenishment Program (CRP), and Collaborative Planning, Forecasting, and Replenishment (CPFR) take this circumstance into account. These methods differ in the visibility of the whole supply chain (Barratt & Oliveira, 2000). The dilemma is that centralized planning is not always possible or suitable and that, thus, the decentralized coordination of supply chains leads to difficulties. Topical research studies compare the benefits of information sharing with cycle time reduction. The results obtained show that in some supply chain settings, e.g., the reduction in cycle time can have a greater impact on supply chain performance than information sharing (Cachon & Fisher, 2000). From operations management it is known that the cycle time of a process is composed of a capacity term, a utilization term and a variability term (Hopp & Spearman, 1996). The cycle time variability is due to the variability of the process times as well as to the flow variability. From the managerial point of view, this variability is of major importance, being the main factor that influences the parametrisation of a process, e.g., what right utilization is so as to satisfy customer requirements. In principle, there is a set of levers to attack variability, i.e.:

- Reduce demand variability, e.g., through improved forecasting, everyday low-price strategy (no price volatility), and incentives to affect arrival patterns;
- reduce delivery cycle time, e.g., increased safety capacity (scale and speed);
- reduce variability in delivery cycle time, e.g., standardized operating procedures, better training, and synchronized flows;
- reduce supply variability, e.g., reliable suppliers, better forecasts, and reservation.

In general, one can reduce uncertainty by information sharing, lead time reduction, etc., but it is not possible to avoid uncertainty. In this respect, an important management lever is inventory management. On the one hand, different types of inventory are necessary to buffer against demand volatility, operational and supply uncertainties but, on the other hand, inventory is sometimes the result of inefficient management of the supply chain processes. Therefore, inventory management is a focal point of managing supply chain processes.
Traditionally, in the course of the management of supply chain processes, inventory management is challenging because it directly impacts both cost and service. Uncertain demand and uncertain supply and/or production lead times make it necessary to hold inventory at certain positions in the supply chain to provide adequate service to the customers. As a consequence, increasing supply chain process inventories will increase customer service and revenue, but it comes at a higher cost. Therefore, the management of supply chain processes has to resolve this trade-off by identifying possibilities to decrease inventories whilst simultaneously improving customer service. A well-known management reactive lever in this respect is risk pooling by different types of centralization or standardization, e.g. central warehouses, product commonalities, postponement, and modularization strategies. In this way and by combination of these concepts, it is usually possible to reduce inventory costs to a large extent.

The core of supply chain management research are the management of company-spanning processes that offer additional aspects for process improvement. Furthermore, customer requirement and customer satisfaction play a key role in this context. Traditionally, the concept of customer focus (orientation) has been heavily researched from a marketing perspective, but it has not yet received the necessary attention from the operations and supply chain management fields. The problem is that the emphasis of existing research in marketing has been on the identification and measurement of customer requirements and satisfaction, having virtually left untouched the connection to processes. In the context of supply chain management, this is not sufficient. It is necessary to extend the customer focus to company-spanning processes (supply chain processes), too. The optimization of the flows of goods, information and funds is not limited to one’s own organization but concerns each firm involved in fulfilling a customer order.

3 Developments in Quantitative Modeling

Here, an overview of developments in quantitative modeling will be given that is primarily based on an article of Bertrand & Fransoo (2002). In the beginning, quantitative modeling in operational research was very much oriented towards solving real-life problems in operations management and not towards developing scientific knowledge. In the 1960s, a strong academic research line appeared that worked on more idealized problems. This research actively built scientific knowledge in operations management. However, in the last three decades, much of this knowledge has lost its empirical foundations. Recently, the need to develop explanatory and predictive theory has come to the forefront.

Quantitative model-driven research can be divided into two different classes. The first class is primarily driven by the idealized model itself and is called the axiomatic research approach. This approach deals with the strict process of theorems
Quantitative Models Based on Empirical Data

and logical proofs (e.g., mathematical models) (Meredith et al., 1989). In this context, axiomatic quantitative research using simulation is an interesting aspect as it captures empirical data (no analytical solutions are possible) and thereby gains scientific relevance. Furthermore, simulation models are a linking bin to the second class of quantitative model-based research.

The second class of model-driven research is determined by empirical findings and measurement. Here, the primary task of the researcher is to make sure that there is a model fit between observation and action in reality. The model is more or less not idealized. Betrand & Fransoo (2002) pointed out that the methodology of quantitative model-driven empirical research offers a great opportunity for further advancing theory. Quantitative empirical research is still in its infancy. Thus, different opinions exist about what is good quantitative empirical research as compared to quantitative axiomatic research. In particular, quantitative model-based empirical studies generate models of causal relationships between control variables and performance variables. This logical positivist/empiricist approach isolates the phenomenon from the context for logical analysis. These models are then analyzed or tested.

The research type used can be descriptive or normative. Descriptive empirical research is interested in creating a model that describes the causal relationships that may exist in reality and leads to improved understanding of the process mechanics, e.g., systems dynamics research (Forrester, 1961), and clockspeed in industrial systems (Fine, 1998). In this sense, simulation is more than a faction of axiomatic quantitative research and can be used in the second class of model-based research, too.

A further type is the normative empirical quantitative research that is interested in developing policies, strategies and actions so as to improve the current situation. There is a wide spectrum of literature about the validation and verification of models. The problem is that so far the verification procedure is not very strong. It is very hard to assess which changes in performance are due to the specific improvement tested and which are due to other changes. However, this form of research is the most complete one (see Bertrand & Fransoo, 2002), and the research cycle is conducted in its entirety (Mitroff et al., 1974):

- Conceptualization,
- Modeling,
- Model solving,
- Implementation.

In many cases, this research is based on research work published earlier that belongs to the axiomatic quantitative research type and where the scientific knowledge for the modeling and model solving parts have already been developed.
Furthermore, operations management and supply chain management research faces the problem that a well-defined methodological framework for identifying and measuring the relevant characteristics of real processes (not idealized) is missing. No objective, situation-independent and generally accepted procedure exists. Of course, each research work deals with this problem somehow. But this is always done in a subjective, situation-dependent way that often is not explicitly reported. As a consequence, it is difficult to judge its scientific value for advancing theory (Bertrand & Fransoo, 2002).

In the context of quantitative model-driven empirical research, measurement occupies an important position. A problem is that in the field of supply chain management, primarily measures are used that more or less come from operations management. Consequently, these measures are usually focused on one company only and do not take into account the company-spanning aspects. Therefore, supply chain management measures have to be used that fulfill this requirement, e.g., the bullwhip effect (see Reiner, 2004).

3.1 Examples - Descriptive Empirical Quantitative Research

Sterman (1989) reports an experiment (which is known as the “beer game”) regarding the management of a simulated inventory distribution system which contains multiple actors, feedback, nonlinearities, and time delays. The interaction of individual decisions with the structure of the simulated firm produces aggregate dynamics that systematically diverge from optimal behavior. In particular, Sterman describes and explains what is called the bullwhip effect (i.e., the first law of supply chain dynamics) which states that, in the supply chain, the magnitude of demand volatility a company faces increases upstream.

Also, Fine (2000) presents a good example of descriptive quantitative research in the field of supply chain management. In the past decade, he studied the dynamics of supply chains of fast-clockspeed industries (e.g., internet services, personal computers) with the main objective to identify robust principles for supply chain design. He identified supply chain design as the core competence of an organization. The clockspeed amplification hypothesis (second law of supply chain dynamics) states that the industry clockspeed a company faces increases the further downstream it is located in the supply chain. To gain this insight, he analyzed different stages of a supply chain. In the personal computer industry, e.g., he studied computer manufacturers, semiconductor manufacturers and semiconductor equipment suppliers. These insights help to understand the unprecedented clockspeed experienced in our economy during the last decade and to peer into the future as well. In particular, they help in identifying and understanding clockspeed accelerators and decelerators.
3.2 Examples - Normative Empirical Quantitative Research

Bertrand & Fransoo (2002) describe different examples of normative empirical quantitative research as regards the field of operations management. Jammernegg & Reiner (2004) give an example of a three-stage supply chain (supplier network). This research deals with the opportunities and challenges for improving the performance of supply chain processes by the coordinated application of inventory management and capacity management. The approach is illustrated by a supplier network in the telecommunications and automotive industries. By using discrete-event process simulation it is demonstrated how the coordinated application of methods from inventory management and capacity management results in improved performance measures of both intraorganizational (costs) and interorganizational (service level) objectives.

4 Discrete Event Simulation Modeling in Quantitative Research

We already discussed above the difficulties of normative empirical quantitative research. In particular, it is very hard to assess which changes in performance are due to the specific improvements provided and which to other changes. Quantitative empirical research has to be designed to test the validity of quantitative theoretical models and problem solutions with respect to real-life data. The model-driven empirical research takes advantage of the high number of published axiomatic quantitative research projects. In particular, the empirical observations are driven by hypotheses that are based on the theories that are developed earlier in primarily axiomatic research projects. Therefore, the usage of simulation models (i.e., discrete-event simulation models) could be an opportunity to support this research type. In particular, in the field of supply chain management simulation there is also a possibility to handle the high complexity of supply chain management research caused by the analysis of multiple stages.

Kleijnen & Smits (2003) mentioned that discrete-event simulation is very important in supply chain management research. Also, they present examples of papers in the area of supply chain management research that use this simulation type.

This kind of simulation represents individual events and incorporates uncertainties. In detail, with discrete event simulation models a system is modeled by defining the events that occur in the system, and describing the logic prevailing at such times. These events are processed in a chronological order and simulated time is advanced from one event to the next. Thus, inventory queuing, manufacturing, business process and supply chain process analysis problems are among the types of situations addressed (Evans & Olson, 2002).
The evaluation of existing process designs and the comparison of alternative configurations require concrete values of different performance measures. In case of existing processes, these values could be obtained from the supply chain partners’ performance measurement systems. However, in many instances the desired performance measures are not provided by these systems. In case of alternative process configurations, the values of performance measures are never a priori available as existing data. If not available, these values can be calculated, estimated, or obtained by simulation. The possibility of exact calculations is limited by the complexity of the problem, and estimation usually is too imprecise. Therefore, dynamic, stochastic computer simulation can be utilized to deliver the required input for the evaluation of supply chains. As already mentioned, risk is an essential factor for the supply chain process evaluation. Stochastic simulation can deal with random variables and generates not just mean values of performance measures, but it also gives useful information about their probabilistic distribution. For an overview of the use of simulation in supply chain management, refer to Wyland et al. (2000).

There is a general consensus amongst researchers that the process presented in Figure 1 should be undertaken for the purpose of discrete-event simulation modeling. Law & Kelton (2000) define this typical simulation process. It should be started with step 1 for formulating the problem; then the objectives of the study should be determined and the specific issues to be considered identified. Second, data should be collected (if it exists) based on the objectives of the study. Step 3 is the validation of the data. Subsequently, step 4 is the construction of a computer model based on a conceptual model. Step 5 consists in carrying out the pilot run and step 6 in conducting the verification and validation. Steps 7 through 10 are the design of experiments, production runs for providing performance data on the systems design of interest, output analysis considering statistical techniques for analyzing the output of the production runs, and the implementation of the best alternative. The main defining feature of this methodology is the collection of tangible data to produce tangible results based on a sequential process (Eldabi et al., 2002). Therefore, discrete-event simulation is a typical quantitative research method. However, under specific circumstances, this research method could also be used for qualitative research; refer to Eldabi et al. (2002) for a more detailed discussion.

The following example introduces a procedural model that uses discrete-event simulation modeling and helps to improve customized supply chain design (Reiner & Trcka, 2004). Starting points for the analysis of an existing supply chain are changes in the supply chain strategy or in the corporate strategy of a supply chain partner, or a continuous improvement cycle (e.g., every year). To analyze different improvement alternatives, it is necessary to establish a target system for supply chain evaluation. At this level of the analysis, it is essential that all data of the whole supply chain network be available. The analysis of the supply chain design can be carried out on the basis of historical data (e.g., of the last year). This in-
cludes the collection of logical data (e.g., process flow diagrams), point of sale (POS) data, as well as order policies (parameter: reorder point, service level ō safety stock), production strategy (make-to-stock, make-to-order, batch size, service level), and the number of elements in the supply chain. In case one partner in the supply chain has problems in sharing information because of its restricted information-sharing policy, the analysis can be carried out on the basis of historical data.

Figure 1: Simulation Study (Law & Kelton, 2000)

The next step consists in building a simulation model of the whole supply chain. It contains a base case process flow model (logical data) and numerical data, stochastic behavior of uncertain indicators as well as disturbing events and information flow. After the validation has been effected, the simulation environment can
be used to evaluate different supply chain design alternatives. Thus, the next step is the identification of design alternatives. This includes the design of experiments (DoE), i.e. the range of each decision variable (such as the variation of the number of elements in the supply chain, batch size, reorder points, or target service level) and company-specific processes as well as supply chain process alternatives (e.g., process flow model). After running these experiments using simulation (with sufficient replications), the effects of changes in the setup of a product-specific supply chain design on the overall work in process, fill rate (service level), bullwhip effect measures and times (e.g., cycle time), which are the key supply chain indicators for some industries, can be studied in detail. It is obvious that there are dependencies between these key supply chain indicators and other performance measures (cost, quality, flexibility). The market winners must be selected out of this set of performance measures. The market winner performance measure triggers the evaluation of supply chain design alternatives, which should provide decision support for the reorganization of supply chain processes. If the results obtained are not satisfactory, the design alternatives have to be refined and simulated again.

5 Aspects of Mixed Methods Research

Krajewski (2002) pointed out that academics should get ahead of current practice and lead the way for improved, more effective operations in the future. This thrust will require linking, e.g., quantitative and qualitative research.

The so-called mixed methods research combines theoretical and/or technical aspects of quantitative and qualitative research within a particular research project (Rocco et al., 2003). This research type is widely used in the social and behavioral sciences. But it also offers opportunities in operations and supply chain management research. For example, the field of operations management has been characterized by a dominant positivist epistemology over the last 50 years while other business fields - such as marketing, organizational behavior, and finance - have matured through the scientific theory-building process.

Voss et al. (2002) show that case method research studies can be used for different types of research purposes such as exploration, theory building, theory testing and theory extension/refinement. One good example of mixed methods research is exploration. In many research projects (e.g., quantitative models based on empirical data), exploration based on case method research is needed to develop research ideas and questions. A further example is theory testing. When case study research is employed for theory testing, it is typically used with survey-based research in order to achieve triangulation (this is the use and combination of different methods to study the same phenomenon so as to avoid sharing the same weaknesses).
6 How to Conduct and Document Research with Quantitative Models Based on Empirical Data?

Model-based quantitative empirical supply chain management research projects should contain sections dealing with the following issues (Bertrand & Fransoo, 2002; Kleijnen & Smits, 2003; Eldabi et al., 2002):

- A high-quality research project should start with a “good” research question. Exploration (based on case method research) would be a possibility to support this research step.

- Next, it is necessary to review the relevant (e.g., axiomatic research) literature. The natural outcome of the literature review is to show what is known about the research question.

- The next step is the identification of the basic assumptions concerning the supply chain processes underlying the theoretical models or problems.

- Researches should identify the kind of supply chain process and the type of decision regarding this process, to which the basic assumptions are assumed to apply. Examples of supply chain processes that may be studied are assembly-to-order versus make-to-order (see Jammernegg & Reiner, 2004), buyer’s market for the supply chain final product versus seller’s market, etc.

- Objective criteria must be developed for deciding whether or not a real-life supply chain process belongs to the class of processes considered and for identifying the decision system in supply chain processes that represents the decision problem under study.

- From the basic assumptions, this step derives hypotheses about process behavior. Process behavior refers to phenomena that can be objectively measured or observed in the supply chain process.

- It is necessary to develop an objective way to do the measurement or to make the observation. Here, the problem is that no formalized construct exists for variables. Furthermore, there is no generally accepted way of measuring if variables exist. Therefore, in quantitative model research based on empirical data, researchers must develop their own way of measuring, and they have to document this carefully. In particular, it is necessary to know how to influence and measure the relevant characteristics of a process. Thus, it is necessary to develop a conceptual model that defines the relevant variables of a system under study, the nature of their relationship, and their measurement.

In this context, one option is to design a simulation model that explains how the supply chain performance metrics react to environmental and managerial control factors. The type of simulation (e.g., systems dynam
ics, discrete-event simulation) depends on the kind of research question to be answered by the model; refer to the examples given in Section 3.

- The next step is the application of the measurement and observation systems, the collection of documentation, and the statistical interpretation of the results. The experiment design used cannot be determined in an arbitrary way. The experiments analyzed result from observations of a real-life system where variables cannot be manipulated at will. Therefore, only realistic alternatives are suitable for conducting experiments.

  If you perform the analysis using a simulation model, it is first necessary to validate this model. Second, the simulation model can be used to provide insight into the behavior of the supply chain and delivers the critical control factors. In quantitative model-based research, empirical data restrictions (see above) have to be taken into account. Hence, it is not possible to optimize the critical control factors. In contrast, it is more important and feasible to find robust solutions when considering real alternatives.

- The final step in quantitative model research based on empirical data is the interpretation of research results related to the theoretical models or problems that were tested. The results are the confirmation of the theoretical model in relation to the decision problem and to the process considered, or a rejection and suggestion for improving the theoretical models.

7 Conclusion

We have shown how quantitative model-driven research - especially when considering empirical data and simulation models – could be conducted in supply chain management research. In particular, we have illustrated our ideas using some research examples.

Managerial relevance is of increasing importance in the field of supply chain management research. Quantitative model-driven empirical research deals with real-life data as well as situations and offers, therefore, the potential for fulfilling the managerial relevance requirement. In detail, empirical model-driven quantitative research has a high potential for addressing more practically relevant problems (e.g., complexity). Furthermore, this type of research is able to validate empirically axiomatic (operational research) models in real-life supply chain processes (Bertrand & Fransoo, 2002).

The most complete form of research is normative quantitative model-driven research based on empirical data. Here, the problem is that the verification process is not strong. Furthermore, it is hard to assess which changes in performance are
caused by a specific improvement alternative tested and which by other facts. In this context, the use of discrete-event simulation model approaches would represent an interesting opportunity, as they are able to take uncertainties into account.

In this article, a few mixed methods research approaches have been discussed. Do such approaches have potential in supply chain management research? This question should be an issue for further methodological developments.

Quantitative model-driven empirical research in the field of supply chain management is already more or less accepted by the scientific community. Some top research journals (e.g., Management Science, Journal of Operations Management, International Journal of Production Economics, Production and Operations Management) support the publication of this type of research. However, continuous improvement of research methodology is still necessary to convince the remaining critics.

8 References

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