USE OF MODEL-DRIVEN DECISION SUPPORT METHODS FOR SUPPLY CHAIN DESIGN

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ABSTRACT

Decision makers frequently consider the use of quantitative models for decision support when they face supply chain related decisions such as localization, make-or-buy, or production and distribution strategy. However, they often do not have the background required to understand, evaluate and select models. This paper briefly outlines when to use such model-driven methods and then suggests a framework that can be used by decision makers when specifying model requirements and evaluating models proposed by modeling experts. There is a need for such a framework in order to improve communication between decision makers and modeling experts, the two groups normally having quite different backgrounds. In order to exemplify the use of mathematical models in supply chain related decisions and to apply the framework as a means of describing the models used, several cases are presented.

Keywords: supply chain design; model-driven decision support; mathematical modeling

INTRODUCTION

A *supply chain*, which is also referred to as a *value chain* or *logistics network*, consists of suppliers, manufacturing centers, warehouses, distribution centers and retail outlets, as well as materials and goods, information and money that flow between the facilities (based on Simchi-Levi et al., 2000). *Supply chain design* is the tactical/strategic process of developing solutions and taking decisions in the supply chain that ensure long-term profitability of the involved organizations. One group of decision support methods involves use of mathematical models, including optimization models, simulation models, cost models etc. This paper briefly outlines when to use such model-driven methods and then suggests a framework that can be used by decision makers when specifying model requirements and evaluating models proposed by modeling experts. There is a need for such a framework in order to improve communication between decision makers and modeling experts, the two groups normally having quite different backgrounds. In order to exemplify the use of model-driven methods and apply the framework as a means of describing the models used, several cases are presented. This research is of an exploratory/descriptive nature. It is based on previous research in supply chain design, decision support and mathematical modelling, as well as participation in relevant projects.

SUPPLY CHAIN DESIGN

Supply chain design is tactical/strategic decision making. Such decisions are characterized by medium- to long-term effects, medium to high levels of risk and uncertainty and relatively large consequences for the involved organizations. Decisions are taken by higher management. There are several decision areas within supply chain design and Strandhagen et al. (2002) classify the different areas in two overall areas; structure and control. Structural decision areas are typically localisation of production plants, warehouses and choice of suppliers and transporters. For decisions within control, the structure of the supply chain is considered as given and focus is on how to most effectively manage the supply chain. Typical decision areas here are production control principles and collaboration between actors. Other authors use different classifications of the decision areas. Ganeshan et al. (1995) for example classify decisions in four main areas; localisation, transportation, storage and production. Semini (2004) organized structural and control related decisions into the eight decision areas shown in table 1. We have also listed other authors that describe these decision areas, different management dilemmas and solution approaches in those areas.

Table 1 - Decision areas within supply chain design

Decision area	**Comment**	**Other references**
Structure		
Localisation of facilities	*Geographical localisation of facilities and production. Some aspects for consideration are cost, time, culture, political situation, human capital and production capacity.*	Camm et al. (1997), Jayaraman (1999)
Make- or- buy decisions	*The companies own production and core competence is considered and evaluated against buying the component from a specialized supplier.*	Platts et al. (2002)
Supplier selection	*Traditional evaluation criteria of suppliers are; quality, delivery precision, price, flexibility, technical competence, financial situation, geographical and cultural distance.*	Talluri & Narasimhan (2003)
Distribution	*Choice of distribution strategy includes choice of transportation mode and distribution pattern such as direct shipping, cross-docking and storage capacity. Use of a 3rd party logistics provider is also a decision in this area.*	Ballou (1998), Bowersox et al. (2002)
Control		
Planning and control systems	*Production is divided into different control areas which can be controlled in different ways. MRP and JIT are two well known control principles used in many enterprises. Inventory management is also another area that is important where we find control mechanisms such as re-ordering point or periodically ordering.*	Alfnes & Strandhagen (2000)
Information and communication technology (ICT)	*ICT is a key enabler for efficient and effective control in the supply chain in for example order management, production, inventory and distribution planning.*	Bolseth (2004) Narasimhan & Kim (2001)
Integration and collaboration systems between actors	*Management of the supply chain can be done with a high integration with the other actors. We find different levels of integration, from coalitions and alliances and a high level of integration to a low level of integration in a market environment.*	Kulp (2002)
Performance measurement	*To measure the supply chains performance the use of performance measures are used and it is important to find measures that ensure a better performance of the whole supply chain.*	Busi (2005)

MODEL-DRIVEN DECISION SUPPORT METHODS

In its broadest sense, any mental or physical construct that supports and improves decision making constitutes a decision support method (DSM). Computer-based tools can be called decision support systems (DSS). This broad definition of DSS is based on Power (2001); we refer to Turban & Aronson (2001) for a review on the many narrower definitions of DSS used in literature and practice. A number of frameworks exist for categorizing DSS (see Power (2002) for references to such frameworks). Power (2001) classifies DSS into data-driven, model-driven, knowledge-driven, document-driven and communications-driven. This classification can be generalized to DSM. In addition to being more general, using the term “method” instead of “system” emphasizes our interest in the underlying conceptual method rather than the data-technical implementation of a DSS. In the next paragraph, we present model-driven DSM, which are the topic in this paper.

Model-driven DSM emphasize access to and manipulation of a model. They use data and parameters provided by decision-makers to aid them in analyzing a situation, but they are not usually very data intensive. Models are simplified representations of systems or problems. They can be classified into three groups (Turban & Aronson, 2001):

- *Iconic* models are physical replica of a system, usually on a different scale from the original
- *Analog* models are symbolic representations of reality, usually two-dimensional charts or diagrams
- *Mathematical* or *quantitative* models, finally, describe the relationships in a system by means of mathematical expressions. These expressions will often be equations, but can also include causal relationships and other mathematical concepts.

Examples of computer-based model-driven DSM are visualizations in simulation software like QUEST (iconic models), EXCEL charts (analog models) and optimization models implemented in an optimization software like XPress-MP. Examples not using computers are physical models of KANBAN-controlled production systems (iconic model), drawings of a logistics network on a blackboard (analog model) and back-of-the-envelope calculations of economic order quantities (mathematical model).

For the remainder of this paper, we will further restrict ourselves to computer-based methods using mathematical models. Further examples of groups of mathematical models include activity-based costing calculations, simulations models, models using principles from investment analysis and models based on decision theory. Understanding methods using such models is particularly demanding since it requires knowledge in conceptually difficult disciplines such as operations research, management accounting and information technology. Also, the use of such methods can involve large expenses and require serious management commitment.

LIMITATIONS OF THE USE OF MODEL-DRIVEN METHODS FOR SUPPLY CHAIN DESIGN

Supply chain design is about creating the best possible offer for the chosen market segment. Porter (1985) pointed out that lowest cost was only one of many different strategies open for a company and that failing to choose a strategy would leave the company “stuck in the middle”. Porter’s theories about gaining competitive advantage has been much discussed and in some cases also refuted by real world examples. However, what he and other authors (ex. Hamel & Prahalad, 1994, Treacy & Wiersema, 1995) seem to agree upon is that a company (or a supply chain) should find some part to emphasize and try to develop this into a unique offer in the marketplace. Supply chain design should be subject to these and other strategic considerations. Supply chains should in other words be designed according to strategic objectives. The supply chain of a typical low cost offer would be different from a supply chain focused on creating differentiated products. Our point here is that supply chain design is subject to choices outside the scope of the design process.

Supply chains also usually consist of parts belonging to separate commercial entities. These entities will normally have different goals and perspectives. Again there is a wealth of different theories shedding light on how firms interact and how alignment of objectives can be improved. Transaction cost theory (ex Williamson, 1989) predicts that transaction costs in a market-type relationship will depend on conditions of uncertainty, the frequency of trades and asset specificity. Originally this was used to explain vertical integration as opposed to market based interactions. Today TC theory is also applied to a continuum of different cooperative forms between these two extremes. Agency theory (Rapp & Thorstenson, 1994) directly addresses the conflict of interests that might exist between a principal and an agent in a contract-like environment. Eisenhart (1989) has developed this into a set of propositions indicating whether the contracts should be formed as behavioral or outcome based. Property rights theory (Hart & Moore, 1990) is also concerned with whether transactions should be performed within a firm or through a market. One problem with most of these approaches is that although the theories are to some extent normative, they are usually difficult to quantify. The concept of asset specificity used in transaction cost economics might be used to order different alternatives but does not readily transform to quantified terms. Agency theory although mathematically based rely heavily on utility functions which are notoriously difficult to assess. Applicability to building quantitative models for supply chain design is therefore limited, even if the theories are important for sorting out viable and good alternatives.

More generally, an important prerequisite for the use of quantitative models is that a certain level of validity can be achieved, i.e. that the relevant concepts can be quantified, measured and predicted with sufficient precision. The problems outlined in the previous paragraph will therefore often limit an analysis to one commercial entity's supply chain. Further, stable and efficient processes will normally be required. Thus, for example, highly automated processes will more likely meet the requirements for quantitative modeling than highly manual processes. Our experience shows that quantitative models are mainly used for two decision types within supply chain design:

- Type I: Number, locations and capacities of plants, warehouses and buffers (strategic)
- Type II: Where to produce and distribute what when and in what quantities and lot sizes (tactical)

On the other hand, we have found little evidence on use of quantitative models in decision areas such as for example introduction of ICT systems, integration and collaboration with other actors and selection of appropriate production control principles (for example JiT vs. MRP). This is presumably due to the difficulty in quantifying relevant concepts.

SIX KEY DIMENSIONS OF MODEL-DRIVEN DECISION SUPPORT METHODS

The following framework intends to aid decision-makers in choosing an appropriate model-driven decision support method for a given *management dilemma*, i.e. a problem or opportunity that requires a management decision (defined by Cooper & Schindler, 2003). It suggests six dimensions along which model-driven methods can be described, discussed and evaluated from a decision maker's perspective, i.e. not requiring advanced modeling and operations research expertise. The framework intends to improve communication between *problem owner* (the decision maker) and *model owner* (the modeler), providing them with a common vocabulary. It will help the problem owner understand and express his/her needs as well as understand assess the models suggested by one or possibly several different modelers. Hopefully, such a systematic approach will lead to less speculating, ignorance, conflict and self-seeking behavior when an appropriate model-driven method has to be chosen.

Controllable variables

What are the controllable variables included in the model? Controllable variables can – in the model - directly be specified and changed by the user. Some of them will to a large extend be considered as given and cannot be influenced by a supply chain design project, for example product and market characteristics and demand information, others will describe characteristics that lie within the scope of the project. Variables belonging to the latter kind are often called *decision variables* and a goal with a model is to find appropriate values for these variables. Examples include facility locations, delivery times and quantities, production batch sizes, safety stock quantities etc. Controllable variables can either be expressed by a fixed value or using a probability distribution. They can be modeled as depending on time (i.e. vary from time period to time period), or assumed to have the same value for every time period. Since most or all of the controllable variables' values are given by the value chain's characteristics, an important question is also how easily the relevant data can be collected and prepared. Obviously, collection of relevant data belongs to the decision maker's responsibilities.

Response variables

What are the response variables included in the model? Response variables are calculated by the model using the controllable variables and the defined mathematical expressions. They express performances associated with the supply chain as it is modeled; in other words, they are performance indicators of a supply chain that behaves like the model. Typical examples are total supply chain costs, total inventory in supply chain, average service level and average delivery time. The choice of relevant response variables will be influenced by higher-level strategies like cost effectiveness or responsiveness.

Model validity
Validity refers to how close the model is to reality. It is the degree to which inferences drawn from the model hold for the real system (Rardin, 1998). Different factors affect validity, including how the relevant concepts are quantified (for example customer satisfaction), how the values for controllable variables are measured and predicted (for example cost price), how predictable these values are (for example customer demand) and how well the relationships describe reality (for example the relationship between transport quantity and transport cost). The more valid the model is, the more directly its results and recommendations can be trusted and used. See Daganzo (1999) and Venkateswaran & Son (2004) for two stimulating discussions about model validity in supply chain analyses.

Model tractability
Tractability refers to how easily we can establish and understand the effect on response variables when changing controllable variables – how much *sensitivity analysis* is practical (Rardin, 1998). By our definition of a mathematical model, it will always be possible to calculate the values of response variables for any given set of values for the controllable variables. This process of evaluating different possibilities is often called *what-if analysis*. More tractable models allow use of an algorithm in order to determine values of some of the controllable variables, satisfying some conditions on response variables, for example minimizing total cost or maximizing total profit (of course, such an algorithm is only useful if it is faster than carrying out a what-if analysis for all possible practical solutions). In highly tractable models, such values can be expressed by formulas in other controllable variables. The economic order quantity (EOQ) model is a famous example of such a highly tractable model.

User interfaces
Requirements to user interfaces depend on how the problem-owner intends to use the model. In some cases, only some final figures may be required, for example total transportation costs in two alternative scenarios. No user interface will be required in such a case. At the other extreme, the end-users want to carry out rich sensitivity analyses, use the model as a commonly agreed-upon representation of the value chain or the management dilemma and re-use the model in the future. Advanced and intuitive user interfaces for both modification of controllable variables and visualizations of response variables and relationships between controllable and response variables will then be essential. Graphical visualizations include iconic and analog models and animations of the value chain, as well as many different types of charts and diagrams.

Modeling resources
Required resources can be expressed in terms of *time*, *expertise* and *equipment*. What amount of time is required to develop and implement the model? Of course, only models that can be finalized and used before the management dilemma has to be solved are worth being considered. What level of expertise is required to develop and implement the model? And what level of expertise will be required to do modifications at a later stage? What specific equipment (typically software) is required to develop and implement the model?

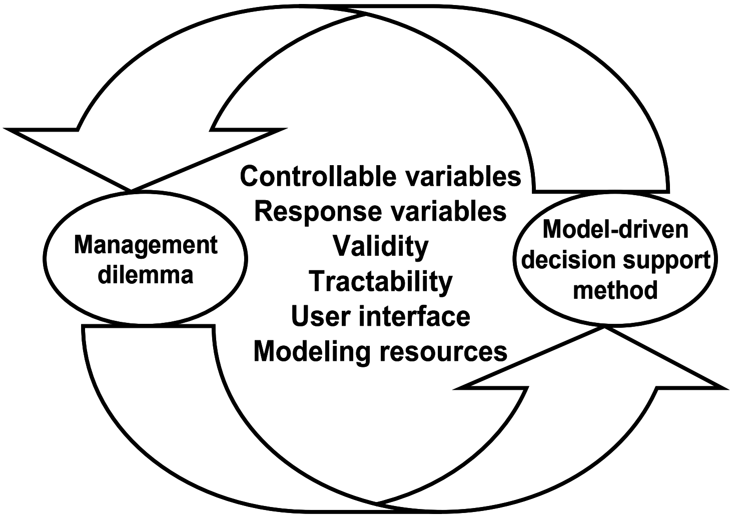

Figure 1 - Six key dimensions of model-driven decision support methods

The above dimensions are not independent and their interdependencies invite to further research and hypothesis testing. For example, *modeling time* and *validity* seem to be positively correlated *number of controllable/response variables* and *modeling time* seem to be positively correlated and *tractability* and *validity* tend to be negatively correlated. Another example is the relationship between *modeling equipment* and *interfaces*.

It is the management dilemma's characteristics that decide upon the right balance between the six dimensions. They include available time and resources, purpose, required accuracy, complexity, data availability etc. If, for example, a dilemma admits many possible practical solutions, a somewhat more tractable model is advisable in order to rapidly identify good solutions. If one basically wants to analyze and better understand one or just a few scenarios, validity will be given more importance. If the model is intended to be used as a basis and common representation in discussions and meetings, suitable visualization will be required.

CASES

Raufoss Water and Gas

Raufoss Water and Gas is a Norwegian SME that manufactures and distributes brass couplings for water and gas pipes. Increased cost pressure lead in 2003 to a logistics improvement project focusing on the entire RWG-owned value chain, including component warehouses, assembly plants and finished parts warehouses located mainly in Norway, France and Germany. As part of the project, it was decided to develop a quantitative model to estimate effects of different improvements on total cost.

Naturally, focus in the model was put on quantifiable aspects within a list of identified improvement areas. Important controllable variables were assembly quantities at the different plants, transportation and assembly lot sizes, supplier and internal lead times, as well as a possible close down of facilities. All these variables were expressed by a fixed value and considered as constant from period to period. The response variables were mainly total costs and inventory levels. Very limited resources (both time and expertise) put serious limitations on both validity and tractability. Due to a relatively low number of practical solutions, high tractability was not of key importance. The questionable validity, however, led to a limited use of the model. Its main effect was the recognition by management that cost savings were possible. The model was developed in Microsoft Excel and included two simple end-user interfaces: one allowed modification of controllable variables, the other one comparison of response variables for different scenarios using bar charts.

A Norwegian slaughterhouse
SINTEF is currently involved in a project with a Norwegian slaughterhouse for pigs. In an approx 9 M Euro investment they are increasing their capacity from around 600 to 800 pigs pr day. This involves large changes in the production systems, such as new equipment and transportation systems. It is important for the management to ensure that the solutions they choose will give increased capacity, so a simulation model using QUEST was developed. The controllable variables are among others transportation system capacity, location and capacity of buffers and machine capacity for several processes. The response variables are mostly the systems output i.e. the amount of pigs processed each day but also variables like internal buffer levels. With large investments in new equipment, validity in the model was of great importance so the management could see that new equipment would give the desired increase in capacity. The models complexity reduced the tractability, but the systems performance as a whole was more important than a tractable model. Using QUEST gave the user a visual 3D movie model, useful for decisions regarding layout of the production system. Statistics were exported from the model for decision making. With a simplified version of the software it is also possible for the user to test different input data on the model to perform analysis. Key personnel in the project had extensive simulation expertise and experience from similar projects. This along with knowledge to the software made the choice for using QUEST easy. The project was then planned with enough time allocated to building such a model.

Decision support in Shipping Logistics (Nyen, 1995)
A major Norwegian ship owner managing twelve Ro/Ro ships and 30 000 containers were facing challenges in positioning containers from import extensive and export extensive areas. With low profit margins, a high utilization of the containers was an important step in lowering costs and a simulation model was built to help in this process. The controllable variables were mostly related to how the containers could be obtained in the different areas to meet demand. There were several possibilities such as regional repositioning, interchanging containers with other freight companies or hiring containers. Response variables were mainly costs and container utilization. The model consisted of three sub-models with different degrees of validity. The Port Activity Model was less valid than the Transportation Network Model due to difficulties in data gathering and mapping of the different activities in the ports. All in all the model was abstracted to a certain level, but had overall good validity. The complex network of routes and decisions made the tractability very limited. The model was coded using SIMULA and a user interfaces created with the MetaCard software. Through the user interface the model owner was for example able to select ports and loads combined with a strategy for container acquisition and a cost was calculated. The model was developed of two experienced programmers during 1994-95 with an approximate cost of 0,5 M Euro. Apart from software in developing the user interface the model only required computational power in running.

Felleskjøpet Trondheim AL
Felleskjøpet Trondheim AL (FKT) is a membership (consisting of farmers) owned company for farm supply. FKT serves northern and middle Norway with all kinds of farm supply ranging from machinery to seeds, fertilizer and animal fodder. Middle and northern Norway is special with sparse population and no great concentration of farms outside Trøndelag. As the owners of the company are the farmers of this region, FKT have special obligations to deliver these products compared to other more commercially oriented suppliers.In this region FKT had 7 facilities for making animal fodder with total annual capacity of 550.000 tons. The demand for animal fodder was at the same time around 300.000 tons. The objective of the project was to analyze which facilities should produce and how fodder should be distributed from the production facilities to the farms. Most

Norwegian farms use animal fodder in bulk (not packed in sacks) and the distribution thereby needs special transports. We decided to use an optimization model for the problem because of the large amount of decision variables.

FKT produces 50+ variants of animal fodder. We simplified this to 6 different groups in bulk and packed in sacks (12 products altogether). The basic distribution area was postal codes in Norway which gave a good representation of geographical distribution of farms and last year's deliveries of each group of products and used that as the demand in the model. Alternative routes from different production facilities to each postal code area were modeled with different prices for fodder in bulk and packed in sacks. The raw material and production costs of each facility was modeled and checked against budgets. The optimal solution was to centralize production using only 3 facilities. This was not a solution acceptable to the board without further analysis. The model was then used to investigate the increase in costs by fixing certain levels of production on selected facilities. In total 12 different scenarios were investigated and presented. This illustrates another benefit of using an optimization model. The results for each of the scenarios were directly comparable because they were all optimal solutions under their given sets of restrictions.

Apokjeden AS

This firm is a wholesale company selling pharmaceuticals and medical supplies. Norwegian legislation concerning pharmaceuticals makes wholesale companies in this business somewhat different than what is found in other countries. First of all wholesale companies must offer all approved brands. They are not allowed to limit their selection to preferred brands of the same medicine. In other words all warehouses must carry the full range of approved brands. The other restriction put on Norwegian wholesale in pharmaceuticals is that they must be able to deliver to all customers within 24 hours. This was why Apokjeden was established with 4 warehouses in Norway. The project was to investigate consequences of reducing the number of warehouses. Distribution was by fixed routes on road transports for the most part. The company wanted to know if some of the warehouses could be replaced by distribution centers and still comply with the 24 hour limit. The warehouse in Oslo would always be part of the solution. This is the natural point for receiving imports as well as the most populated part of Norway. In other words we needed to investigate 8 different alternatives (2^3). The only alternative for the warehouse in Bergen (western Norway) was to serve the district from Oslo. This further reduced the number of alternatives as this could be evaluated separately. We then decided to work out consequences for each of the alternatives as scenarios without using any optimization model. The result was that we found that the increase in transport cost was less than the operating costs for two of the warehouses (Western and middle Norway). These warehouses were then closed in 2003. The projected reduction in costs was around 16 M NOK yearly.

CONCLUSIONS

Model-driven decision support methods can be the right choice for supply chain design when corporate level strategic objectives are formulated and the relevant concepts can be quantified, measured and predicted with sufficient precision. Model-driven methods can be characterized along the six dimensions *controllable variables*, *response variables*, *validity*, *tractability*, *user interface* and *modeling resources*. This classification scheme is supposed to provide a systematic approach when decision makers specify model requirements and evaluate models proposed by experts.

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