Supply chain multi-structural (re)-design

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In the framework of supply chain (re)- design (SCD), different structures (functional, organizational, informational, etc.) are (re)- formed. These structures are interrelated and change in their dynamics. How is it possible to avoid structural incoherency and consistency and to achieve comprehensiveness by (re)- designing supply chains? This paper introduces a new approach to simultaneous multi-structural SCD with structure dynamics considerations. We elaborate a new conceptual model and propose new tools for multi-structural SCD – multi-structural macro-states and dynamical alternative multi-graphs. The research approach is theoretically based on the combined application of operations research, agent-based modelling, and control theory. The results show the multi-structural and interdisciplinary treatment allows comprehensive and realistic SCD problem formulation and solution. We emphasize the flexibility of the proposed approach and optimization-supported simulation. The proposed methodology enhances managerial insight into supply chains at the strategic and tactical levels and serves to assist decision-makers in SCD.

Keywords: supply chain (re)- design, multiple structure design, structure dynamics, multi-structural states, dynamical alternative multi-graph, optimisation-supported heuristics and simulation.

1. Introduction

Supply chain design (SCD) has been a very visible and influential topic in the field of production, operations, and supply chain management over the past two decades. SCD is a critical source of competitive advantage given that as much as 80% of total product cost may be fixed by these decisions (Harrison et al. 2005). One of the main issues in SCD is supply chain *structuring* in accordance with a given competitive strategy, supply chain strategy, coordination strategy, distribution strategy, product program, and financial plans (Chopra and Meindl, 2007) as well as with demand and supply uncertainty (Lee et al., 1997, Tsiakis et al., 2001, Santoso et al., 2004).

It should be emphasized, that supply chains consist of different structures: business processes, technological, organizational, technical, topological, informational, and financial structures. All of these structures are interrelated and change in their dynamics. The literature on Supply Chain Management (SCM) indicates various multi-structural frameworks that received managerial attention when designing supply chains (Lambert and Cooper 2000; Bowersox et al. 2002). The issue of how to avoid structural incoherency and inconsistency by designing supply chains is very important, first, for SCD itself and secondly, for designing robust supply chains (Van Landeghem and Vanmaele, 2002) and re-designing supply chains for new products, new order penetration points, and a variety of disruptive factors. Third, supply chain execution is accomplished by permanent changes to internal network properties and the external environment. In practice, structure dynamics is frequently encountered.

SCD is composed of several problems that are solved by various modelling techniques such as optimization, simulation, heuristics, and statistics (Vidal and Goetschalckx, 1997, Goetschalckx et al., 2002, Simchi-Levi et al., 2004, Ivanov, 2009, Kuehnle, 2007). As a rule, cross-linked SCD issues require combined application of various modeling techniques. It should be mentioned, that supply chains are characterized by different goals and uncertain interactions of their elements. This means, the supply chain elements are *active*. They compete and act based on their own interests and goals. This results in the necessity of taking into account this human uncertainty by SCD analysis regarding the structural stability.

Though a wealth of literature and research on SCD exists, there is an apparent lack of multi-structural supply chain design that considers structure dynamics. In the period 2000–2007, a number of projects and studies were conducted in Chemnitz (Germany) and Saint Petersburg (Russia) with industrial and academic partners in the field of SCD. This paper has resulted partially from these projects.

The main goals of this paper are:

(1) to contribute to the comprehensiveness of SCD decisions;

(2) to investigate possibilities of the supply chain multi-structural (re)-design;

(3) to consider supply chain structure dynamic; and

(4) to propose methods and tools for implementing multi-structural (re)- design with structure dynamic considerations.

The paper proposes a conceptual framework for the supply chain multi-structural design with structure dynamic considerations. It is organized as follows. We start with the state-of-the-art research analysis of the SCD. In Section 3, we describe the basics of the SCD multi-structural treatment. Section 4 grounds and describes the interdisciplinary research approach, which is theoretically based on combined application of control theory, operations research, and agent-based modelling. Sections 5 and 6 present SCD conceptual and mathematical models. In Section 7, the main results and implementation are discussed.

2. The State of the Art

Research in SCD can be divided into three primary approaches. These are: optimization, simulation, and heuristics (Harrison, 2005). *Optimization* is an analysis method that determines the best possible method of designing a particular supply chain. Optimization methods for SCD have been a very visible and influential topic in the field of *operations research.* The formulation of strategic production–distribution models for SCD has been widely investigated. Most of these formulations are introduced in the form of mixed integer linear programming (MILP) models. Beginning with the seminal work of (Geoffrion and Graves, 1974) on multi-commodity distribution system design, a large number of optimization-based approaches have been proposed for the design of supply chain networks (Vidal and Goetschalckx, 1997). (Arntzen et al., 1995) develop a mixed integer programming model, called GSCM (Global Supply Chain Model), that can accommodate multiple products, facilities, stages (echelons), time periods, and transportation modes.

(Beamon, 1999, Tayur et al., 1999, Goetachalckx et al., 2002; de Kok and Graves, 2004, Simchi-Levi et al., 2004, Harrison et al., 2005, Chopra and Meindl 2007, Shen, 2007) provide a systematic summary of operations research on quantitative models for SCD. (Graves and Willems, 2005) develop a dynamic program with two state variables to solve the supply chain configuration problem for supply chains that are modelled as spanning trees and applied it to optimizing the supply chain configuration for new products. A closely related topic to the problem addressed in this paper is research on *vendor evaluation and selection* (Abdel-Malek and Areeratchakul, 2004). (Das et al., 2006) explore finding optimal configuration for suppliers' integration based on empirical data from 300 US companies. (Stock et al., 2000) examine the fit between an organization's enterprise integration capabilities and its supply chain structure. (Meepetchdee and Shah, 2007) develop a framework of logistical network design with robustness and complexity considerations and used a MILP model for concept implementation. (Gunasekaran and Ngai, 2005) present a summary of research in SCD concerning the BTO (Build-to-Order) SCM. (Yan et al., 2008) propose a strategic production–distribution model for supply chain design with consideration of bills of materials (BOM) formulated as logical constraints in a mixed integer programming model.

The drawback of using optimization is difficulty in developing a model that is sufficient detailed and accurate in representing complexity and uncertainty of SCD, while keeping the model simple enough to be solved (Harrison, 2005). Furthermore, most of the models in this category are largely deterministic and static in nature. Additionally, those that consider stochastic elements are very restrictive in nature. Unless mitigating circumstances exist, optimization is the preferred approach for SCD.

Simulation is imitating the behaviour of one system with another. By making changes to a simulated supply chain, one expects to gain understanding of supply chain dynamics. Simulation is an ideal tool for further analyzing the performance of a proposed design derived from an optimization model. Regarding SCD, discrete-event simulation, and agent-based paradigms, such as complex adaptive systems (CAS), multi agent systems (MAS), and system dynamics are the most popular simulation techniques. Past research on the utilization of the MAS in SCD has mostly dealt with agent-based frameworks and software architectures (Shen et al., 2001).

Although the techniques of solving large-scale problems in a decentralized way have been developed, most are based on poorly grounded heuristic principles. The valuable theoretical perspective on decentralized network management these paradigms offer has generally been underestimated. (Nillson and Darley, 2006) proposed to combine CAS and MAS and to use CAS as a theoretical approach and MAS as an implementation method. (Kuehnle, 2007) considers agents a part of a complex of interrelated models for SCD planning. (Ivanov et al., 2007; Ivanov, 2009) consider agents a part of generic model constructions. The agents are expressed as conceptual modelling entities or active modeling objects. Besides the MAS, a number of other approaches, such as system dynamics (Towill et al., 1992, Sterman, 2000), are often applied in SCD investigations.

Heuristics are intelligent rules which often lead to good, but not necessary the best solutions. Heuristic approaches typically are easier to implement and require less data. However, the quality of the solution is usually unknown. Unless there is a reason not to use the optimization, heuristics is an inferior approach. In SCD settings, nature based heuristics such as genetic algorithms (Huang et al., 2005) and ACO (Ant Colony Optimization) (Teich, 2003) are usually applied.

Besides the approaches described above, the control theory can also be used for SCD (Ivanov et al. 2004, 2005, Ivanov, 2006). It can serve as the general methodological basis for complex systems synthesis and analysis. However, the disadvantage of research grounded in modern *systems and control theories* regarding complex business systems is that the system elements are controlled by a central decision maker and cannot change their states and interactions of their own free will (the system elements are passive). In complex business systems, the elements are *active* (they can compete and have conflicting aims, interests, and strategies). Classic methods of the control theory do not allow developing practical comprehensive models to take into account the *goal-oriented (active) behaviour* of enterprises.

The Table 1 provides a summary of SCD problems and methods to solution of these problems.

[Insert Table 1 here]

Selection of a solution method depends on data fullness, problem scale, whether one or multiple criteria are considered, requirements for output representation, and interconnection of a problem with other problems. In practice, partial SCD problems are highly interconnected. Transportation and inventory are primary components of the order fulfilment process in terms of cost and service levels. Therefore, companies must consider important interrelationships among transportation, inventory, and customer service in determining their policies. Suppliers' selections are linked not only to their capacities, costs, etc., but also to their ability to collaboration with each other and with the focal enterprise. Therefore, coordination between the various players in the chain is the key to its effective management. Pricing and inventory decisions (Muriel and Simchi-Levi, 2004) as well as product, distribution, and production decisions are also matched.

One promising area is the study of combining different modelling techniques. (Harrison et al., 2005) reports on the development of a high level language based on XML, which allows detailed describing an arbitrary supply chain. This Supply Chain Markup Language (SCML) permits the exchange of supply chain models in a way that is free of any particular solution method or computer implementation. (Kuehnle, 2007) considers a combination of agents and optimization. (Ivanov et al., 2007; Ivanov 2008) present a multi-disciplinary approach called DIMA (Decentralited Integrated Modeling Approach) for modelling production and logistics networks. (Borshchev and Filippov, 2004) report on implementing a combination of heuristics, optimization, system dynamics, and agents in simulation tool AnyLogic and present SCD solutions.

The review highlights some common disadvantages and serious limitations of the approaches to SCD described above. First, these approaches do not consider system elements activity (accept that of the MAS). Moreover, supply chain structures are considered separately without comprehensive interlinking and structure dynamics consideration. Most of the elaborated models consider supply chains as static and deterministic systems, focusing on a single or limited number of objectives without balancing goals of the supply chain partners, which can not represent the ever-changing nature of a supply chain. Research concentrates on different levels, for example the organizational level or the facilities level. There is a lack of formalized multi-structural treatment of the SCD. Different interlinked problems of the SCD configuration are considered separately for the different structures with fragments of heterogeneous and inconsistent models. There are no models to estimate supply chain structural stability.

3. Multi-Structural Treatment of the Supply Chain Design

In this section, we describe the basics of the SCD multi-structural treatment. One of the main supply chain features is the multiple structure design and changeability of structural parameters because of objective and subjective factors at different stages of the supply chain life cycle. In other words, SCD structure dynamics are constantly encountered in practice (s. Figure 1).

[Insert Figure 1 here]

In Fig. 1, S is a supply chain *multi-structural macro-state*, δ is a number of the supply chain multi-structural macro-states in dynamics, and the set {0,…,K} represents instants of time of a supply chain evolution and life cycle. The multi-structural macro-state of a supply chain is composed of the different structures and their interrelations. At different stages of the supply chain evolution, the elements, parameters, and structural interrelations change. In these settings, a supply chain can be considered a *multi-structural process*.

Why is the SCD multi-structural treatment so important? First, SCD design decisions are dispersed over different structures. Secondly, the structures and decisions at different stages of supply chain execution change in their dynamics. Output results of one operation are interlinked with other operations (the output of one model is at the same time the input of another model). This necessitates structure dynamics considerations. In the case of disruptions, changes in one structure will cause changes in other relevant structures. Structure dynamics considerations may allow establishing feedback between supply chain design and operations.

Such multi-structural treatment of SCD also helps to systemize many other areas of research in the SCM, i.e., to classify the various sources of uncertainty in accordance with the different structures, or to establish links to supply chain execution and control (Ivanov et al., 2008). Uncertainty must not only be correctly reflected in SCD models, but also efficiently handled while the supply chain is being executed. The multi-structural SCD treatment also is very important for re-designing supply chains. Structure dynamics-based supply chains reconfiguration is presented in details in (Ivanov et al. 2008).

4. Multi-disciplinary Treatment of the SCD

This section grounds and describes the interdisciplinary research approach, which is theoretically based on combined application of control theory, operations research, and agent-based modelling.

4.1. Necessity for multi-disciplinary treatment of the SCD

The necessity of the SCD multi-disciplinary treatment is caused by a complex composition and tight interlinking of different SCD problems, which exist in different structures and change in their dynamics. (Beamon, 1999) emphasize that supply chain systems are inherently complex. Thus, the models and methods used to accurately study these systems are, expectedly, also complex. In practice, SCD problems do not allow a comprehensive solution by a single method. At different stages of the supply chain life cycle, a particular problem can be solved by means of different modelling techniques due to changeability of data nature, structure, and values, as well as requirements for output representation. To address the problem of complexity, a combination of various modelling approaches should be applied. On the other hand, solving the problem may require the combined application of different techniques. The activity and autonomy of supply chain elements should also be considered (i.e., simulation of suppliers' selections are connected not only to optimizing certain criteria, but also to their interactions, taking their goal-oriented behaviour into account).

4.2. Basics of the SCD multi-disciplinary treatment

The basics of the SCD multi-disciplinary treatment were developed according to the DIMA (Decentralized Integrated Modeling Approach) methodology (Ivanov, 2009, Ivanov, 2006) to contribute to comprehensive supply chain modelling and to establish foundations for SCM theory as called for by an increasing number of researchers (Beamon, 1999; Chen and Poutraj, 2004, Giannakis and Croom, 2004, Kuehnle, 2007).

The main principles of the DIMA are as follows. These principles take into account the supply chain elements' *activity, multiple modeling*, *integration, and decentralization*. We are the first to consider agents as a part of the generic model constructions (Ivanov et al., 2007). The agents are expressed as conceptual modelling entities or active modeling objects. They are part of a multidisciplinary complex of models used not only at simulation stage, but also at the levels of conceptual modelling, formalization, and mathematical modelling. *Integration* is considered from three perspectives: integration of various modeling approaches and frameworks, integration of planning and execution models, integration of decision-making levels, and implementation of throughout integration "conceptual model → mathematical model → software". *Decentralization* in the DIMA methodology considers the main principle of management and decision making in the SCD. It means all the models contain elements of decentralized decision making and SCD elements' activity. Decisions about SCD are not established and optimized "from above" but are a product of iterative coordinating activities of the enterprises (agents) in a supply chain and a supply chain coordinator (e.g., an original equipment manufacturer or a 4PL-provider).

In the DIMA-methodology, it is understood under multiple modeling that various modeling approaches like control theory, operations research, agent-based modelling, fuzzy logic, and the psychology of decision making are not isolated, but are considered as a united modelling framework. For instance, the multi-agent ideology is considered as a basis for *active elements modelling*. The control theory serves as a *theoretical background* of systems analysis and synthesis. *Operations research* grounds optimization techniques.

Integration and combined application of various models is implemented by means of multiple-model complexes (Ivanov et al., 2007, Ivanov, 2009), which are based on the application of functors (Sokolov and Yusupov, 2004). Let us discuss an example of multiple-model complexes applied to the integration of static and dynamic models. The problem of SCD analysis and synthesis is mostly formalized using either graph (network) models or those of linear and integral programming. As a rule, the problem of analyzing and synthesizing programs for supply chain execution is formalized with the help of dynamic models. However, the problems of coordination and consistency of the results remain unsolved. To obtain a constructive solution to these problems, we propose a functoral transition from the category of digraphs that specify the models of execution of operations into the category of dynamic models that describes processes of supply chain execution. In this case, a constructive covariant functor establishes a correspondence between the nodes of the graph in the static scheduling model and dynamic models, as well as between the arcs and the mappings of dynamic models. This is called adjacency morphism.

Such a multidisciplinary treatment makes it possible to avoid isolated problem solutions, incoherent and inconsistent model fragments, and synthetic or rather anecdotal solution procedures and model verifications.

5. Conceptual Model of the Supply Chain Design

In this section, we introduce conceptual models of the multi-structural supply chain design. Let us emphasise the main distinguishing features of our approach. Traditionally, SCD conceptual models are presented in the following way (Reiner and Trcka, 2004) (s. Figure 2).

[Insert Figure 2 here]

Conventionally, SCD models are based on optimizing one structure by specifying a number of other structures, i.e., the most MILP-based models select suppliers from a candidate set of material (or component) suppliers, as well as locate a given number of production producers and distribution centres, subject to the producer and distribution centres' capacity restrictions. A number of alternatives to the organizational-geographical structure are identified based on other specified structures and according to supply chain goals. These alternatives are then evaluated and the best is selected. These models have some shortcomings. They consider the supply chains from the organizational point of view ("a supply chain is a network of manufacturers …"). However, a supply chain is also a process, which has different dimensions that can be expressed in the form of structures. By specifying a number of structures, the space of optimality potential of the whole supply chain as a multi-structural system is significantly reduced. Optimality can be reached by simultaneously optimizing and balancing interrelated structures. Moreover, in case of re-design of a structure, the re-design of the model of a supply chain is very complex. Such an approach is not flexible enough at the design stage, and even less flexible in the case of supply chain re-design to overcome disruptions or market changes.

In our approach, we propose an SCD conceptual model that is based on the notion of forming multi-structural supply chain (s. Figure 3).

[Insert Figure 3 here]

The SCD conceptual model is based on simultaneous consideration of different structures in their interrelations and dynamics. The set of SCD multi-structural alternatives is formed based not on concrete values of structure-relevant parameters, but first upon data structures. Then we specify one or several structures with deterministic or stochastic parameters and select solution procedures (optimization or heuristics) for partial SCD sub-problems. Therefore, a number of SCD multi-structural alternatives are identified and evaluated, and the best is selected.

Such a model is flexible. Within the model, we can simulate various combinations and interrelations changing one set of structures and specifying parameters of others (e.g., how the supply chain is affected by changes to coordination strategy, product structure, demand, suppliers structure or by combination of different changes to different structures). Here interdisciplinary supply chain modeling may be demonstrated. Using optimization methods and heuristics for some SCD problems (s. also Table 1), we can apply the simulation that is necessary in such complex problems to studying different scenarios and visualizing the computational results. Therefore, optimization-supported heuristics and simulation are possible. The search for optimality is enhanced by simultaneously optimizing and balancing interrelated structures. Moreover, to re-design a structure, the re-design of the model for the SCD is very simple. Such an approach is flexible at the design stage, and even more so in supply chain re-design. The other advantage are the above-mentioned structure dynamics considerations, which make it possible to build different supply chain structures and to evaluate their dynamics (capabilities, bottlenecks, etc.) for requirements such as different demands, production programs, facility locations, coordination strategies or alternative suppliers.

6. Modeling Multi-Structural Supply Chains

In this section, we introduce mathematics to the conceptual model presented above. We try to avoid excessively complex mathematics and introduce mathematical symbols only where these are absolutely necessary. The mathematical model is based on the DIMA (Decentralized Integrated Modeling Approach) and combines elements drawn from operations research and mathematical programming (multiple objective management decision making, dynamic programming), control theory (dynamic decentralized systems), and agent-oriented modeling. This model aims to synthesize simultaneous supply chain configuration, plans, and execution dynamics (operations) of alternative supply chain structures. The model works simultaneously as (i) a multi-structural design of a supply chain, consisting of suppliers, manufacturers, careers, distribution centres, and retailers; (ii) proof of the fit of a supply chain design to different demands subject to customers' orders; and (iii) a method of planning supply chains within the different SCD alternatives.

6.1. Data structures

At the first stage, the data structures and interrelations between the data of different supply chain structures must be defined. For this purpose, we used the CASE tools, special languages, such as UML, and systems dynamics and ontology analysis. Because these are large-scale data models, we introduce only an extract here.

Class 1. Organizational structure: structure of enterprises, management departments, and workers

Subclass 1.1. Structure of enterprises: competencies, location, etc,

Subclass 1.1.1. Competencies: capacities, costs, reliability, quality

Subclass 1.1.2. Collaboration of enterprises

Class 2. Business process structure: coordinating parameters (demand, inventories, or orders), operations (distribution, production, replenishment; matched with subclasses), functions (in relations with the management departments)

Class 3. Product structure: product variety, demand, bill-of material etc.

Class 4. Technological structure: operations, machines (in relation to the technical devises of the subclass 1.1), quality data etc.

Class 5. Topological structure (locations, movements etc.)

Class 6. Financial structure (costs in correspondence to the classes 1-5).

6.2. Construction of multi-structural supply chain alternatives and multi-criteria goal formulation

Let $G = \left\{ G_{\chi}, \chi \in NS \right\}$ be the set of structures that are being formed within the SCD. To interconnect the structures let us consider the following dynamic alternative multi-graph (DAMG):

$$G_{\chi}^{t} = \left\langle X_{\chi}^{t}, F_{\chi}^{t}, Z_{\chi}^{t} \right\rangle, \quad (1)$$

where the subscript χ characterizes the SCD structure type, $\chi \in NS = \{1,2,3,4,5,6\}$, the time point t belongs to a given set T; $X_{\chi}^{t} = \{x_{\chi l}^{t}, l \in L_{\chi}\}$ is a set of elements of the structure G_{χ}^{t} (the set of DAMG vertices) at the time point t; $F_{\chi}^{t} = \{f_{<\chi,l,l'>}^{t}, l, l' \in L_{\chi}\}$ is a set of arcs of the DAMG G_{χ}^{t} and represent relations between the DAMG elements at time t; $Z_{\chi}^{t} = \{f_{<\chi,l,l'>}^{t}, l, l' \in L_{\chi}\}$ is a set of parameters that characterize relations numerically.

The graphs of different types are interdependent, thus, for each operation the following maps should be constructed:

$$M_{<\chi,\chi'>}^{t} : F_{\chi}^{t} \to F_{\chi'}^{t}, \tag{2}$$

Composition of the maps can be also used at time t:

$$M_{<\chi,\chi'>}^{t} = M_{<\chi,\chi_1>}^{t} \circ M_{<\chi,\chi_2>}^{t} \circ \ldots \circ M_{<\chi'',\chi'>}^{t}. \tag{3}$$

A multi-structural state can be defined as the following inclusion:

$$S_{\delta} \subseteq X_1^t \times X_2^t \times X_3^t \times X_4^t \times X_5^t \times X_6^t, \quad \delta = 1,\ldots,K_{\Delta} \tag{4}$$

Now we obtain the set of the supply chain multi-structural macro-states in dynamics:

$$S = \{S_{\delta}\} = \{S_1,\ldots,S_{K_{\Delta}}\} \tag{5}$$

Allowable transitions from one multi-structural state to another one can be expressed by means of the maps below.

$$\Pi^{t}_{<\delta,\delta'>} : S_{\delta} \rightarrow S_{\delta'} \quad (6)$$

Here we assume that each multi-structural state at time $t \in T$ is defined by a composition (2).

Now, the problem of SCD with structure dynamics considerations can be regarded as a selection of multi-structural macro-states $S^{*}_{\delta} \in \{S_1, S_2, ..., S_{K_{\Delta}}\}$ and transition sequence (composition) $\Pi^{t_1}_{<\delta_1,\delta_2>} \circ \Pi^{t_2}_{<\delta_2,\delta_3>} \circ \Pi^{t_f}_{<\delta',\delta>}$ $(t_1 < t_2 < ... < t_f)$, under some criteria of effectiveness, e.g., service level and costs.

Dynamics of the supply chain execution is presented as a *dynamic alternative multi-graph* to relate the above sets and structures. The DAMG is characterized by *macro-structural macrostates (MSMS)*. The DAMG and the MSMS have been developed to meet the requirements on multi-structural design and to link planning and execution models, taking into account the structure dynamics.

6.3. Fit of the SCD to the production tactics

The next step is to prove the fit of the SCD to the production tactics. For this stage, a set of interlinked dynamic models was elaborated. These models are: a model of order dynamics management, models of operations dynamic management, models of flows management, a model of resource dynamics management, a model of structure dynamics management, a model of macrostructural macrostates. The main advantage of the elaborated models is the structural and functional constraints of supply chain planning and control are defined explicitly. We will not describe the details of these models in terms of complex mathematics.

The elements of the organizational graph are described as active agents in terms of agent-based modelling, so the models of enterprise collaboration and interactions can be elaborated. At this stage, we combine graph-theoretical modeling with agents to describe active elements of the graph, as well as to implement dynamics of the supply chain active objects collaboration. We introduced a specific description of these active objects in terms of agent-based modeling and defined some aspects of agents' activities mathematically (Ivanov et al., 2005, Ivanov et al., 2007). These papers also present interactions of agents. The experiments validated the finding that, in the framework of the considered polymodel description, not only functionality conditions, but also conditions of the general position of adjacency mapping are maintained (Sokolov and Yusupov 2004).

7. Implementation and Managerial Insights

The methodologies and models presented above are under implementation for supply chains of machinery and textile branches in Russia and Germany. In both countries, an increase in economical efficiency regarding supply chain responsiveness, costs, robustness, and flexibility has been achieved. In this section, we discuss the managerial implications.

7.1. Lessons learned

The main lesson learned from the projects with industrial partners and application of the models described above is that SCD requires simultaneous consideration of the interrelations in different supply chain structures. This means supply chains should be considered not only as a set of enterprises, but also as processes, which are designed with a number of interrelated structures (functional, organizational, informational, etc.). The complex multi-structural supply chain consideration can inform an approach to increasing efficiency of (re)-designing supply chains. Below are some other insights:

- One of the main supply chain features is the multiple-structure design and changeability of structures' parameters because of objective and subjective factors at different stages of the supply chain life cycle;
- Supply chain design decisions are dispersed over different structures. Decisions in all the structures are interrelated;
- Structures and decisions on different stages of supply chain execution change in their dynamics. In other words, supply chain structure dynamics are constantly encountered. In the case of disruptions, the changes in one structure cause changes in other relevant structures. As supply chains are highly dynamic systems, comprehensive multi-structural modelling is mandatory not only at the planning stage but also at the execution stage.

Some examples of the structural interrelations follow. Business processes are designed in accordance with supply chain goals and are executed by organizational units. These units fulfil management operations and use certain technical facilities and information systems for planning and coordination. Business processes are supported by information systems. Organizational units have a geographical (topological) distribution that also may affect the SCD decisions. Collaboration and trust (the so-called "soft facts") in the organizational structure do affect other structures, especially the functional and informational structures. Managerial, business processes (distribution, production, replenishment etc.), technical and technological activities incur supply chain costs, which also correspond to different supply chain structures. Therefore, the supply chain can be interpreted as a *complex multi-structural system*.

7.2. Implementation

The proposed mathematical framework is implemented in software and serves as a simulation and optimization engine in informational architecture, which contains a Web-platform, an ERP System, and a supply chain monitor (s. Figure 4).

[Insert Figure 4 about here]

Figure 4 shows the general environment of the elaborated "engine" in the settings of the complete informational infrastructure. The "engine" itself is elaborated based on a tool – AnyLogic - which allows implementation of a combination of simulation, optimization, and heuristics. Another advantage of AnyLogic is to combine agent-based modelling of enterprise collaboration, systems dynamics, and discrete event simulation (s. Figure 5).

[Insert Figure 5 about here]

Another part of the "engine" is the "Supply Network Dynamics Control" software which allows optimization of the multi-structural macrostates of supply chains. An interface of the supply chain multi-structural macrostates representation (at a given instant) is shown in Figure 6. [Insert Figure 6 about here]

This interface depicts the relationships of multi-structural macrostates to different supply chain elements, and how these states change in dynamics. The information systems infrastructure presented above falls under the categories of Supply Chain Event Management and Supply Chain Design Management systems.

7.3. Benefits

In this subsection, let us focus on some benefits resulting from the multi-structural supply chain treatment.

- The complex multi-structural supply chain consideration can inform an efficient approach to (re)designing supply chains to avoid structural incoherency and inconsistency;

- The multi-structural SCD treatment allows managers to simulate supply chain execution dynamics in different structures as an complete system, investigate supply chain behaviour in the case of disruptions, determine supply chain bottlenecks, and make necessary management adjustments (e.g., to change distribution channels, introduce additional resources, change coordination parameters, introduce new sourcing points, allocate suppliers, etc.);
- The other advantage of the structure dynamics considerations is that, being based on given demand forecasts, it is possible to simulate how the designed supply chain suits these forecasts. On the other hand, demand uncertainty can be taken into account to gain insights into (i) what infrastructure should be used when demand deviates or new products are added to existing lines and (ii) at what demand points additional sources of supply are needed and where they should be located. This means, supply chain design and tactical planning can be modelled simultaneously. On the other hand, tactical changes can be reflected in the SCD to keep supply chain structures in correspondence with an actual execution environment;
- The multi-structural SCD treatment is very important for re-designing supply chains for new products, new order penetrations points, and a variety of disruptive factors (machine failures, human

errors, information systems failure, cash-flow disruption or simply catastrophic events).

7.4. Obstacles

Of course, this approach does not constitute an “overall” concept of supply chain design. This is just an approach, which has been implemented successfully in practice, and contributes to the theoretical foundations of supply chain management. It has also some limitations. Gathering initial data structures and establishing their interlinking is very time intensive. Simultaneous work with different structures and modelling methods also requires solid professional skills. Balancing optimization, heuristics, and simulation parts is also challenging. However, increasing supply chain design and re-design efficiency will repay these efforts.

7.5. Scientific novelty

The novelty of this research is that it advances the multi-structural treatment of SCD, introduces the structure dynamics and stability considerations, elaborates a new conceptual model for the multi-structural SCD, proposes new tools for the multi-structural SCD – multi-structural macro-states and dynamical alternative multi-graph, and enhances the SCM methodological foundations by advancing inter-disciplinary supply chain modelling. The main advantages of the proposed approach concern SCD itself as well as supply chain robustness and adaptation capabilities.

Conclusions

One of challenges of SCD consists of the number of interrelated structures. Supply chain execution is accomplished by permanent changes of the internal network properties and external environment. We focus on strategic-level issues of the supply chain design and consider it a problem of multi-structural network synthesis. The results show multi-structural and inter-disciplinary treatment of supply chain design allows comprehensive and realistic design problem formulation and solution. The proposed multi-structural treatment also allows establishing links to comprehensive uncertainty analysis and especially to supply chain execution and reconfiguration. The findings suggest how to implement a simultaneous multi-structural supply chain synthesis as well as how to encapsulate the structure dynamics into supply chain design and planning. This paper introduces an approach to enhance the existing frameworks of the supply chain design by means of simultaneous multi-structural network synthesis considering structure dynamics. The proposed methodology contributes to advancing theoretical foundations of supply chain management, supports managerial insight into supply chains at the strategic and tactical levels, and serves to enhance decision making in production and logistics networks planning. In future research, we will focus on further investigation of structure interrelations and their dynamics. Especially interesting and useful for practice is an interrelation of business processes and information systems, which both serve as infrastructures for business processes and ensure their implementation. The other possible direction for future research is to embed financial flows in interrelations with material and information flows.

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Table 1. Summary of SCD problems and methods of solution

Strategy	Data	Problems	Method of solution
Initial Data: Competitive strategy; Supply chain strategy; Financial strategy			
Supply Chain Goals	Costs, Service Level, Assets, Quality, Stability	How can be achieved an optimal compromise of supply chain goals? How to deal with multiple criteria?	Analytical Hierarchy Process; Pareto-Optimality; Heuristics; Control theory
Production program strategy	Product variety Stock keeping units, Bill-of-material relationships, Demand, Response time, Time-to-market	Which products, in what quantity, variety, batches etc. to produce? Product availability, Technological plans building	Linear Programming; System Dynamics, Ontology-Analysis, Graph-Theory, Mixed Integer Programming
Coordination strategy	Levels of coordination: orders, forecast-	How enterprises will collaborate? What information	UML/IDEF Multi-agent systems,

	ing, point-of-sale	systems must be used?	Fuzzy-Logic, Game Theory
Distribution and production strategy	Location data (costs, geo-referenced data, taxes etc.), Demand, Inventories, Process data (capacities, costs, etc.), Movements data (transportation costs, time, mode, and capacity)	How many facilities of what capacities and of what location are needed? Suppliers' selection and their allocation to plants How the transportation should be organized? How to deal with demand uncertainty?	Linear Programming; MILP; Queues theory; Dynamic programming, Decision Analysis, Assignment methods; System Dynamics, Discrete-events simulation, Stochastic optimization; Multi-agent systems; Fuzzy-Logic; Linear dynamic systems, Heuristics

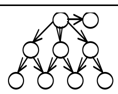
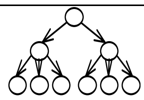
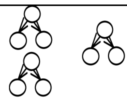
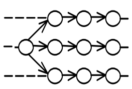
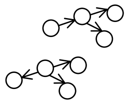
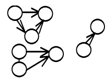
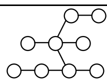
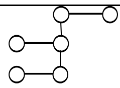
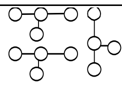
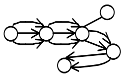
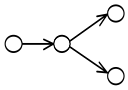
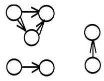
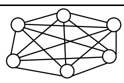
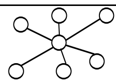
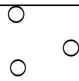
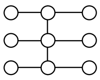
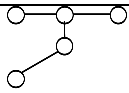
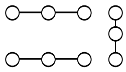
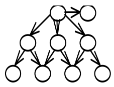
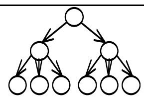
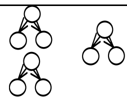
Variants of multi-structural states / Supply chain structures	Supply chain structure dynamics			
	$S_0^{(\delta)}$	$S_1^{(\delta)}$	...	$S_K^{(\delta)}$
Product structure			...	
Functional (business-process) structure			...	
Organizational structure			...	
Technical-technological structure			...	
Topological structure			...	
Financial structure			...	
Informational structure			...	

Figure 1. Supply chain multi-structural composition and structure dynamics

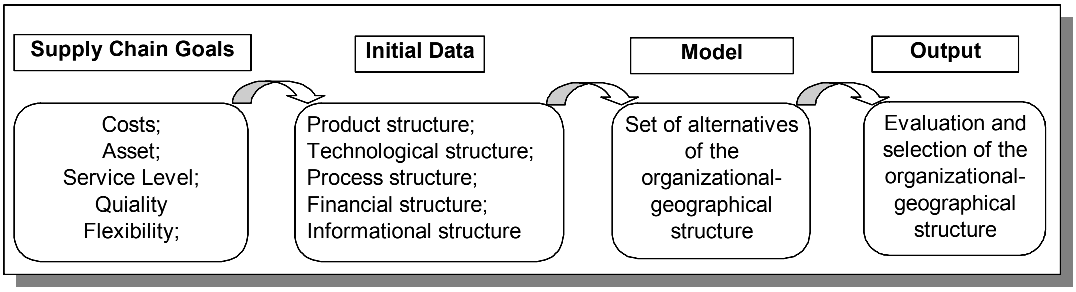


Figure 2. Conventional SCD conceptual model

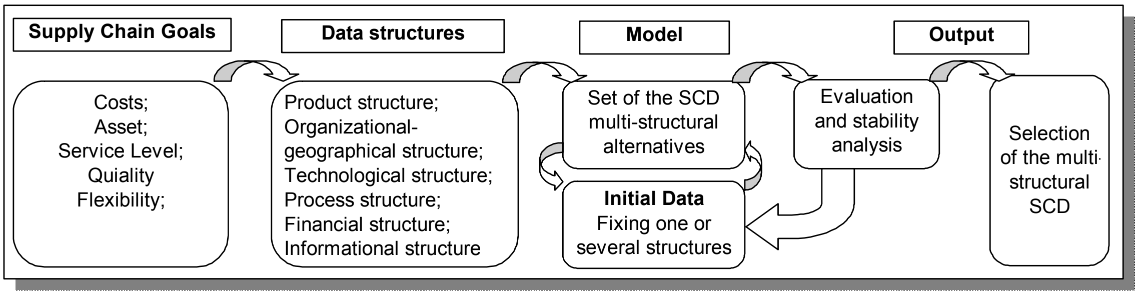


Figure 3. Multi-structural SCD conceptual model

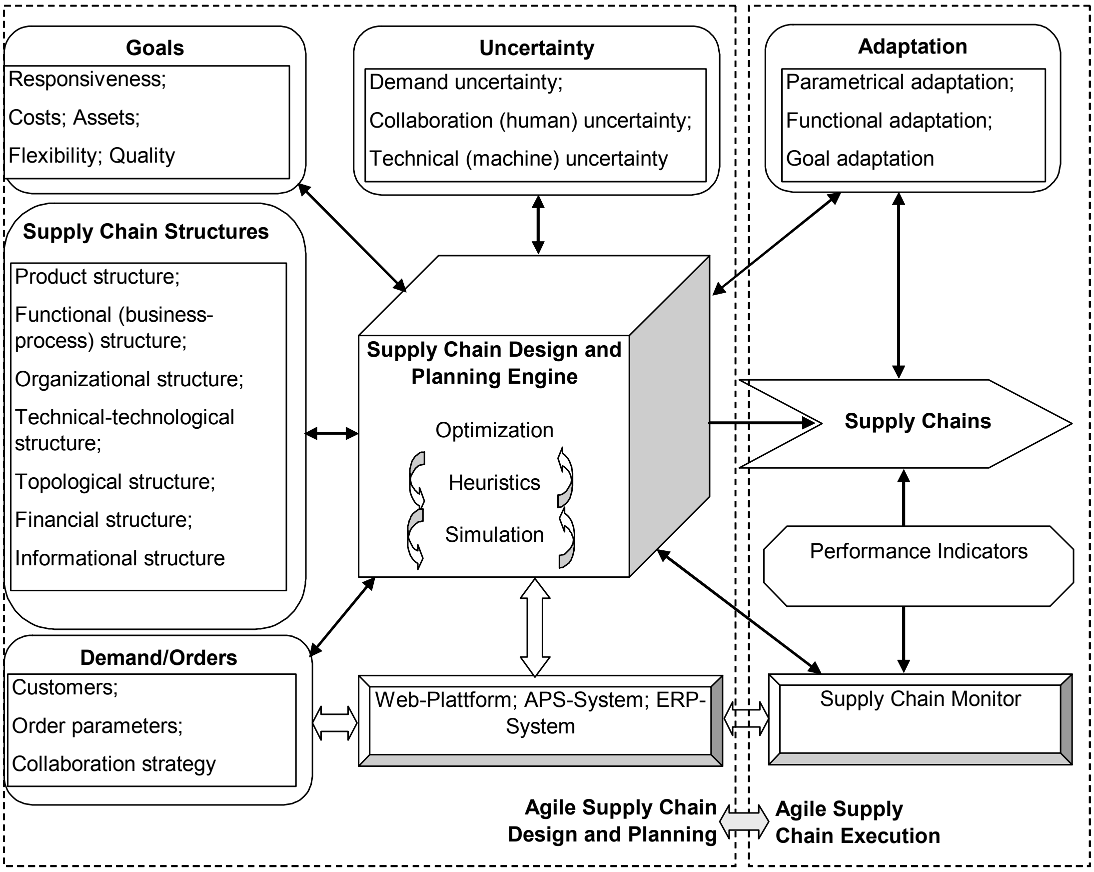
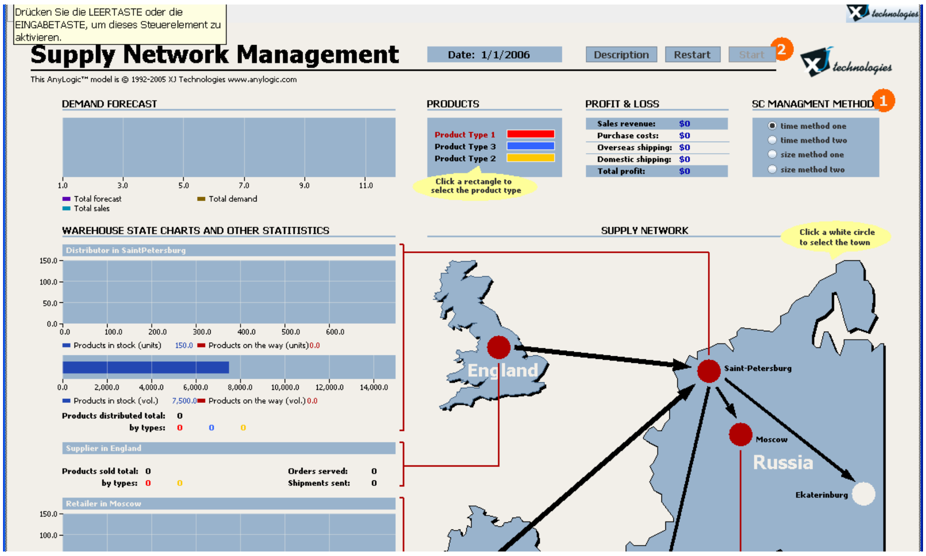


Figure 4. Supply Chain Design and Planning Engine



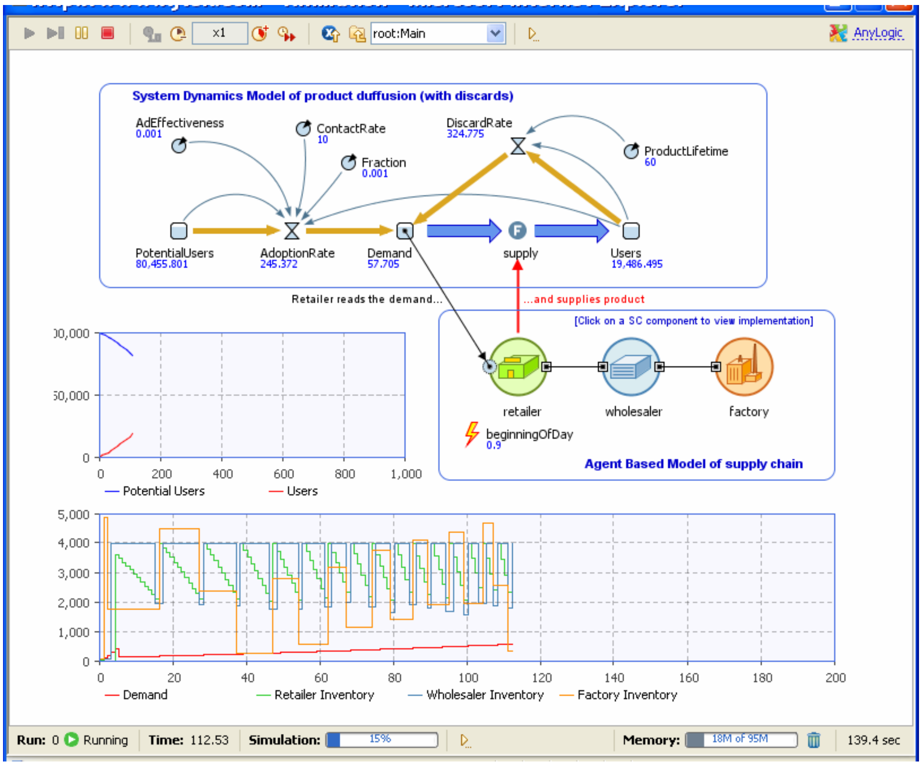


Figure 5. Supply Chain Modeling in the AnyLogic

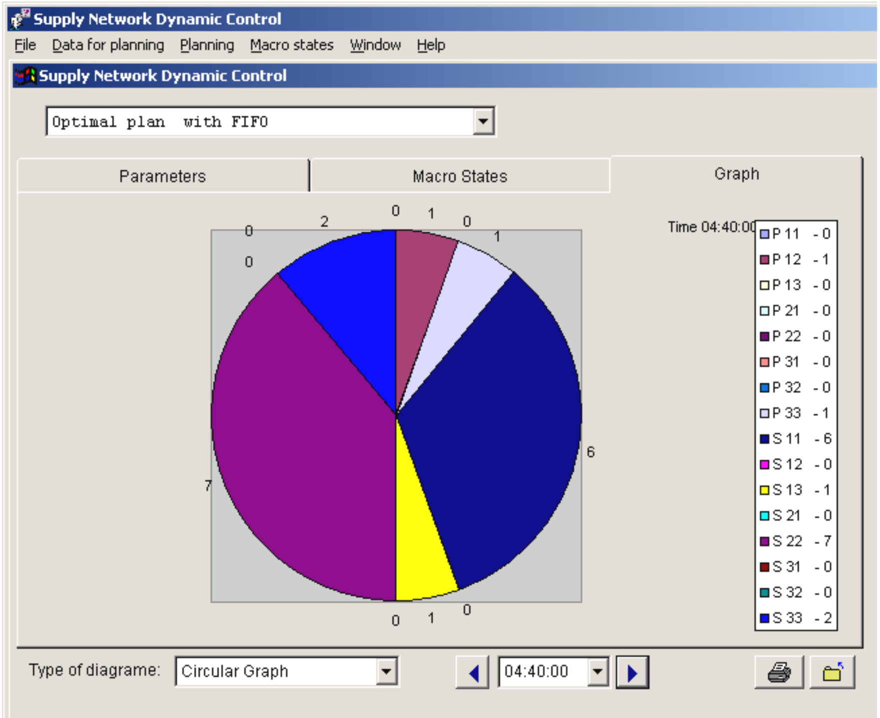


Figure 6. Supply Chain Dynamics in terms of the multi-structural macro states