A multi-structural framework for adaptive supply chain planning and operations control with structure dynamics considerations

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A trend in up-to-date developments in supply chain management (SCM) is to make supply chains more agile, flexible, and responsive. In supply chains, different structures (functional, organizational, informational, financial etc.) are (re)formed. These structures interrelate with each other and change in dynamics. The paper introduces a new conceptual framework for multi-structural planning and operations of adaptive supply chains with structure dynamics considerations. We elaborate a vision of adaptive supply chain management (A-SCM), a new dynamic model and tools for the planning and control of adaptive supply chains. SCM is addressed from perspectives of execution dynamics under uncertainty. Supply chains are modelled in terms of dynamic multi-structural macro-states, based on simultaneous consideration of the management as a function of both states and structures. The research approach is theoretically based on the combined application of control theory, operations research, and agent-based modelling. The findings suggest constructive ways to implement multi-structural supply chain management and to transit from a "one-way" partial optimization to the feedback-based, closed-loop adaptive supply chain optimization and execution management for value chain adaptability, stability and crisis-resistance. The proposed methodology enhances managerial insight into advanced supply chain management.
Key words: supply chain management, adaptive supply chain, planning, control, operations, multiple structures, multi-disciplinary modelling, structure dynamics, adaptation.

1. Introduction

In many branches, wide-broaden hierarchical supply chains with a predetermined suppliers' structure and long-term static product programmes evolve into flexible dynamic supply chain structuring. Research in adaptive/agile supply chains has been conducted for the last decade (Goranson, 1999; Christopher and Towill, 2001; Ross, 2004; Yusuf et al., 2004; Gunasekaran and Ngai, 2005). Nowadays and in future, adaptive supply chains (ASCs) with heterogeneous structures and extensive application of Web services are expected to be more flexible and reactive, and capable of rapid evolution and surviving competition.

Conventionally, the investigations into supply chain planning (SCP) are performed on the structure of physical distribution, manufacturing, and procurement. However, supply chains can be considered not only from this organizational point of view, but also from a process point of view (Beamon, 1998). It should be emphasized that supply chains consist of different structures:

business processes and technological, organizational, technical, topological, informational, and financial structures. All of these structures are interrelated and change in their dynamics. Especially in adaptive supply chains with high dynamics, the issue of how to achieve structural comprehensiveness, responsiveness, and flexibility as well as to avoid structural incoherency and non-consistency by supply chain planning and operations is very important. The adaptation of one structure causes changes in the other related structures. To ensure a high responsiveness level, the supply chain plans must be formed extremely quickly, but must also be robust. That is why it becomes very important to plan and run supply chain plans in relation to all the structures. This can be realized if (i) different SC structures are considered simultaneously and (ii) the execution dynamics in all the structures can be reflected to establish bilateral feedback between SC plans and operations.

Even though adaptive supply chains are a strong trend in practice, research into adaptive supply chains is still limited. In 2000–2007, a number of studies have been conducted in Chemnitz (Germany) and Saint Petersburg (Russia) with industrial and academic partners. This paper has partially resulted from those projects.

This paper aims to propose a multi-structural framework of adaptive supply chain planning with structure dynamics considerations. This paper is organized as follows. We start with a state-of-the-art analysis. In Section 3, we describe the vision of adaptive supply chain management. In Section 4, we describe the basics of the ASC multi-structural treatment. Section 5 describes the research approach, which is theoretically based on the combined application of control theory, operations research, and agent-based modelling. Sections 6 and 7 present conceptual and mathematical models of the ASC planning and operations. In Section 8, the validation of the proposed framework and main results are discussed. We conclude the paper by summarizing the most important features of the proposed framework.

2. State-of-the-art

There is considerable work regarding the ASC planning and operations problems from different perspectives (Christopher and Towill, 2001; Mason-Jones et al., 2000; Ross, 2004; Yusuf et al., 2004; Vanderhaeghen and Loos, 2007; Aragwal et al., 2006; Ivanov et al., 2007; Ivanov, 2006, 2009). In recent years, the concepts of agile collaborative production and logistics have been increasingly developed. BTO supply chains, agile supply chains, virtual enterprise, changeable, reconfigurable, or collaborative networks can be named among them (Goranson, 1999;

Camarinha-Matos et al., 2005; Gunasekaran and Ngai, 2005; Teich, 2003). (Gunasekaran and Ngai 2005) present a summary of research into BTO (build-to-order) supply chains. Frameworks for the configuration of collaborative networks were proposed in (Camarinha-Matos et al., 2005). (Stock et al., 2000) examined the fit between an organization's enterprise integration capabilities and its supply chain structure.

Mathematical research into the ASC can be divided into three primary approaches: optimization, simulation, and heuristics. *Optimization* is an analysis method that determines the best possible method of designing a particular supply chain. Earlier literature presents several optimization-based approaches to ASC planning. (Sarkis et al., 2007) have presented a strategic model for agile virtual enterprise partner selection. (Chauchan et al., 2007) have addressed the problem of short-term supply chain design using the idle capacities of qualified partners in order to seize a new market opportunity. (Wu et al., 1999) have applied integer programming to support partner selection. (Ip et al., 2004) presented a branch and bound algorithm for subcontractor selection in an agile manufacturing environment. All of them use total costs as an optimality criterion. Extending the solitary cost criterion, e.g. (Mikhailov, 2002) presented models that account for multiple criteria, such as organizational competitiveness and social relationships. A closely related topic to the problem addressed in this paper is *vendor evaluation and selection*. For the ASC execution, a number of models for the ATP/CTP have been developed (i.e., Zschorn 2006). The drawback to using optimization is the difficulty in developing a model that is sufficiently detailed and accurate in representing the complexity and uncertainty of the ASC, while keeping the model simple enough to be solved. However, when the problem is not too complex to solve, optimization produces the best possible insights into questions related to the ASC management.

Simulation is imitating the behaviour of one system with another. By making changes to the simulated ASC, one expects to gain understanding of the ASC dynamics. Simulation is an ideal tool for further analysing the performance of a proposed design derived from an optimization model. Regarding the ASC, complex adaptive systems (CAS) and multi-agent systems (MAS) are two of the most popular simulation techniques (Swaminanthan et al., 1998). The past research on utilization of the MAS for the ASC has mostly dealt with agent-based frameworks and software architectures. It is mostly underestimated that these paradigms offer a valuable theoretical perspective on decentralized network management. (Nillson and Darley, 2006) proposed to combine CAS and MAS and to use the CAS as the theoretical approach and the

MAS as the implementation method. (Kuehnle, 2007) considers agents as a part of the complex of interrelated models for ASC planning. (Ivanov et al., 2007; Ivanov, 2009) consider agents as a part of the generic model constructions. Besides the MAS, a number of other approaches such as system dynamics (Towill et al., 1992; Sterman, 2000) are often applied to supply chain dynamics investigations. In practice, new information tools such as Supply Chain Event Management (SCEM) (Ijioui et al., 2007) and Supply Chain Design Management (SCDM) are introduced to simulate supply chains in the case of structural adaptation and to forecast adaptive supply chains' behaviour.

Heuristics are intelligent rules that often lead to good, but not necessarily the best, solutions. Heuristic approaches are typically easier to implement and require less data. However, the quality of the solution is usually unknown. Unless there is a reason that optimization cannot be used, heuristics are an inferior approach. In the ASC settings, the nature-based heuristics such as genetic algorithms (Huang et al., 2005) and ACO (Ant Colony Optimization) (Teich, 2003) are usually used. For instance, (Fischer et al., 2004) elaborated an approach for optimizing the selection of partners in production networks based on an ACO algorithm. (Kopfer and Schoenberger, 2006) considered a genetic algorithm-based online optimization of problems with several multi-layered objectives with preventive and reactive SC adaptation.

Besides the above-described approaches, the control theory can also be used for the ASC planning (Disney and Towill, 2002; Ivanov, 2009). It can serve as the general methodological basics of complex systems synthesis and analysis with feedback closed-loops. The most important feature of control theory application for SCN is the negative feedback system that allows taking into account current execution dynamics of processes in supply chains. However, the disadvantage of the research grounded in modern *systems and control theories* regarding complex business systems is that the system elements are being controlled from a central automatic controller 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). The classic methods of the control theory do not allow the development of practical comprehensive models taking into account the *goal-oriented (active) behaviour* of enterprises.

The review highlighted some common disadvantages and serious limitations of the above-described approaches regarding the ASC planning. First of all, these approaches do not take into account system elements' activity (only the MAS). Besides, 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, focus on a single or limited number of objectives and can not represent the ever-changing nature of the supply chains. Some research concentrates on the organizational level, other on the facilities level etc. There is a lack of formalized multi-structural treatment of the SC. Different interlinked problems of the SC planning and operations are considered separately for the different structures with heterogeneous and non-consistent models' fragments. There is a lack of feedbacks between SC operations and planning to ensure the SC's adaptation to a current execution environment. These gaps have launched the research presented in this paper.

3. Vision of the Adaptive Supply Chain Management (A-SCM)

In this section, the basics of the A-SCM approach are considered. We start with the main definitions, then we consider the A-SCM framework. Based on the frameworks of the control and systems theory, let us introduce some basic definitions.

Definitions

The adaptability of supply chains is an ability of a supply chain to change its behaviour for preservation, improvements, or acquisitions of new characteristics for the achievement of SC goals in the conditions of environment varying in time, the aprioristic information about which is incomplete.

Adaptive management is a management method of a supply chain with varying unknown characteristics of environment, at which for the final time are reached defined (satisfactory, wished, or optimum) goals of SC management by means of a change of parameters of the supply chain or characteristics of control influences on the basis of feedback systems.

Adaptive planning is a method of planning in which the plan of a supply chain is modified periodically by a change of parameters of the supply chain or characteristics of control influences on the basis of information feedback about a current condition of a supply chain, the past and the updated forecasts of the future.

An adaptive supply chain is a networked organization wherein a number of various enterprises

(i) collaborate (cooperate and coordinate) along the entire value chain and product life cycle to: acquire raw materials, convert these raw materials into specified final products, deliver these final products to retailers, design new products and ensure post-production services;

(ii) apply all modern concepts and technologies to make supply chains responsive, flexible, robust, sustainable, cost-effective, and competitive in order to increase customer satisfaction and decrease costs, resulting in increasing supply chain profitability.

An adaptive supply chain is a complex multi-structural system. A supply chain can be named adaptive if it can adapt to (1) changes in the market environment and uncertainty impacts, (2) changes in the operations execution environment, and (3) internal changes in the supply chain itself by means of additional structural-functional reserves and better coordination through an extensive application of information technologies, especially Web services.

Adaptive supply chain management studies the resources of enterprises and human decisions in regard to cross-enterprise collaboration processes to transform and use these resources in the most rational way along the entire value chain and product life cycle, from customers up to raw material suppliers, based on cooperation, coordination, agility, and sustainability throughout.

Framework

In the adaptive supply chain management framework, we do not set off different value chain strategies with each other, but consider them as an integrated framework. SCM serves as a basis for integration (organizational: suppliers and customer; functional: collaborative business processes; managerial: strategic, tactical, and operative decision-making levels), cooperation, and coordination. The strategies of agility enrich SCM by means of a general information space with the help of Web services and higher flexibility/responsiveness through concentration on core competencies and building virtual alliances/environments. Sustainable SCM integrates the consideration of the product development, utilization, product end-of-life, and recovery processes. On the other hand, sustainable SCM brings into consideration policy and society issues, which may affect the supply chains and which may be affected by supply chains. Encapsulation of the advantages of supply chain management, agility, and sustainability enables adaptive supply chain management (see Figure 1).

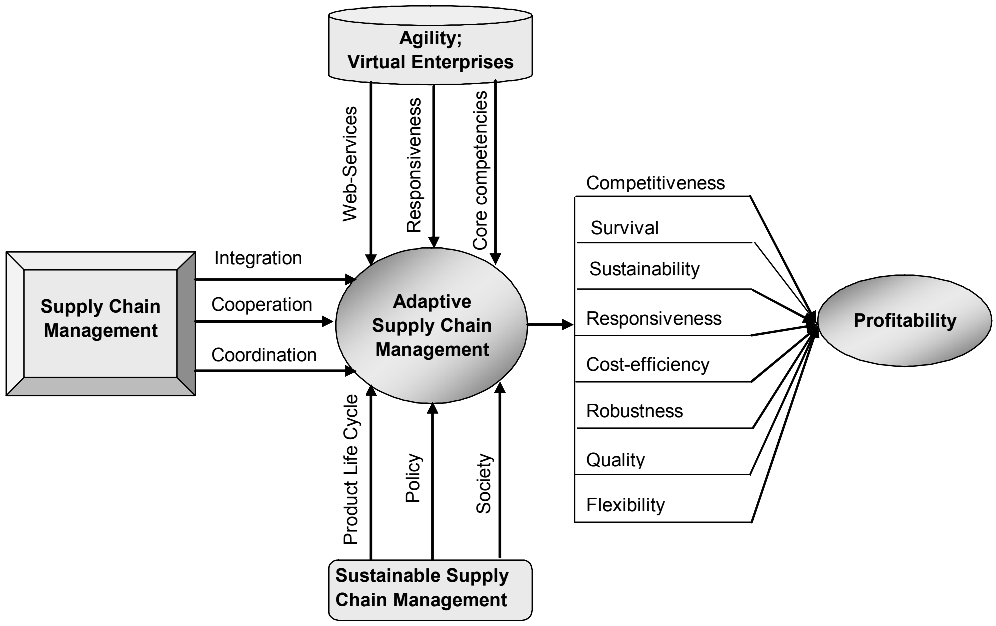


Fig. 1. Framework of Adaptive Supply Chain Management

In adaptive supply chain management, all three value chain drivers – products and their life cycles, customers and their orders, and suppliers/outsourcers – are enhanced by combining the elements from the SCM, agility, and sustainability. Moreover, these drivers are interlinked within a unified information space.

Adaptive supply chain management unites a supply chain owner (an original equipment manufacturer (OEM) or a 4 part logistics (PL) provider), customers, and suppliers. The organizational structure consists of a real supply chain environment and a virtual alliance/partnership environment. In the real supply chain environment, the supply chain owner collaborates with its customers and suppliers in regard to the existing products and product lines in all the stages of the product life cycle. The virtual alliance/partnership environment is an adaptation reserve of the real supply chain environment.

In the case of market changes, new products, or an impact of operational inefficiencies due to a variety of disruptive factors (machine failures, human decision errors, information systems failure, cash-flow disruption, or simply catastrophic events), these *structural-functional reserves* are activated to adapt the supply chain. Secondly, in the virtual alliance/partnership environment new products are designed (with the integration of potential customers and suppliers).

4. Multi-structural treatment of the adaptive supply chain planning and operations

In this section, we describe the basics of the ASC multi-structural treatment. We also consider possibilities of a comprehensive uncertainty analysis and establishing links to the ASC execution based on the proposed ASC 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, ASC structure dynamics are constantly encountered in practice (s. Figure 2).

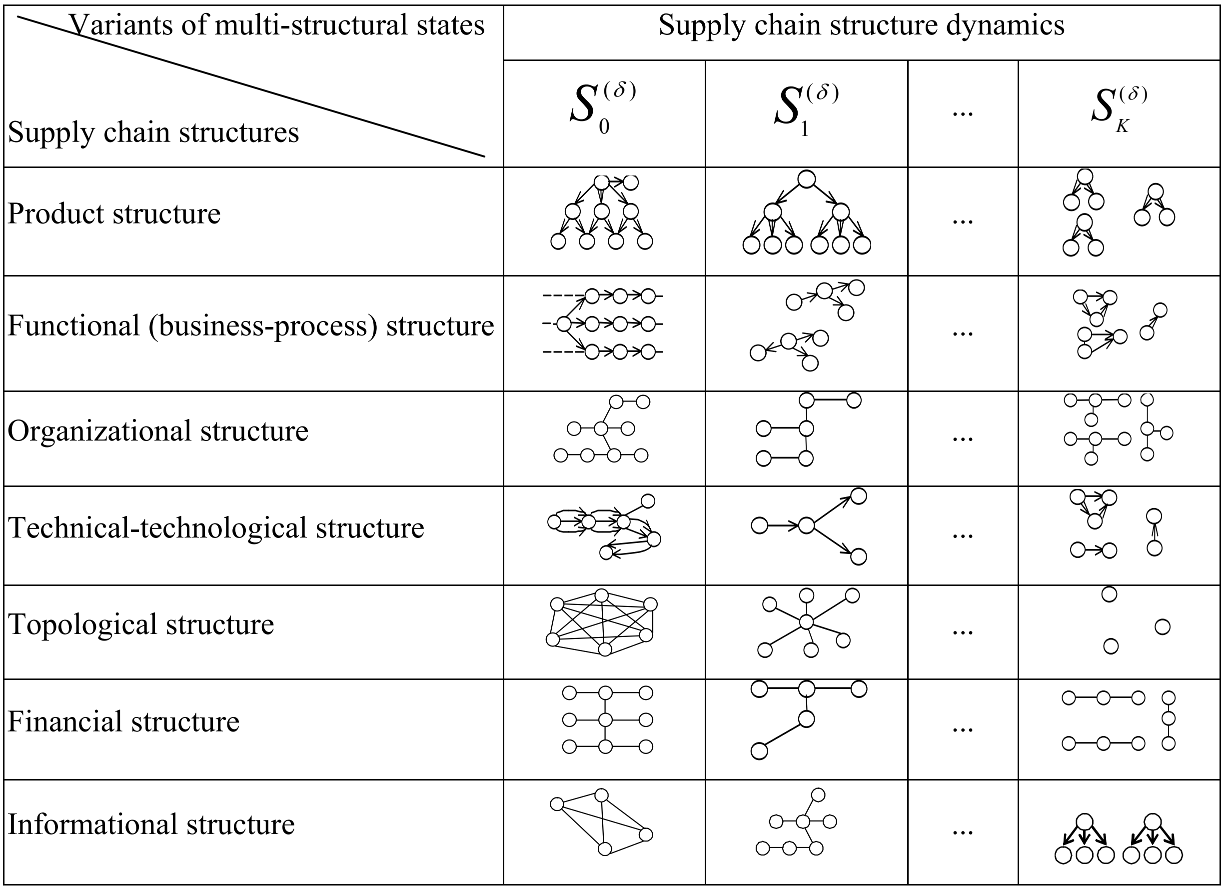


Figure 2. Supply chain multi-structural composition and structure dynamics

In Fig. 2, 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*. The main supply chain structures are the following:

- product structure (bill-of-materials),
- functional (structure of management functions and business-processes),
- organizational (structure of facilities, enterprises, managers and workers),
- technical-technological (structure of technological operations for product production and structure of machines, devises etc.),
- topological (geographical) structure,
- informational (structure of information flows according to the coordination strategy), and
- financial (structure of supply chain costs and profit centres).

Why is the ASC multi-structural treatment so important? 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 planning 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. So the supply chain can be interpreted as a *complex multi-structural system*.

The ASC planning and operations decisions are dispersed over different structures. Furthermore, the supply chain execution is accomplished by permanent changes of internal network properties and external environment. In practice, structure dynamics is frequently encountered. Decisions in all the structures are interrelated. Changes in one structure affect the other structures. Furthermore, the structures and decisions on different stages of supply chain execution change in 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.

The other advantage of the structure dynamics considerations is that it is possible to simulate how the designed supply chain suits demand fluctuations (s. also recent research in structure dynamics, e.g. Sterman, 2000). 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, operational changes can be reflected in the supply chain plan to keep supply chain structures in correspondence with an actual execution environment. The multi-structural SC treatment is very important for reconfiguration of supply chains (Ivanov et al. 2008).

5. Multi-disciplinary treatment of the adaptive supply chains

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

5.1. Necessity of the ASC multi-disciplinary treatment

The necessity of the ASC multi-disciplinary treatment is caused by a complex composition and tight interlinking of different ASC problems, which exist in different structures and change in their dynamics. (Beamon, 1998) emphasize that supply chain systems are inherently complex. Thus, the models and methods used to accurately study these systems are, expectedly, also complex. 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).

Cross-linked ASC planning and operations control problems require combined application of various modeling techniques (optimization, statistics, heuristics, and simulation). 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. Selection of a solution method depends on data fullness, problem scale, one or multiple criteria, requirements on output representation, and interconnection of a problem with other problems. Different approaches from the operations research, control theory, and agent-based modelling have a certain application area and a certain solution procedure. Isolated application of only one solution method leads to a narrowing in problem formulation, overdue constraints and sometimes unrealistic or impracticable goals.

5.2. Basics of the ASC multi-disciplinary treatment

The basics of the ASC 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; 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 ASC. It means all the models contain elements of decentralized decision making and ASC elements' activity. Decisions about ASC 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. 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).

6. Conceptual model of the ASC operative planning and operations

Supply chain planning is complicated by multiple criteria, execution uncertainty, and unavoidable plan changes. In this approach, supply chain planning and control are addressed from perspectives of the plan execution dynamics under uncertainty. The model is based on a dynamical interpretation of operations in supply chains due to implementing feedbacks and closed control loops from the control theory interconnected to the methods of operations research and multi-agent systems. The model is based on a simultaneous consideration of management as the function of both states and structures. Closed-loop supply chain models with positive and negative feedbacks have the following advantages: disturbance rejection; guaranteed performance even with model uncertainties, when the model structure does not match perfectly the real process and the model parameters are not exact; unstable processes can be stabilized; reduced sensitivity to parameter variations.

Operative plans in the ASC are formed dynamically based on offer parameters of the enterprises (e.g., lead time, available capacities, costs, etc.), customer's requirements (delivery time, desired quantity, product technological structure etc.), as well as so-called soft factors (e.g., reputation, trust, etc.). The existence of alternative suppliers for various project operations, which differ from each other by operation parameters (costs, delivery time, etc.), is remarkable. The collaboration is formed in a decentralized way. Partners manage collaboration with their suppliers and customers. There is no general management unit in ASC. The projects are coordinated by an external or internal unit (a coordinator, i.e., 4PL provider), who is responsible for the project success (customer side) and for coordinating the network participant activities (supply side). The cybernetic scheme of adaptive supply chain planning and control is shown in Figure 3 (Ivanov et al., 2007).

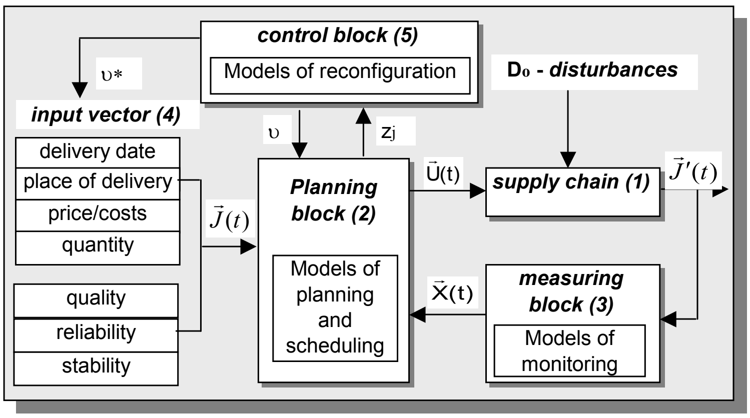


Figure 3 – The cybernetic scheme of adaptive supply chain planning and operations

The proposed schema of the ASC planning and control consists of five main parts: *supply chain* (1) as a plan and control object, *planning block* (2) with relative models and algorithms of planning and scheduling, *measuring block* (3) with monitoring models, *input system* (4) for setting input vector parameters, and *control block* (5) with reconfiguration models. The main loop (blocks 2, 1, 3) ensures the functioning of the ASC and is meant for the maintenance of the output parameter values $\vec{J}'(t)$ of an SC in accordance with the required ones of the input signals $\vec{J}(t)$ so that the deviation $\vec{E} = (\vec{J}'(t) - \vec{J}(t))^2$ possesses the minimal value. The complementary loop (blocks 5, 4, 2, 1, 3) serves both for monitoring and for corrective actions u and u^* in the case of disruptions.

The main task of the planning block is processing input parameters and the ASC building according to these parameters through the necessary influences $\vec{U}(t)$. The main task of the measuring block is monitoring the actual parameters of the ASC operation and their comparison with the planned ones. In the case of deviations from the plan, the control block is activated. The control block serves for the elaboration of the compensating signals (u, u^*) on the basis of actual control data (z_j). The compensating signals can be directed to the functions, organization, parameters, and input goals vector of the ASC (e.g., rush orders, resource reallocation, operative outsourcing, setting new start and end points of operations, change of input goal parameters, etc.).

The above-described schema is meant for a whole planning procedure. Let us consider in detail the planning procedure for one customer order. The ASC planning cycle is presented in Figure 4.

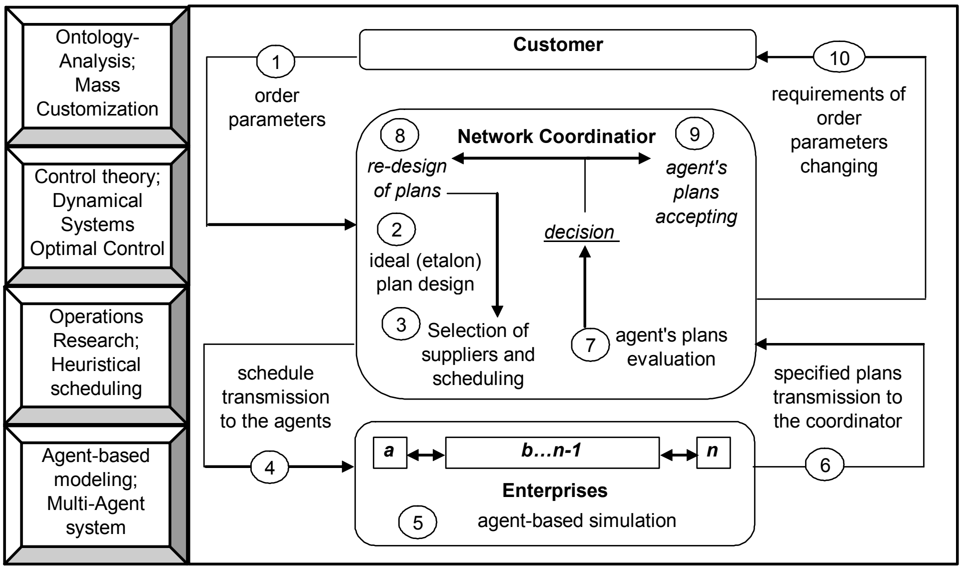


Figure 4. ASC planning conceptual model

The ASC planning problem consists of determining a pool of currently available partners in accordance with the technological details of the product (1), synthesis and evaluation of alternative SC structures from a pool of selected executors according to the various project stages, as well as the selection and scheduling of the configured supply chain (2, 3). The ASC planning is performed as an iterative process of matching the interests of the network coordinator and enterprises (4–9). In some cases, such balancing is impossible and changing customer requirements is needed (10).

For the generation of optimal plans, methods of control theory, in particular dynamical systems optimization, are used. In real-world settings, the selection of suppliers and scheduling must be performed under time pressure. That is why we use heuristics to obtain timely satisfactory results. After that, the communication stage starts. The agents evaluate the proposals of the coordinator and generate their own propositions, which can either be accepted by the coordinator (in comparison with the ideal and heuristics plans) or rescheduled for further balancing.

7. Mathematical model of the ASC planning and operations

In this section, we introduce mathematics to the above-presented conceptual model. We try to avoid too complex mathematics in the paper and will introduce mathematical symbols where this is absolutely necessary only. We consider step by step the four main stages: ASC planning, ASC analysis, ASC monitoring, and ASC reconfiguration. We also show how to interconnect planning and operational models.

6.1. Planning

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).

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

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

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:

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

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

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

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

$$S_{\delta}\subseteq X_{1}^{t}\times X_{2}^{t}\times X_{3}^{t}\times X_{4}^{t}\times X_{5}^{t}\times X_{6}^{t},\quad \delta=1,\ldots,K_{\Delta} \qquad (4)$$

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

$$S=\{S_{\delta}\}=\{S_1,\ldots,S_{K_{\Delta}}\} \qquad (5)$$

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

$$\Pi_{<\delta,\delta'>}^{t}:S_{\delta}\to S_{\delta'} \qquad (6)$$

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

Now, the problem of ASC with structure dynamics considerations can be regarded as a selection of multi-structural macro-states $S_{\delta}^{*}\in\{S_1, S_2,\ldots, S_{K_{\Delta}}\}$ 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.

The general model construction of the ASC planning is presented in (7). The goal is to find such $<U^t_*,\ S^{*t_f}_\delta>$ at the following constraints.

$$J_\theta\left(X^t_\chi, \Gamma^t_\chi, Z^t_\chi, F^t_{<\chi,\chi'>}, \Pi^t_{<\tilde{\delta},\tilde{\tilde{\delta}}>}, t \in (t_0, t_f]\right) \rightarrow \underset{<U^t, S^{*t_f}_\delta > \in \Delta_g}{extr},$$

$$\Delta_g = \left\{ <U^t, S^{t_f}_\delta > \middle| R_\beta\left(X^t_\chi, \Gamma^t_\chi, Z^t_\chi, F^t_{<\chi,\chi'>}, \Pi^t_{<\tilde{\delta},\tilde{\tilde{\delta}}>}\right) \le \tilde{R}_g; U^t = \Pi^{t_1}_{<\delta_1,\delta_2>} \circ \Pi^{t_2}_{<\delta_2,\delta_3>} \circ \Pi^{t_2}_{<\tilde{\delta},\tilde{\tilde{\delta}}>}; \beta \in \mathbf{B} \right\}, \quad (7)$$

where U^t are control actions for synthesis, J_θ are supply chain goals (costs, service level, etc.), $\theta \in \Theta = \{1,\ldots,l\}$ is a set of goal numbers; Δ_g is a set of dynamic alternatives of supply chains; **B** is a set of business processes numbers; $\tilde{R}_g$ are parameters of production orders; $T = (t_0, t_f]$ are interval of time for synthesis. Other symbols were explained above.

In the result, the ASC is planned (suppliers are selected for each operation and the supply chains are scheduled). The dynamics of the plan execution is presented as a *dynamic alternative multi-graph* to relate the above-named sets and structures. The DAMG is characterized by *macro-structural macro states*. The DAMG and the MSMS are developed to answer multi-structural design and structure dynamics in ASC and to link planning and execution models taking into account the structure dynamics.

6.2. Matching planning and operational models

The next step is to prove the fit of the SC plans to the execution environment. For this stage, a set of interlinked dynamic models was elaborated. We will not go into the details of these models under the terms of specific mathematics. The 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 functors' application (Sokolov and Yusupov, 2004). An example of how to use the multiple-model complexes applied to the integration of static and dynamic models has been presented in (Ivanov, 2009). The problem of ASC analysis and synthesis is mostly formalized using either graph (network) models or models of linear and integral programming. As a rule, the problem of analysing and synthesizing programmes for supply chain execution is formalized with the help of dynamic models. However, the problems of coordination and consistency of the results remain open. To obtain a constructive solution to these problems, we propose to use a functorial transition from the category of digraphs that specifies the models of operations' execution, in the category of dynamic models, which describes the 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, called the adjacency morphism.

The simplified mathematical model of the above-described transition can be presented as follows:

$$\Psi = \left\{ \begin{array}{l} t \in (t_0, t_f] = T;\ a'_{vj}(t_0) = 0;\ a'_{vj}(t_f) = a_{vj}; \\ \mathbf{u} \mid a'_{vj} = \sum_{j=1}^{f} u_{ij}; \sum_{i=1}^{n} u_{ij}(t) \le 1; \sum_{j=1}^{l} u_{ij} \le 1; u_{ij}(t) \in \{0,1\}; \\ \sum_{j=1}^{l} u_{ij} \left[\sum_{\varepsilon \in \Gamma_{1i}^{-}} (a_{\varepsilon} - a'_{\varepsilon}(t)) + \prod_{\varphi \in \Gamma_{i2}^{-}} (a_{\varphi} - a'_{\varphi}(t)) \right] = 0; i = 1,\dots,n;\ j = 1,\dots,l \end{array} \right\} \tag{8}$$

where variable $a'_{vj}(t)$ reflects the execution of the operation j of the v - customer order at the instant of time t; a_{vj} is the planned operation execution; $u_{ij}(t)$ is the adjustment action; $\varepsilon \in \Gamma_{1i}^{-}$, $\kappa \in \Gamma_{2i}^{-}$ sets of operations, which follow or go ahead of the operation E_{vj}.

The investigations have shown that, in the framework of the considered polymodel description, not only functionality conditions are held, but also the conditions of the general position of the adjacency mapping (Sokolov and Yusupov, 2004).

6.3. Monitoring

The formal description of the supply chain execution is based on the mathematical structure that determines the following model of the supply chain dynamics:

$$\boldsymbol{x}(t) = \varphi(\boldsymbol{x}(t), \boldsymbol{u}_{\text{пр}}(t), \boldsymbol{v}(\boldsymbol{x}(t),t), \xi(t), \beta, t), \tag{9}$$

$$\boldsymbol{y}(t) = \psi(\boldsymbol{x}(t), \boldsymbol{u}_{\text{пр}}(t), \boldsymbol{v}(\boldsymbol{x}(t),t), \xi(t), \beta, t), \tag{10}$$

$$\boldsymbol{u}(t) \in Q(\boldsymbol{x}(t),t), \quad (11)$$

$$\boldsymbol{v}(\boldsymbol{x}(t),t) \in V(\boldsymbol{x}(t),t), \quad (12)$$

$$\xi(t) \in \Xi(\boldsymbol{x}(t),t), \quad (13)$$

$$\boldsymbol{x}(t) \in \widetilde{X}(t), \quad (14)$$

$$\beta \in \mathbf{B}, \quad (15)$$

where $\boldsymbol{x}(t)$, $\boldsymbol{y}(t)$ – general vectors of the ASC macro-structural macro-states and outputs, accordingly; $\boldsymbol{u}(t)$, $\boldsymbol{v}(\boldsymbol{x}(t),t)$ – general vectors of the supply chain execution plans and control at the execution stage (plans under disturbances); $\xi(t)$ – vector of disturbances, which may be either goal-oriented or not; β – vector of SC structure parameters that determine SC configuration at the moment $t \in (T_0, T_f]$; T_0, T_f – initial and final moments of the time period for the SC planning, accordingly; $Q(\boldsymbol{x}(t),t)$, $V(\boldsymbol{x}(t),t)$, $\Xi(\boldsymbol{x}(t),t)$ – given areas of admissible management actions, online managing actions, and disturbances accordingly; $\widetilde{X}(t)$ – area of admissible current magnitudes of the vector of SC dynamics; $\mathbf{B}$ – admissible area of structure parameters' deviations; φ, ψ – given transition and output functions that generally may be described analytically (with logic-algebraical, logic-linguistical, and classical mathematical structures) and algorithmically. A combined variant is also possible.

In our approach, the ASC monitoring is based on the monitoring of macro-structural states. The particular feature of the SC monitoring in the terms of macro-states is that, at each monitoring stage, the parameters controlled are extracted from the parameter vector of the DAMG. The extracting rules depend on the management goals at the stage monitored. This makes it possible to consider all the parameters of supply chain execution described as the DAMG, and on the other hand to extract the necessary parameters to be controlled in a current execution situation. The models of monitoring have been elaborated, and will be presented in detail in one of our future papers. The other particular feature of the SC monitoring is the analysis of the supply chain *stability.* Based on the stability analysis, different situations and disturbances will be corresponded to certain adjustment adaptation steps. These adaptation steps may range from operations adaptation, plan adaptation, configuration adaptation up to supply chain strategy adaptation.

6.4. Reconfiguration

Figure 5 presents the dynamics of the ASC execution in the case of deviations.

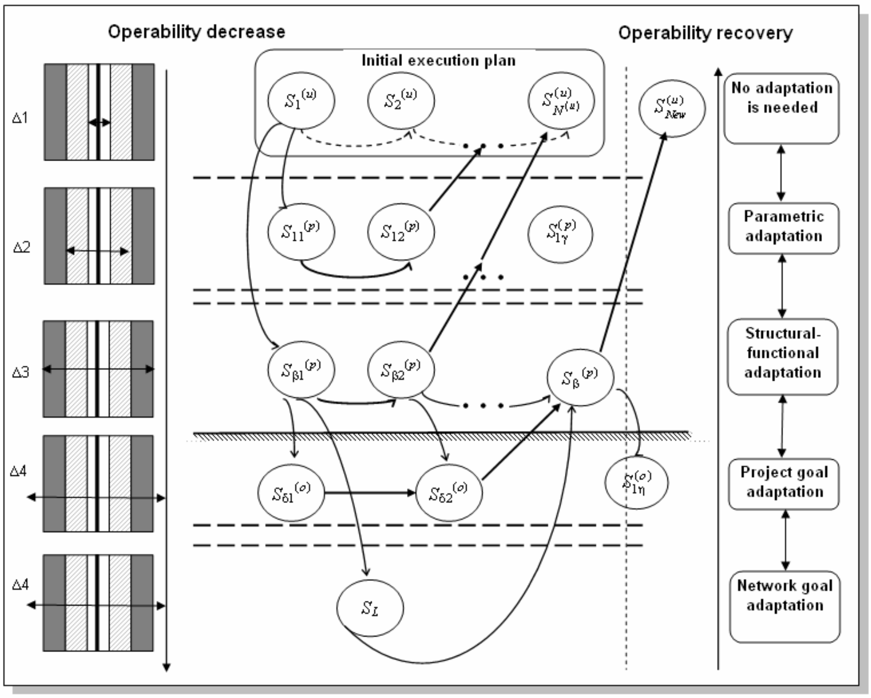


Figure 5. Dynamics of the ASC execution

Figure 5 depicts various variants of system behaviour change in the case of any perturbation impacts to the system state $S_1^{(u)}$ of the initial execution plan. The perturbation impacts may cause various execution parameter deviations $\Delta\ p_i$ and operability decrease regarding the final goals $J\ (t=end) = \{J_{1\ldots\ldots}, J_c\}$. To match the system stability analysis and recover the supply chain operability, we elaborated a concept of the complex SC adaptation, which is built as a five-level structure. Each adaptation level characterizes a certain control loop in accordance with oscillations and deviations and corresponds to certain management actions.

The schema of the SC adaptation contains the following steps: interactions between the SC coordinator (i.e., a 4PL provider) and the agents (new SC execution plans generated by the network coordinator are adjusted and specified by the agents' interactions) → decision-making about the SC reconfiguration (in this particular case of the parametrical adaptation – a rush order) → generation of a new SC execution plan. This case illustrated a so-called reactive adaptation (reaction of any deviations appearing at any SC state while operating this state). Another situation is a preventive adaptation or adjustment, which is undertaken in the case of any deviations appearing at any SC states in the future while operating other SC states). The schema of the SC adaptation will be the same with the only exception that the backwards principle of adaptation will be used. Mathematical algorithms of the parametrical and structural SC adaptation are elaborated (Ivanov et al., 2008).

7. Validation and main results

7.1. Experimental environment

The proposed framework has been validated in a special software environment, which contains a simulation and optimization "engine" of ASC planning, a Web platform, an ERP system, and a supply chain monitor. The simulation and optimization "engine" for model validation is composed of software SNDC (Supply Networks Dynamic Control) to design and to plan supply chains in accordance with the multiple-structure approach and structure dynamics considerations and a simulation tool, AnyLogic, which combines heuristics, optimization, agents, and system dynamics.

Figure 6 shows the general experimental environment of the elaborated "engine" in the settings of the whole informational infrastructure.

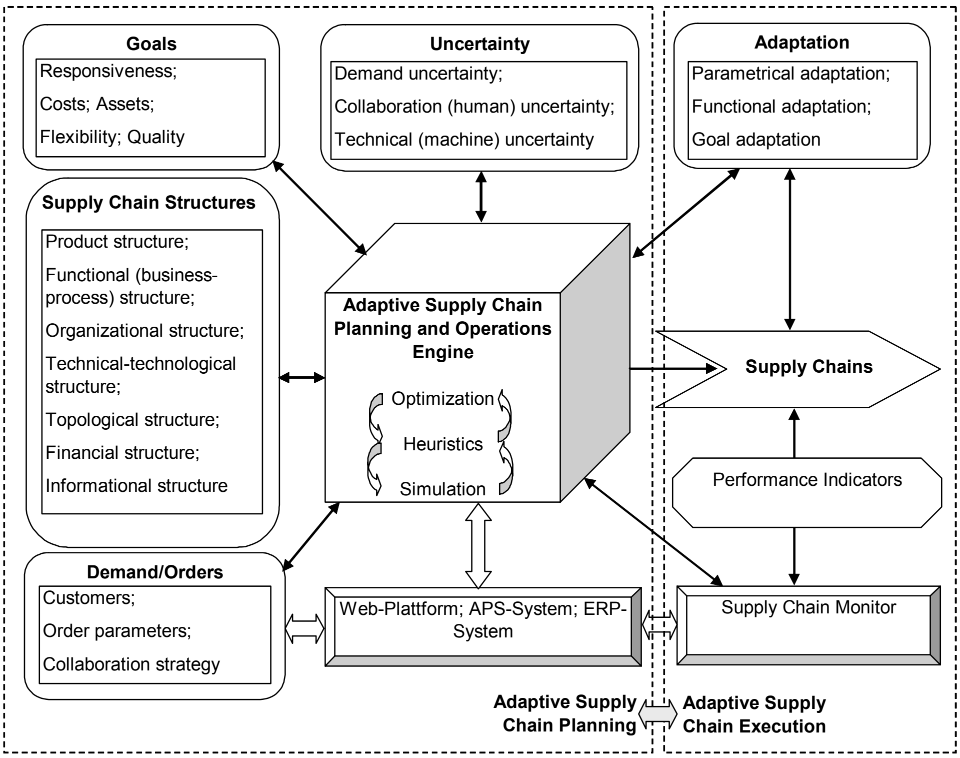


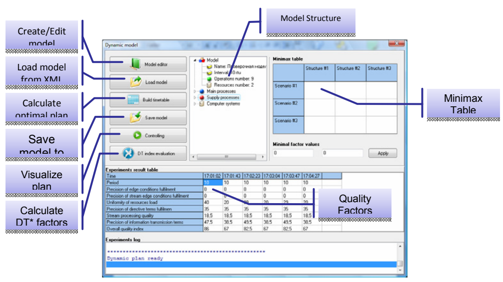
Figure 6. Adaptive supply chain planning and operations engine

The ASC planning and operations are based on the simultaneous consideration of different structures in their interrelations and dynamics. The set of supply chain multi-structural alternatives is formed not on the basis of concrete values of structure-relevant parameters, but first upon data structures. Then, we specify one or several structures with deterministic or stochastic parameters as well as select solution procedures (optimization or heuristics) for partial planning sub-problems (i.e., demand forecasting, production planning, procurement planning etc.). Therefore, a number of supply chain multi-structural alternatives are identified, evaluated in regard to the goal criteria (costs, supply cycle time), and stability, and the best one is selected. Because of the limited size of the paper, we will consider the experimental procedure without integrating data flows from/to the ERP, Web, and supply chain monitor.

7.2. Experimental procedure

Let us discuss an experimental procedure for the validation of the model. We consider the following case. A supply chain consists of a structural stable part of operations (the link "operation–supplier" is predetermined) and a structural adaptive part of operations (the link "operation–supplier" is composed of a number of alternatives). There are 18 enterprises described through their core competencies, 9 customer orders to be planned, and 8 technological blocks for each of the orders. The model works simultaneously as (i) a multi-structural planning of a supply chain, consisting of suppliers, manufacturers, careers, distribution centres, and retailers; (ii) proof of the fit of a supply chain plan to uncertainty; and (iii) the scheduling of supply chains within the different ASC alternatives and execution scenarios. In Table 1, the validation procedure is presented step by step.

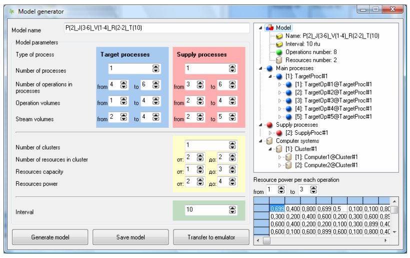
Table 1 – Validation procedure

Validation step	**Software interfaces**
Step 1. Initial data (see also Fig. 6). 1. Set of enterprises. 2. Set of technological infrastructure (machines, information systems, etc.). 3. Set of technological operations. 4. Set of management operations. 5. Set of core competencies (subject to sets 1 and 4/5), which is characterized by hard factors (costs, inventory,	

and capacities) and soft factors (supplier reliability, trust, etc.).

6. Set of products with bill of materials and SKU (stock keeping units).
7. Set of customers.
8. Set of orders that are characterized by delivery date, prices, and volumes.
9. Set of uncertainties (demand fluctuations, machine failure, and human errors).
10. Set of collaboration (enterprise preferences).

Automatic



Applied in research mode:
Automatic model creation by random-generating its parameters according to specified bounds.

Step 2. Plan synthesis (s. also Fig. 6)

Heuristic plan synthesis.

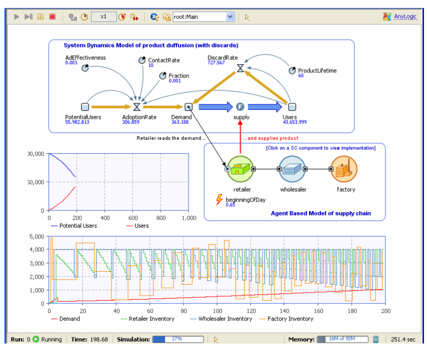
At this stage, a heuristic solution (e.g., FIFO or Equal Charge) is generated.

Optimizing heuristic plan

At this stage, the heuristic plan is being optimized. In the right column, two plans – heuristic (on the top) and optimized (below) – can be seen. The solution to this multi-criteria dynamic problem is based on a multiple-step simultaneous solution of partial problems for different structures, e.g., by means of mixed-integer programming and transport optimization.

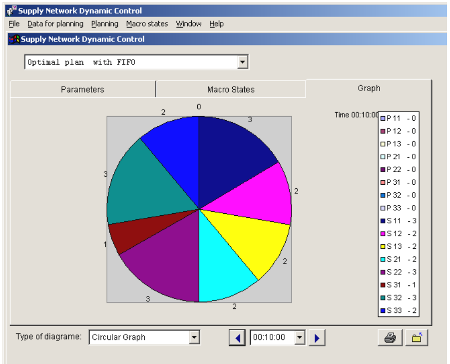
Agent-based plan modification

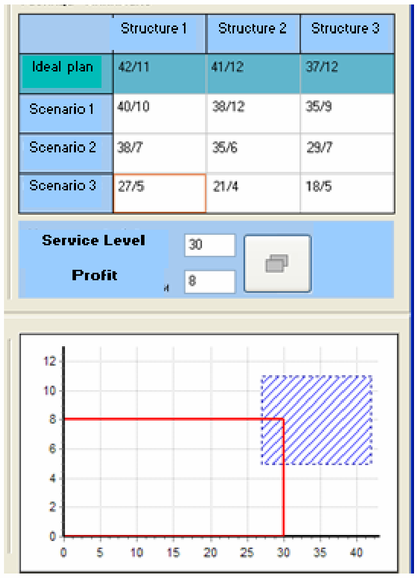
Once an optimal ASC plan is calculated (by means of a linear dynamic system), agent-based modelling is applied to take into account various uncertainties (environmental, such as demand, uncertainty of human behaviour etc.) to make the model reality-relevant. So, we can talk about the optimization-supported heuristics and simulation. The seeking for the optimality is enhanced by simultaneous optimizing and balancing interrelated structures.



Step 3. Plan analysis and real-time monitoring

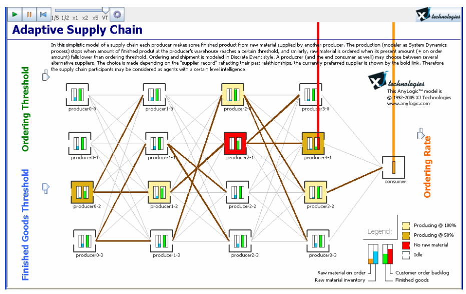
The multi-structural macro-states make it possible to implement the above-described structure dynamics considerations which makes it possible to evaluate the ASC dynamics (capabilities, bottlenecks etc.) in the case of different demands, production programmes, coordination strategies, suppliers, etc. The multi-structural ASC treatment lets managers simulate the order execution dynamics complex in different structures as well as investigate the supply chain behaviour in the case of disruptions, determine supply chain bottlenecks, and elaborate the necessary management adjustments.





Another important aspect of plan analysis is stability analysis. Using the stability analysis results, a decision-maker can estimate the degree of stability of alternative supply chain plans.

The implementation of the model in the tool AnyLogic allows the visualization of the plan analysis and real-time supply chain monitoring.



Monitoring is performed in regard to the final supply chain goals (service level and supply chain costs) and operative supply chain performance measures (e.g., delivery performance DR1, supply chain response time FR1, and inventory days of supply AT2), according to the Supply Chain Operations Reference Model (SCOR).

Step 4. Plan reconfiguration (s. Sections 7.4 and 7.5).

Based on the monitoring results and stability analysis, alerting is activated. The plan adaptation is based on changes of planning model parameters. Adaptation "to the past" is based on previous plan execution analysis and adaptation "to the future" is based on simulating different disturbance scenarios and stability analysis. In regard to what kind of deviation nature (s. Section 7.5) occurred, reconfiguration measures are indicated. The following steps are similar to steps 2–3 in this Table.

7.3. Findings discussion

The novelty of this research consists of advancing the supply chain multi-structural treatment, introducing the structure dynamics considerations, elaborating a new conceptual model for the multi-structural adaptive supply chain planning, proposing new tools for the multi-structural SC planning – multi-structural macro-states and a dynamical alternative multi-graph, and enhancing the SCM methodological foundations by means of advancing the ASC modelling.

The paper described conceptual and mathematical models of the A-SCM from the perspectives of adaptability that provides achievement of the management goals with a sufficient degree of stability and crisis-resistance instead of the "ideal" optimal plans which fail in real perturbed execution environment. The supply chain optimization is considered from the perspectives of the throughout value chain consideration. Not only this adaptive and dynamic understanding of supply chains, but also the solution methods are new in the SCM domain. The proposed mathematical approach is based on the combined application of control theory (to implement the dynamics and feedbacks), operations research (to optimize partial models' parts), and agent-oriented modeling (to implement the self-interest and autonomous behavior of supply chains elements). These multiple-model complexes allow the statement and the solution of complex problems which reflect the real-world demands. Based on dynamical alternative multi-graphs and multi-structural macro-states, the supply chains are modeled as multi-structural systems and as a function of both states and structures.

Finally, let us discuss the limitations of the proposed framework. By now, this concept has been applied to the special machinery building and textile branches. In both cases, there is the possibility to attaching alternative suppliers to a number of operations in the value value-adding process. For example, this could not be implemented in the automotive sector because of the strict quality policies of OEMs. So, the proposed concept can be applied in two cases: (i) for unique products (as in a special machinery industry) or for products without strict technical quality policies (i.e., the textile branch). Another very important point is the trust and collaboration in the network. Before automation, a huge amount of organizational work should be done carried out to convince the OEMs and suppliers to collaborate within a common informational space, share the data, actualize the data, and ensure financial trust. While automating, this it is important to elaborate and to maintain a throughout product and process technological documentation and classification. And last, but not least – the firms themselves should perceive the necessity for such collaboration. Especially small and medium enterprises can be interested in such an approach.

There are also some technical complications. 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, practice-relevant complex problem formulations and decision-making support as well as increasing supply chain planning and replanning efficiency will repay these efforts.

Conclusions

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. Structures and decisions on different stages of supply chain execution change in their dynamics. In other words, supply chain structure dynamics are constantly encountered. The main application areas of the proposed framework are the adaptive tactical and operative planning of supply chains. The results show that multi-structural and inter-disciplinary treatment of supply chain planning allows comprehensive and realistic planning problem formulation and solution. The proposed multi-structural treatment also allows the establishment of links to comprehensive uncertainty analysis and especially to supply chain execution and reconfiguration. The proposed methodology contributes to advancing theoretical foundations of supply chain management, supports managerial insight into supply chains at the tactical and operational levels, and serves to enhance decision-making in the planning of production and logistics networks. In future research, we will focus on further investigation into 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. In general for future research, we are going to investigate in-depth some referenced SCM problems with the help of the control theory. Furthermore, a promising area of applying the control theory is supply chain monitoring and event management.

Acknowledgments

The research described in this paper is partially supported by grants from Saint- Petersburg Government (grants 36-350-II/1-04, 36-353-II/1-04), the Russian Foundation for Basic Research (grants 07-07-00169, 06-07-89242, 08-08-0040305-08-18111), and the German Research Foundation (CRC 457 Non-hierarchical regional industrial networks, C2/Coordination, and PAK 196 Competence Cell-based Production Networks, P6/Automated Running of Production Networks).

References

Aragwal A, Shankar R, Tiwari MK. Modeling the metrics of lean, agile and leagile supply chain: an ANP-based approach. European Journal of Operational Research 2006; 173(1); 211-225.

Barbasi AL. Network theory—the emergence of the creative enterprise. Science 2005; 308; 639–641.

Beamon BM. Supply Chain Design and Analysis: Models and Methods. International Journal of Production Economics 1998; 55(3); 281-294.

Camarinha-Matos LM, Afsarmanesh H, Ortiz A. (Eds.). Collaborative Networks and Their Breeding Environments. Springer: Boston et al.; 2005.

Chauhan SS, Proth JM, Sarmiento AM, Nagi R. Opportunistic supply chain formation from qualified partners for a new market demand. Journal of the Operational Research Society 2006; 57; 1089 – 1099.

Christopher M, Towill DR. An integrated model for the design of agile supply chains. International Journal of Physical distribution and Operations Management 2001; 31; 235–244.

Crispim JA, de Sousa JP. Multi criteria partner selection in virtual enterprises. In: Camarinha-Matos et al. (Eds.), Establishing the foundation of collaborative networks. Springer: Boston; 2007. p. 197-206.

Disney SM, Towill DR. A discrete linear control theory model to determine the dynamic stability of Vendor Managed Inventory supply chains. International Journal of Production Research 2002; 40(1); 179–204.

Fischer M, Jaehn H, Teich T. Optimizing the selection of partners in production networks. Robotics and Computer-Integrated Manufacturing 2004; 20; 593–601.

Goranson HT. The Agile Virtual Enterprise – Cases, Metric, Tools. Quorum Books: CITY; 1999.

Gunasekaran, A, Ngai, N.W.T. Modeling and analysis of build-to-order supply chains. European Journal of Operational Research 2008; in press, available on-line 27 March 2008.

Huang G, Zhang Y, Liang L. Towards integrated optimal configuration of platform products, manufacturing processes, and supply chains. Journal of Operations Management 2005; 23; 267-290.

Ijioui R, Emmerich H, Ceyp M (Eds.). Supply Chain Event Management Konzepte, Prozesse, Erfolgsfaktoren und Praxisbeispiele. Springer: Berlin; 2007.

Ip WH, Yung KL, Wang D. A branch and bound algorithm for subcontractor selection in agile manufacturing environment. International Journal of Production Economics 2004; 87; 195–205.

Ivanov D. DIMA – A Research Methodology for Comprehensive Multi-Disciplinary Modelling of Production and Logistics Networks. International Journal of Production Research 2009; 47(5); 1153-1173.

Ivanov D, Kaeschel J, Sokolov B. Structure dynamics control-based framework for adaptive reconfiguration of collaborative enterprise networks. International Journal of Manufacturing Technology and Management 2008; in press.

Ivanov D, Kaeschel J, Sokolov B. Integrated modeling of agile enterprise networks. International Journal of Agile Systems and Management 2007; 2(1); 23-49.

Ivanov D, Arkhipov A, Sokolov B. Intelligent planning and control of manufacturing supply chains in virtual enterprises. International Journal of Manufacturing Technology and Management 2007; 11(2); 209-227.

Ivanov D 2007. MARINA: Method of analysis, reconfiguration, and integrated network adjustment. In: Proceedings of the 4. IFAC International Conference on Management and Control in Production and Logistics (MCPL2007); 2007. p. 408-414.

Ivanov D. DIMA – Decentralized Integrated Modeling Approach. Ein Ansatz zur interdisziplinären Modellierung von Produktions- und Logistiknetzwerken. Verlag der GUC: Chemnitz; 2006.

Kallrath J. Combined strategic and operational planning – an MILP success story in chemnical industry. OR Spectrum 2002; 24; 315-341.

Kim DH 2007. Towards an architecture modeling language for networked organizations. In: Camarinha-Matos L.. et al. (Eds.). Establishing the foundation of collaborative networks. Springer: Boston. 2007. p. 309-316.

Ko CS, Kim T, Hwang H. External partner selection using tabu search heuristics in distributed manufacturing. International Journal of Production Research 2001; 39(17); 3959–74.

Kopfer H, Schoenberger J 2006. Die Lösung von Optimierungsproblemen mit mehrschichtigen Zielsetzungen durch die Adaption von selbststeuernden Planungsagenten. In: Ivanov D. et al. (Eds.) Logistics, Supply Chain Management, and Information Systems. SPbGPU: Saint Petersburg; 2006. p. 93-102.

Kuehnle H. A system of models contribution to production network (PN) theory. Journal of Intelligent Manufacturing 2007; 18(5); 543-551.

Mason-Jones R, Naylor B, Towill DR. Engineering the leagile supply chain. International Journal of Agile Management Systems 2000; 2(1); 54–61.

Mikhailov L. Fuzzy analytical approach to partnership selection in formation of virtual enterprises.Omega 2002; 30; 393–401.

Nilsson F, Darley V. On complex adaptive systems and agent-based modeling for improving decision-making in manufacturing and logistics settings. Int. Journal of Operations and Production Management 2006; 26(12); 1351-1373.

Ross A. Creating agile supply chain. IEEE Manufacturing Engineer 2004; 82(6); 18–21.

Santoso T, Ahmed S, Goetschalckx M. and Shapiro A. A stochastic programming approach for supply network design under uncertainty. European Journal of Operational Research 2005, 167(1); 96-115.

Sarkis J., Talluri S., Gunasekaran A. A strategic model for agile virtual enterprise partner selection. International Journal of Operations & Production Management 2007; 27(11); 1213-1234.

Sokolov BV, Yusupov RM. Conceptual foundations of quality estimation and analysis for models and multiple-model systems. International Journal of Computer and System Sciences 2004; 6; 5–16.

Spitter JM, Hurkens CAJ, de Kok AG, Lenstra JK, Negenman EG. Linear programming models with planned lead times for supply chain operations. European Journal of Operational Research 2005, 163(3); 706-720.

Stadtler H. Supply chain management and advanced planning – basic, overview and challenges. European Journal of Operational Research 2005, 163(3); 575-588.

Stock G, Greis N, Kasarda J. Enterprise logistics and supply chain structure: the role of fit. Journal of Operations Management 2000; 18; 531-547.

Sucky E. Coordinated order and production policies in supply chains. OR Spectrum 2004; 26; 493-520.

Swaminathan JM, Smith SF, Sadeh NM. Modeling supply chain dynamics: a multiagent approach. Decision Science 1998; 29 (3); 607–632.

Teich T. Extended Value Chain Management (EVCM). GUC-Verlag: Chemnitz; 2003.

Tolkacheva V, Ivanov D, Arkhipov A 2007. Assessment of Structural Stability of Collaborative Networks. In: Establishing the Foundation of Collaborative Networks, edited by L.M. Camarinha-Matos, H. Afsarmanesh, P. Novais, C. Analide. Springer: Boston. 2007. p. 75-82.

Vanderhaeghen D, Loos P. Distributed model management platform for cross-enterprise business process management in virtual enterprise networks. Journal of Intelligent Manufacturing; 2007, in print.

Wu N, Mao N, Qian Y. An approach to partner selection in agile manufacturing. Journal of Intelligent Manufacturing 1999; 10(6); 519–529.

Yusuf MA, Gunasekaran A, Adeleye EO, Sivayoganathan K. Agile supply chain capabilities. Determinants of competitive objectives. European Journal of Operational Research 2004, 159(2); 379-392.

Zschorn L. An extended model of ATP to increase flexibility of delivery. International Journal of Computer Integrated Manufacturing 2006; 19 (5); 434-442.