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Review Article

A framework for aligning planning decisions on supply chain strategy, design, tactics, and operations

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Abstract. Over the last decade, a wealth of valuable approaches to supply chain strategic, tactical, and operational planning has been extensively developed. However, conventionally the planning decisions at each of these levels have been considered in isolation from the other levels. Moreover, decisions on supply chain strategy, design, tactics, and operations are interlinked and dispersed over different supply chain structures (functional, organizational, informational, financial, etc.).

This study develops a framework to increase the efficiency, consistency, implacability, and sustainability of decisions on how to design, plan, and run supply chains. In this paper, we propose to consider the planning as an adaptive process that encapsulates the planning decisions to be interrelated at all the decision-making levels. We describe a conceptual model interlinking the supply chain strategy, design, planning, and operations on adaptation principles. Subsequently, we present a mathematical modelling complex and its realization in a software environment.

This study contributes to developing methodical basics and practical tools to transit from simple open time slots incremental planning to dynamic, feedback-based adaptive supply chain planning. The elaborated framework serves to increase the efficiency, consistency, implacability, and sustainability of decisions on supply chain strategy, design, tactics, and operations. The decisions' alignment can help to increase organizations' wealth by producing demand-corresponding products in the most cost-effective manner through increasing agility, responsiveness, reaction speed to market changes, and continuous comprehensive improvements/adaptation of supply chains.

Keywords: supply chain management, decision-making, planning, adaptation

AMS Subject Classification: 90B50; 49L20; 93D25.

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D. Ivanov. A framework for aligning (re)- planning decisions on supply chain strategy, design, tactics, and operations

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Review Article

A framework for aligning (re)-planning decisions on supply chain strategy, design, tactics, and operations

1 Introduction

The term “supply chain management” (SCM) was coined in the 1990s (Lambert and Cooper 2000, Bowersox *et al.* 2002). Presently, SCM is considered as the most popular strategy for improving organizational competitiveness in the twenty-first century. SCM studies the resources of enterprises and human decisions in relation to cross-enterprise collaboration processes to transform and use these resources in the most rational way along the entire value chain, from customers up to raw material suppliers, based on functional and structural integration, cooperation, and coordination throughout.

A supply chain is a networked organization wherein a number of various enterprises (suppliers, manufacturers, distributors, and retailers)

- (i) collaborate (cooperate and coordinate) along the entire value chain to: acquire raw materials, convert these raw materials into specified final products, and deliver these final products to customers;
- (ii) apply all modern concepts and technologies to make supply chains agile, responsive, flexible, robust, sustainable, cost-effective, and competitive in order to increase customer satisfaction and decrease costs, resulting in increasing supply chain profitability.

Planning of supply chains is composed of setting management goals and defining measures for their achievement (Kreipl and Pinedo 2004). On the basis of the goals of the superordinated level of a supply chain, plans of a current level are formed. E.g., strategic goals can be referred to the service level and costs. The measures are in this case the realization of customers' orders. To fulfil these orders, schedules are to be constructed. Over the last decade, a wealth of valuable approaches to supply chain strategic, tactical and operational planning has been extensively developed (Simchi-Levi *et al.* 2004; de Kok and Graves 2004; Chopra and Meindl 2007). However, conventionally the planning decisions at each of these levels have been considered in isolation from the other levels. In practice, the interrelation of these three management levels is very important. Moreover, decisions on supply chain strategy, design, planning, and operations are interlinked and dispersed over different supply chain structures (functional, organizational, informational, financial, etc.). The efficiency and applicability of the decisions decrease if decision-supporting models are considered in isolation for different supply chain managerial levels and structures (Ivanov *et al.* 2009).

This study develops a framework to increase the efficiency, consistency, implacability, and sustainability of decisions on how to design, plan, and run supply chains. In this paper, we propose to consider planning as an adaptive process that encapsulates the planning and control decisions to be interrelated at all the decision-making levels. As such, the contribution of this study lies in the development of methodical basics and practical tools to transit from simple open time slots incremental planning to dynamic, feedback-based adaptive supply chain planning.

The rest of this paper is organized as follows. In Section 2, we analyse the related literature on supply chain planning from different perspectives. Section 3 describes the challenges and the methodical basics of aligning decisions on supply chain strategy, design, tactics, and operations. In Section 4, a conceptual model interlink-

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ing the supply chain strategy, design, planning, and operations to the adaptation principles is presented. In Section 5, we elaborate a supply chain (re)synthesis model to establish feedback between supply chain operations, plans, and design in the direct and the reverse way. In Section 6, we present an elaborated software environment. We conclude the paper by summarizing the main features of the elaborated framework and discussions on future research.

2 State of the art

The issues of aligning the supply chain strategy, design, tactics, and operations have been highlighted in literature episodically. (Sabri and Beamon 2000) developed an integrated multi-objective supply chain model for use in simultaneous strategic and operational SC planning. Multi-objective decision analysis is adopted to allow the use of a performance measurement system that includes cost, customer service levels, and flexibility (volume or delivery). This model incorporates production, delivery, and demand uncertainty, and provides a multi-objective performance vector for the entire SC. Harrison (2005) and Chopra and Meindl (2007) emphasize that supply chain design decisions are closely linked to the corporate and supply chain strategy. Chen (2007) presents a survey on integrated models of supply chain design. He pays particular attention to the strategic and tactical levels, considering three types of integrated problem: location-inventory, inventory-routing, and location-routing. Guille'n *et al.* (2006) address the integrated planning/scheduling of supply chains with multi-product, multi-echelon distribution networks, taking into account financial management issues. In order to tackle this problem, a mathematical formulation is derived, combining a scheduling/planning model with a cash flow and budgeting formulation. They also enhance the model by considering not only the insertion of financial aspects within an supply chain planning formulation, but also the choice of a financial performance indicator, i.e. the change in equity, as the objective to be optimized in the integrated model (Guille'n *et al.* 2007). Moon *et al.* (2007) deal with the integration of process planning and scheduling. They formulate a mixed integer programming (MIP) model to solve this problem of integration. This model considers alternative resources: sequences and precedence constraints, and is solved with an evolutionary search approach. (Ivanov *et al.*, 2009) presented a conceptual framework and a mathematical model of multi-structural supply chain planning. Ivanov (2009) developed a multi-disciplinary approach for integrated modelling supply chains. (Chandra and Grabis, 2007) reported on the simulation tool Flextronics which is used to transform supply chains in accordance with the changes in a market environment.

Within SCM, two problem classes can be distinguished: cooperation (vendor selection and outsourcing) and coordination (information exchange). Cooperation decisions in SCM can be divided into strategic (supply chain design), tactics (planning), and operations. As the term implies, strategic decisions are typically made over a longer time horizon. Supply chain design deals with strategic issues of distribution networks and supplier/customer integration (Cohen and Lee 1988; Beamon 1999; Tayur *et al.* 1999; de Kok and Graves 2004; Simchi-Levi *et al.* 2004). Supply chain design is a critical source of competitive advantage and consists of supply chain *structuring* in accordance with the given competitive strategy, supply chain strategy, product programme, coordination strategy, distribution strategy, and financial plans (Chopra and Meindl 2007) as well as with demand and supply uncertainty (Lee *et al.* 1997; Santoso *et al.* 2005). Conventionally, the supply chain design's central question is to determine which suppliers, parts, processes, and transportation modes to select at each stage in the supply chain. The literature on SCM indicates a need in multi-structural supply chain treatment to take into account the product, business processes, technological, organizational, technical, topological, informational, and financial structures (Lambert and Cooper 2000; Bowersox *et al.* 2002).

Supply chain planning considers a shorter time horizon (months, weeks) and deals with demand forecasting, master production planning, supply planning, replenishment planning, inventory management, and transport

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planning. Operational decisions are short-term, and focus on activities on a day-to-day basis. While the supply chain is running, problems of operative order planning, supply chain monitoring, and reconfiguration in the case of operative disruptions (i.e., machine failures, human errors, information systems failure, cash-flow disruption, or simply catastrophic events) as well as tactical/strategic changes (i.e., new products, new order penetration points, etc.) are to be solved (Graves and Willems 2005; Ijounu *et al.* 2007; Ivanov 2008).

Coordination in SCM plays a fundamental role to mitigate uncertainty (Holweg and Pil 2007) with the help of synchronizing information flows from a point-of-sale up to the raw material suppliers and material flows in the reverse way. One key problem in nearly all supply chains is the so-called bullwhip effect (Lee *et al.* 1997). Different concepts of coordination have been developed over the last two decades, such as Efficient Consumer Response, Collaborative Planning, Forecasting, and Replenishment in retail as well as Just-in-Time and Vendor Managed Inventory in industries. Enablers of the coordination are information technologies, such as Enterprise Resource Planning, Advanced Planning Systems, Electronic Data Interchange, and Radio Frequency Identification. The customer integration in supply chains has been resulted in a so called Build-to-Order SCM (Gunasekaran and Ngai 2005).

Decision-supporting methods can be divided into three primary approaches. These are: optimization, simulation, and heuristics. *Optimization* is an analysis method that determines the best possible method for a particular supply chain. Optimization methods for supply chains have been a very visible and influential topic in the field of *operations management* (Stevenson 2005). The drawback of using optimization is difficulty in developing a model that is sufficient detailed and accurate in representing complexity and uncertainty of supply chain design, while keeping the model simple enough to be solved. 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 SCM.

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 SCM, 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

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 supply chain design settings, nature based heuristics such as genetic algorithms are usually applied.

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. One promising area is the study of combining different modelling techniques (Ivanov 2009).

3 Challenges and methodical basics of conducting research into aligning decisions on supply chain strategy, design, tactics, and operations

This section discusses the challenges and develops methodological drivers to conduct research into aligning the supply chain strategy, design, planning, and operations, taking into account particular features of supply chains such as a *complex multi-structural decentralized system with active independent elements*.

3.1. Main challenges of the research into aligning the supply chain strategy, design, tactics, and operations

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Let us point out the main challenges of the research into aligning the decisions on supply chain strategy, design, planning, and operations. Firstly, a main challenge is the above-mentioned *multi-structural* nature of supply chains. Secondly, issues in SCM are fundamentally and inheritable *interdisciplinary* in nature. At different stages of the supply chain life cycle, one particular problem can be solved by means of different modelling techniques that have a certain application area and a certain solution procedure. The isolated application of only one solution method leads to a narrowing of the problem formulation, overdue constraints, and sometimes unrealistic or impracticable goals. Cross-linked SCM problems between and within the strategic, tactical, and operations levels require the combined application of various modelling techniques (optimization, statistics, heuristics, and simulation) with the help of integrating elements drawn from operations research, distributed artificial intelligence, systems science, control theory, and fuzzy logic. Thirdly, SCM is characterized by increased *uncertainty*. The uncertainty origins lie both in the environmental (demand fluctuations, machine failure, information system destruction) and human (errors, false information interpretation, and local goal-oriented behaviour) areas. There is a need for special techniques for designing robust supply chains, stability analysis of supply chains, monitoring supply chains, and reconfiguration of supply chains.

In works (Ivanov *et al.* 2009a,b; Ivanov 2009), the issues of multi-structuring and interdisciplinary and constructive ways to their decision have been extensively discussed. The methods of supply chain multi-structural modelling in terms of dynamical alternative multi-graphs and multi-structural macro-states has been developed. The basics of the supply chain multi-disciplinary treatment were developed in the DIMA (Decentralized Integrated Modelling Approach (Ivanov 2009). The main principles of the DIMA are as follows. These principles take into account the supply chain elements' *activity, multiple modelling, integration, and decentralization*. In this study, we will pay particular attention to the challenge of uncertainty and dynamics.

3.2. *Uncertainty and dynamics*

The existing planning approaches can be divided into incremental planning, which concentrates on situation predictions in terms of mathematical models, satisfactory planning, which considers supply chain reactions to external impacts, and adaptive planning, which supports supply chain interaction with the environment. In the SCM domain, the incremental planning is widespread. The shortcoming of the incremental planning is that this does not include dynamic feedback. Such an approach can be justified for such problems as those where a single schedule computation should be fulfilled. These problems may be of either a very strategic nature or a very operative nature. In the most tactical–operational problems that refer to the supply chain dynamics to be under control, the negative feedback is mandatory.

Although the feedback has been extensively investigated in the system dynamics (Sterman 2000), these models have been successfully applied only to strategic issues of network configuration and have shown many limitations with regard to the tactical and operation control levels. With regard to these two levels, the recent literature indicates an increasing renewed interest in the theoretical background of control theory (Disney *et al.* 2002; 2006; Ivanov *et al.* 2007, 2009; van Houtum *et al.* 2008). Control theory is a multi-disciplinary scientific discipline that contains powerful conceptual and constructive tools to conduct research into the dynamic problems of the flexible (re)distribution of a variable set of jobs to a variable set of resources. The closed-loop control systems are of a particular interest in these settings. One of the efficient approaches to implement control of the systems in this class is adaptive planning (Oktilev *et al.* 2006; Andreev *et al.* 2007). Adaptive planning uses not only simple open time slots (in contrast to incremental planning) but employs conflict-driven plan changes during the system execution. Adaptive planning implies problem resolution and redefinition through the learning process, rather than problem solving. Different models of supply chain adaptive behaviour have been extensive studied over the past years. (Chauchan *et al.* 2007) addressed the problem

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of short-term supply chain design using the idle capacities of qualified partners in order to seize a new market opportunity. (Hung *et al.* 2004) presented a new modelling approach for realistic supply chain simulation with regards to flexible supply chain configuration and operative decisions. (Andreev *et al.* 2007) considered adaptive planning for supply chain networks from the perspective of multi-agent approach.

4. Conceptual framework of supply chain adaptive planning and control

Supply chain strategy, design, planning, and operations are interlinked while constructing ideal supply chain states as well as while reconfiguring supply chains in relation to a current execution environment. This evidence is depicted in Figure 1.

[Insert Figure 1 about here]

In practice, partial supply chain strategy, design, planning, and operations decisions are highly interlinked. Let us consider some examples. 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' selection is linked not only to their capacities, costs etc., but also to their collaboration abilities 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 together.

Let us consider the supply chain strategy, design, tactics, and operations as a whole system in details (see Figure 2).

[Insert Figure 2 about here]

On the basis of the competitive and supply chain strategy, supply chain structures are configured. Based on demand and supply forecasts, input $\bar{U}(t)$, supply chain plans are generated within the designed structures. If concrete orders penetrate a supply chain, supply chain operations plans are generated according to the orders' parameters (price, delivery place, batch size, etc.). While running a supply chain, different disturbances can affect the supply chain and cause deviations and disruptions. Supply chain monitoring is meant for the maintenance of output parameter values $\bar{J}'(t)$ of a supply chain in accordance with the required ones of input signals $\bar{J}(t)$ from the supply chain plans, design, and strategy so that the deviation $(\bar{J}'(t) - \bar{J}(t))^2$ possesses the minimal value. The results of the supply chain monitoring are reflected in the supply chain performance block. The supply chain adaptation serves for implicating monitoring results while the supply chain is running and for corrective control actions u and u^* to supply chain operations, plans, design, and strategy. The adaptation is meant not only for processes but also for supply chain models, which should cohere with the current execution environment.

Tables 1–3 depict the interlinking of problems and data at supply chain strategic, tactical, and operational levels.

[Insert Tables 1-3 about here]

1 *D. Ivanov. A framework for aligning (re)- planning decisions on supply chain strategy, design, tactics, and*
2 *operations*

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5 Tables 1–3 provide evidence of tight interlinking supply chain strategy, design, planning, and operations. The
6 output data of one decision level/problem are the input data of another decision level/problem. Besides, the
7 tables depict the multi-structural and interdisciplinary nature of supply chains. They also provide evidence of
8 feedback between operations, planning, design, and strategy to adapt supply chains and their models to an
9 actual execution environment.

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11 Let's consider the general conceptual scheme of decision making on supply chain planning between two deci-
12 sion making levels under uncertainty (s. Figure 3).

13 [Insert Figure 3 about here]

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16 On the basis of the goals of the higher level of a supply chain, plans are formed. While supply chain function-
17 ing, the conformity of the actual course of events with the planned values is analysed. In the case of devia-
18 tions, the necessary managerial influences on the correction of processes, plans up to supply chain configura-
19 tion upgrade will be taken. The given scheme describes the basic functions of SCM in the conditions of inter-
20 action with a perturbed environment. Such a scheme can be realized on each of three levels of decision mak-
21 ing (strategic, tactical, and operative). The interrelation of these three management levels is very important,
22 since it allows us to realize the construction of realistic plans balanced with each other, and to provide feed-
23 back for the adaptation of these plans taking into account the real performance of supply chain processes.

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26 Let us consider the general loop of supply chain control decisions (s. Figure 4).

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28 [Insert Figure 4 about here]

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31 As shown in Figure 4, the supply chain functions are explicitly divided into the planning (process manage-
32 ment level) and execution stage (event management level). It is an essential point, because the process will be
33 presented as events. This will be considered further in the paper. At the planning stage, different reserves to
34 mitigate uncertainty and to ensure supply chain security are built. This results in a number of alternative sup-
35 ply chain plans with different values of economical efficiency and security indices. The planning ends with
36 the simulation of different execution scenarios for different supply chain configurations and plans with a sub-
37 sequent evaluation of these alternatives by managers according to their individual risk perceptions.

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39 After planning, the stage of supply chain operations execution follows. At the physical security level, cargo
40 movement control takes place. The data from primary control devices (e.g., radio frequency identification -
41 RFID) are transmitted, accumulated, and evaluated within the information systems level. At the interface be-
42 tween the information systems level and the event management level, based on supply chain event manage-
43 ment (SCEM) tools, supply chain monitoring and reinstating (adaptation) take place. This results in decisions
44 on supply chain processes, plans, or goal correcting, amending, or replacing on the basis of the disturbances
45 that occurred and the control actions that existed.

46
47 **Let us consider an example. As a result of the perturbation influence “Delay in delivery from the supplier”,**
48 **the supply chain can appear inefficient or in a disabled state (it is defined on the basis of the stability analy-**
49 **sis). In the case of a disabled condition, it is a question of disturbance in the performance of the supply chain**
50 **function “Start of manufacturing a product lot” owing to the absence of necessary material (a deviation in the**
51 **parameter “Start term of manufacturing a product lot”). Further, this disturbance can be classified as a failure**
52 **or deviation. In the case that the broken function nevertheless can be executed (i.e. the parameter “End term of**
53 **manufacturing a product lot” does not deviate from the planned value) without correcting managing influ-**
54 **ences, for example, on the basis of the safety stock use, it is a question of deviation. If the function can be**
55 **executed only with the application of control influences, it is a question of failure, which should be eliminated**
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on the basis of managerial decisions on the restoration of an efficient supply chain state (for example, process corrections on the basis of the urgent material acquisition from other suppliers). In the case of impossibility of performance of all the planned orders according to the goals (delivery time, costs, quality), plan correction, for example redistribution of the resources between various orders, attraction of additional suppliers etc., is necessary. If there is a situation of the plan failure, goal adaptation is necessary, i.e., replanning (for example, changes in delivery times). An extreme case of failure is the catastrophic situation when the restoration of the supply chain plans (at all three levels of management) is impossible and a new strategy and control system for supply chains is necessary. In this case, it is possible to talk about a loss by a supply chain of its resilience and stability.

Each adaptation level characterizes a certain control loop in accordance with oscillations and deviations and corresponds to certain management actions. We distinguish parametric adaptation (i.e., rush orders), structural-functional adaptation (i.e., supplier structure changing), project goals' adaptation (i.e., delivery delay), and supply chain goals' adaptation (i.e., network profit changing), as well as supply chain strategy and models' adaptation. This makes it possible to match the results of the stability analysis and the actual execution analysis. It also provides a decision maker with a tool to make decisions about the supply chain adjustment in a real-time mode. The presented concept amplifies the application area of stability analysis to the supply chain performance adjustment and makes it possible to increase the quality of decision making of the supply chain reconfiguration and adjustment.

5. Model of synthesis of supply chain design, tactics, and operations

This model aims to synthesize simultaneously the supply chain configuration, plans, and execution dynamics (operations) of alternative supply chain structures. The model works simultaneously as (i) the multi-structural design of a supply chain, consisting of suppliers, manufacturers, careers, distribution centres, and retailers, (ii) proof of the fit of the supply chain design to different demands subject to customers' orders, and (iii) planning and scheduling of supply chains within different alternative supply chain strategies and plans.

Let the number of initial data be denoted in the following way.

A set of potential supply chain participants.

A set of technical infrastructure (machines, transport, IT systems) subject to the set I

A set of operations, which are characterized by available capacity, costs, risk, product availability, and information coordination capabilities.

A set of products and stock keeping units (SKU) which may be produced, stored, and sale.

A set of customers.

A set of orders to be planned subject to the set 5. Each order has a technological sequence of operations. Each order is to complete according to a delivery time and total supply chain costs.

A set of uncertainty (demand fluctuations, machine failure, delivery delays, pricing, new products, human factors (errors, coordination failure), purposeful disruptions (thefts, terrorism)).

A set of enterprise collaboration preferences.

The goal is to determine supply chain design structures, supply chain plans, and to simulate different operations execution scenario with different plans and strategies. The goal criteria are subject both to extreme economical performance indicators and plan stability. Because of the limited size of the paper and the complex mathematics, we will not present the formal models. However, the general modelling construct can be of interest to readers.

Model block 1. Multi-structural modelling. The dynamics of the supply chain execution is presented as a *dynamic alternative multi-graph (DAMG)* to relate the above-named sets and structures. The DAMG is char-

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acterized by a *macro-structural macro state (MSMS)*. The DAMG and the MSMS are developed to meet the requirements of multi-structural design and to link the design, planning, and execution models, taking into account the supply chain structure dynamics (Ivanov et al. 2009a,b).

Model block 2. Adaptive planning. The main purpose of the adaptation framework is to ensure tuning of the dynamic planning models' parameters with regard to changes in the execution environment. In the proposed framework, the plan adaptation is connected to the model adaptation. The proposed approach is based on a combination of the model predictive control (MPC) and adaptive control (AC) frameworks. A basis of the proposed approach is the adaptive planning in which the supply chain plan is modified periodically by a change in supply chain parameters or characteristics of control influences on the basis of information feedback about a current supply chain state and the past and the updated forecasts of the future. For the forecast updating, the MPC technique has been used; the AC application has been extended from the signal identification to the whole complex system dynamics with the help of structure dynamics control theory (Ivanov et al. 2009a,b). The parametric adaptation is enhanced by a structural adaptation. By designing the controller, the delays between the deviations' identification and the adjustment decision making are handled within the structure dynamics control approach and a combined people-machine adjustment system for the supply chain adaptation in the case of different disruptions is used. A hierarchy of adjustment actions is brought into correspondence with different deviations in the supply chain execution. As such, the controller serves both for the deviations' identification and the adjustment measures' generation, taking into account the distributed system nature and delays in managerial decisions. Besides, this allows the transit from continuous control models that are characterized for the process industry and to apply the adaptive planning and control to many other branches with discrete operations. Hence, a supply chain is regarded as an object of control and can be modelled in a non-stationary, non-linear, and high-dimensional manner with difficult-to-formalize aspects.

Model block 3. Operation dynamics modelling. The proposed approach is based on fundamental scientific results of the modern control theory in combination with the optimization methods of operations research. In the model, a multi-step procedure for solving the multiple-criteria task of adaptive planning and scheduling is implemented. In doing so, at each instant of time while calculating solutions in the dynamic model with the help of the maximum principle, the following mathematical programming problems are under solution: linear programming problems to allocate jobs to resources and integer programming problems for (re)distributing material and time resources. The process control model will be presented as a dynamic linear system while the non-linearity and non-stationarity will be transferred to the model constraints. This allows us to ensure convexity and to use the interval constraints. As such, the constructive possibility of discrete problem solving in a continuous manner occurs. The modelling procedure is based on an essential reduction of a problem dimensionality that decreases under solution at each instant of time due to connectivity.

Model block 4. Agent-oriented modelling. As the elements (enterprises) of models are *active and goal-oriented*, able to act autonomously, reactive and adaptive, and able to communicate with other agents, we introduce the specific description of these active objects in terms of multi-agent theory. The agents try to fill up the capacities for each competence so as to maximize the discrepancy between price and costs within a set of alternatives of resource allocation. The agent functions are formulated in Ivanov et al. (2007). In order to take into account so-called soft factors (e.g., reputation, trust etc.), we also consider a reputation function of the agents.

Model block 5. Plan stability analysis. The model of supply chain plan stability analysis addresses the problem of the direct connection of supply chain stability estimation and analysis with supply chain economic efficiency. The model uses the method of attainability areas (Okhtilev et al. 2006). The economic sense of the attainability areas consists of the following: the attainability area (ATA) characterizes a set of supply chain plans and the values of the supply chain potential economical goals corresponding to them. The model is

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based on the dynamic interpretation of the supply chain's functioning process. The model allows multiple-criteria estimation and the analysis of supply chain stability to be made, considering the combined variants of initial data about possible perturbation influences (the determined, indistinct, stochastic, interval data, and their combinations). The model allows (i) an analysis of the stability of various alternative supply chain plans to be made concerning various kinds and scales of perturbation and control influences, (ii) a stability index to be calculated for each of the plans and possible scenarios, having given to the decision maker the possibility of a choice of that plan that corresponds to his/her individual risk perception.

The developed modelling complex allows the simultaneous synthesis and analysis of supply chain strategic, tactical, and execution (operational) plans in order to prove the fit of supply chain design to possible demands and operative execution plans. The other advantage is balancing the supply chain effectiveness and the feasibility of these goals on the basis of the stability analysis.

6. Implementation in software

The methodologies and models presented above are under implementation for supply chains of machinery and textile branches. It should be emphasized, that improvements and enhancements in managerial insights into the aligning of decisions in supply chain strategy, tactics and operations can be considered as practical results of the above-presented theoretical framework. Understanding of issues and possible ways of consistency in SCM decisions is a critical issue in practice which is faced by the elaborated framework. 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 (enterprise resource planning) system, and a supply chain monitor (Ivanov et al. 2009a).

For experiments, we elaborated a software environment composed of software prototype "Supply network dynamics control". This software depicts the relationships of multi-structural macro-states to different supply chain elements, and how these states change in dynamics. Let us consider an example of tactics and operational levels interrelations. The model interprets dynamical supply chain scheduling as a response to planning goals changes, demand fluctuations and resource availability. Thus, in this interpretation the problem is now to schedule supply chains in order to achieve the plan goals (e.g., supply chain service level), and not to find the optimal schedule in regard to, in example, minimizing the lead time of certain customer orders. The model is scalable to other management levels of supply chains. I.e., orders and operations can be presented as supply chain configuration elements and orders correspondingly. The transformation of parameters and goal criteria is also possible. I.e., the lead-time can be considered as the supply chain cycle time. Hence the supply chain strategic configuration and tactical planning can be optimized. The developed prototype provides a wide range of the analysis possibilities from the such points of view like supply chain structure content (initial data for scheduling), approachability of the tactical planning goals, taking into account individual managers' risk perception, the execution dynamics of customers' orders and operations within these orders (incl. key customer orders and bottle-neck operations).

Conclusions

This study introduced an original approach to aligning planning decisions on supply chain strategy, tactics, and operation based on the adaptive planning principles. The findings suggest qualitative and quantitative methods to transit from simple open time slots incremental planning to dynamic, feedback-based, closed-loop adaptive supply chain planning to implement adaptability, stability, and crisis-resistance throughout the value chain. The conducted verbal, formal, and software-supported experiments showed that the decisions on supply

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chain strategy, design, planning, and operations are tightly interlinked. In Tables 1–3, we provided evidence that the output of decisions at a more long-term management level is at the same time the input for the level of a shorter time horizon. The efficiency and applicability of these decisions can be increased if decision-supporting models are also considered as interlinked for different supply chain managerial levels and structures.

In this study, we considered the planning problem of supply chain management as an adaptive process for taking into account uncertainty in supply chains and the interrelations of all the management levels. We described a conceptual model interlinking the supply chain strategy, design, planning, and operations on adaptation principles. In the presented approach to the structural-operational supply chain dynamics, the planning and execution problems in supply chains are tightly interlinked. First, the planning and execution models are inter-reflected. In the both of the models, decision-making principles of the other model are reflected. Secondly, the planning and execution stages are interlinked through the monitoring level.

Subsequently, we presented a mathematical modelling complex and its realization in a software environment. The elaborated framework serves to increase the efficiency, consistency, implacability, and sustainability of decisions on supply chain strategy, design, planning, and operations. The decisions' alignment can help to increase organizations' wealth by producing demand-corresponding products in the most cost-effective manner through increasing agility, responsiveness, reaction speed to market changes, and continuous comprehensive improvements/adaptation of supply chains.

The presented study also has 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 the optimization, heuristics, and simulation parts is also challenging. However, increasing supply chain design and redesign efficiency will repay these efforts. For concrete application cases, it is nevertheless almost impossible to take into account the whole variety of complex inter-related constraints and parameters. Hence, certain model simplifications will be needed. A great challenge is the calculation precision both in the planning model itself and at the interface between the adaptation loops and the operation dynamics model. In the developed mathematical model, the calculation precision is subject to individual decision-maker perceptions. The operation dynamics model itself is implemented in a software prototype, but the adaptation loops are still under programming. The constructive methods for calculation precision with regard to the interrelations of measured and calculated (control) parameters are to be further developed. Finally, the mathematical formalization of uncertainty factors is complicated by a high complexity of stochastic dynamic models.

Another very important point is the trust and collaboration in the network. Before automation, a huge amount of organizational work should be 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, it is important to elaborate and to maintain throughout the product and process technological documentation and classification. Last, but not least, the firms themselves should perceive the necessity for such collaboration.

This study provides a large variety of possible directions for future research, e.g., 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. We are also going to investigate in depth some referenced SCM problems with the use of control theory, e.g. supply chain monitoring and event management. Both problem areas will lead us to a deeper understanding of the interrelations between control theory, operations research, and agent-oriented modelling.

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Acknowledgements

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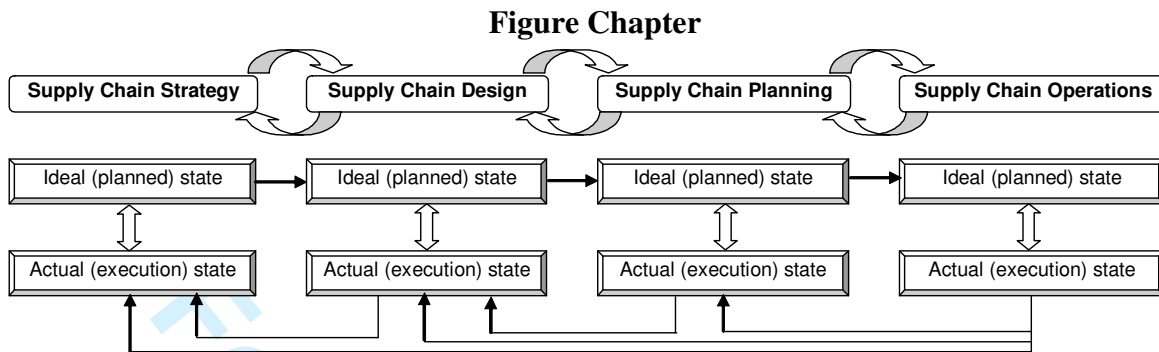


Figure 1. Interlinking supply chain strategy, design, planning, and operations

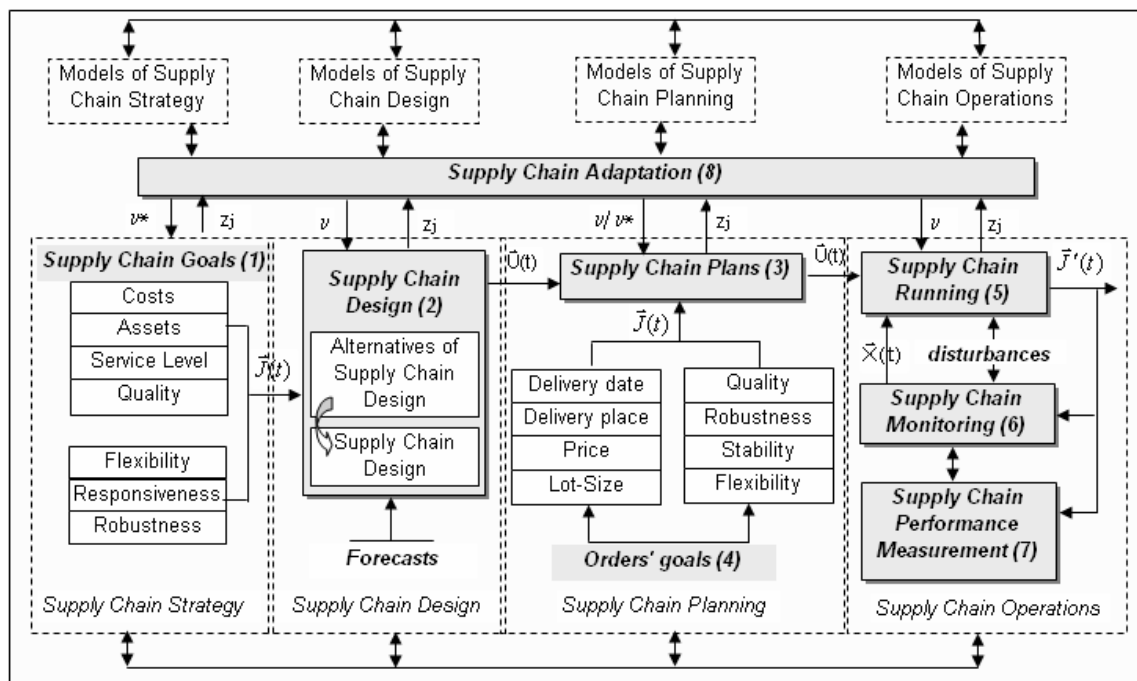


Figure 2. Conceptual model of linking supply chain strategy, design, tactics, and operations

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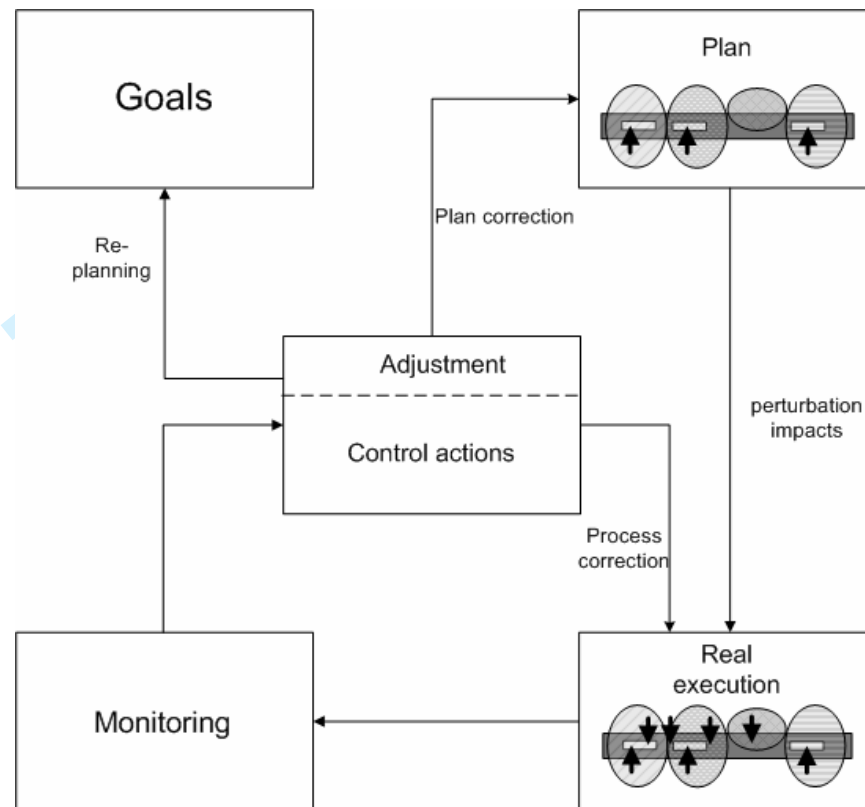
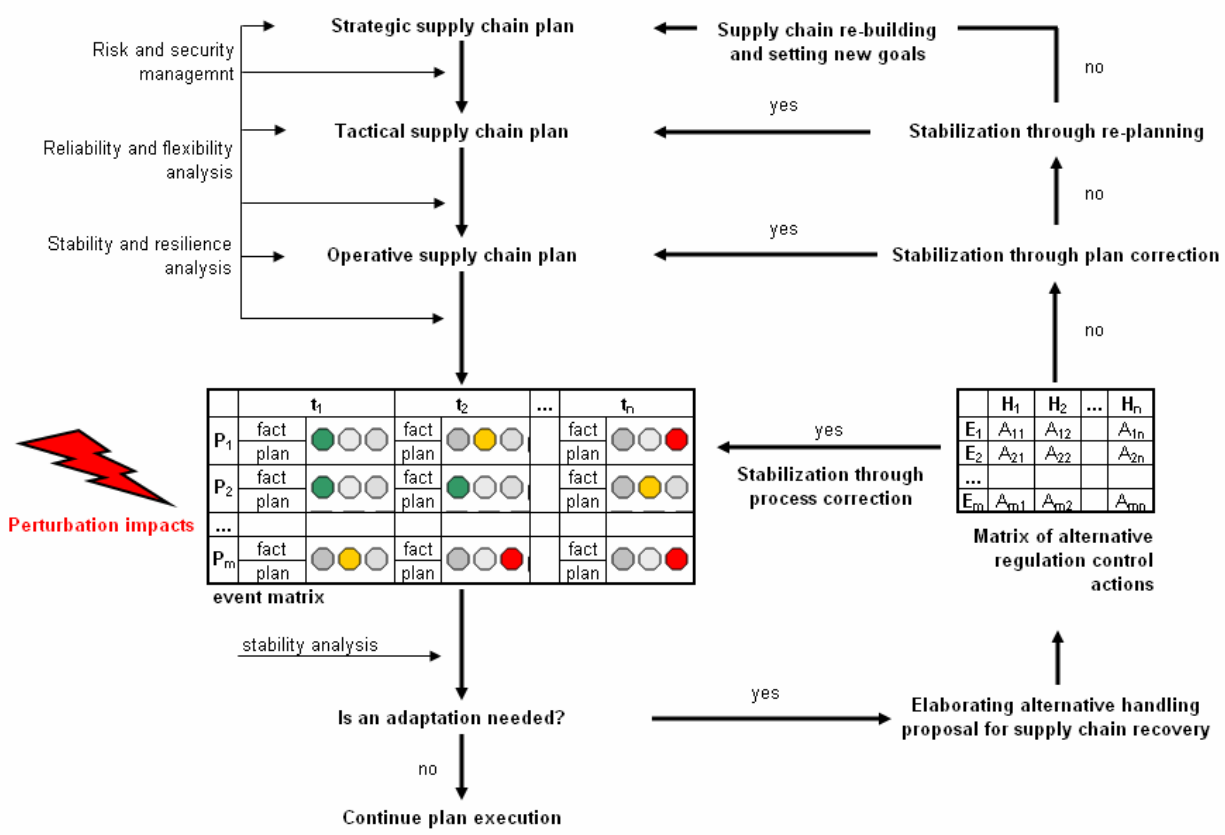


Figure 3. Supply chain planning system with feedback

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Comments: Event and control matrices are presented in static form for the purpose of clearness. In fact, these are dynamic multi-dimensional matrices.

H₁...H_n - Decision making points in supply chain (managers, operators, etc.). A - Regulation control actions alternatives
E - Events in supply chain
P₁...P_m - Supply chain parameters

Figure 4. Supply chain planning and control adaptation system

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Tables

Table 1. Classification of supply chain design decisions and decision-supporting methods

Strategic Decisions	Input Data	Output Data	Decision-Supporting Methods
Background information: Corporate strategy; Supply chain strategy; Financial strategy; Marketing competitive strategy			
Supply chain goals	Profit Assets Reliability Flexibility	How the optimal compromise of the supply chain goals can be achieved? How to deal with multiple criteria?	Analytical hierarchy process Pareto optimality Heuristics
Production programme design	Product variety Stock keeping units Bill-of-material Demand Response time Time-to-market	Which products, in what quantity, variety, batches etc. to produce? Product availability Technological plan building	Linear programming System dynamics Ontology analysis Graph theory
Cooperation and coordination design	Levels of coordination: orders forecasting point-of-sale	How the enterprises will collaborate? What information systems must be used?	Multi-agent systems Fuzzy logic Game theory
Distribution and production design	Location data (costs, geo-referenced data, taxes etc.) Demand Inventories Process data (capacities, costs, etc.) Movement 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? How to secure the supply chain with regard to purposeful disruptions, e.g. thefts or terrorism?	Mixed integer programming Information modelling Dynamic programming Decision analysis Assignment methods System dynamics Discrete-events simulation Stochastic optimization Multi-agent systems Heuristics

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Table 2. Classification of supply chain planning decisions and decision-supporting methods

Planning Decisions	Input Data	Output Data	Decision-Supporting Methods
Background information: Collaboration strategy; Product structure; Suppliers' structure; Facilities' structure; Distribution and production structure			
Distribution and production plans	Demand Costs Capacities Inventory Production volume	Demand forecasts Cycle and safety inventories Capacity utilization Product availability	Statistics and probability theory Mixed integer programming Dynamic programming Queues theory Multi-agent systems Evolutionary heuristics
Replenishment plans	Demand Costs Capacities Inventory Volume	Economical order quantity (EOQ)	Linear programming Statistics and probability theory
Shipment plans	Geographic data Transport data (costs, time, mode, capacity)	Routing	Combinatorial methods Multi-agent systems Evolutionary heuristics

Table 3. Classification of supply chain operational and execution decisions and decision-supporting methods

Operative Decisions	Input Data	Output Data	Decision-Supporting Methods
Background information: Distribution, production, replenishment, and shipment plans			
Scheduling	Delivery date Price Delivery place Batch size	Production scheduling Routing	Simulation Evolutionary heuristics Optimization
Available-to-Promise / Capable-to-Promise (ATP/CTP)	Customer orders; Inventories, capacities; Operational and tactical plans	ATP/CTP response	ATP/CTP algorithms
Monitoring	Demand Supply Costs Capacities Inventory Production volume	Comparison plan–fact	Operative analysis methods
Adjustment	Deviations and disruptions	Adaptation steps for operations Adaptation steps for tactical plans and design	Simulation All the methods of the supply chain design and planning
Deliveries to customers	Delivered products Payments	Performance management	Supply chain reference model (SCOR)

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