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DIMA – A Research Methodology for Comprehensive Multi-Disciplinary Modelling of Production and Logistics Networks

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D. Ivanov. DIMA - Decentralized Integrated Modeling Approach

DIMA – A Research Methodology for Comprehensive Multi-Disciplinary Modelling of Production and Logistics Networks

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Abstract. The paper presents a multi-disciplinary methodology DIMA (Decentralized Integrated Modeling Approach) for comprehensive modelling production and logistics networks. The DIMA allows implementing principle of throughout modeling “conceptual model → mathematical model → software”. In the paper, the DIMA is illustrated on the problem of collaborative network (CN) dynamical synthesis and reconfiguration. This problem is described in a comprehensive way on the conceptual and mathematical levels. This description allows interlinking synthesis and analysis issues of the CN planning and control taking into account system elements’ activity, uncertainty factors, and structure dynamics. The paper reports a novel approach for comprehensive multi-disciplinary modeling distributed large-scale business systems with decentralized decision making and control. In this paper, the main features of the DIMA are summarized based on recently developed partial models and algorithms for a large spectrum of the CN management issues.

Keywords: modeling, collaborative manufacturing, systems analysis.

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AMS Subject Classification: 93A30; 93A14; 93A15.

1 Introduction

Competition landscape in production and logistics is characterized by enterprise networks rather than by separate enterprises. Evolution of classical enterprise cooperation and collaboration forms is being forced by advancing information technologies (IT), collaborative organisational strategies, and globalization. In many branches, wide-broaden hierarchical supply chains with pre-determined suppliers structure and product programs evolve into customer-oriented, temporary networking of core competences of small and medium enterprises. These concepts, known as Virtual Enterprise, Changeable, Reconfigurable or Agile Networks, become a popular form of competitive organizations. In this paper, the term Collaborative Network (CN) is used as a general definition (Camarinha-Matos et al., 2005). The main features of the CN are the following: network and enterprise collaboration are organized project-oriented, each network participant specialises on certain functional competencies, network participants are independent and act autonomously and self-goal-oriented, for each project a coordinator exists, who is responsible for the project success (customer side) and coordinating network participant activities (supply side). The CN concept is based on using Internet for project operative coordination. The main economical advantages of the CN lie in a faster and more flexible reaction to market changes as well as in cutting time-to-market through operative distribution and coordination of resources (competencies) in all phases of product life cycle. Participation in enterprise networks is a one of the key factors of the enterprise competitiveness.

CN modeling problems differ from classical those. CN is characterized by different goals and uncertain interactions of its elements. The CN elements are *active*. They act based on their own interests and goals. Active elements cause the necessity of CN partner interests balancing, additional uncertainty (because of partner interactions uncertainty), and CN structure dynamics. Besides, the CN execution is accomplished by permanent changes of internal network properties and external environment. It requires dynamical CN adaptation in ac-

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cordance with the *current execution environment* and the goals and decisions of the configuration phase. So, reflections of CN configuration and execution models are needed. The CN can be described by *various models* (static and dynamic, stochastic and deterministic, analytical and simulation, etc). As a rule, the multi-disciplinary and cross-linked CN management issues require combined application of various modelling techniques. The other issue of CN modeling is interlinking of conceptual models, mathematical models, and software in order to achieve accurate models (adequate, scaleable, and representative) and provides application independence.

Even though a lot of research has been conducted in the field of emergent industrial and logistics networking in recent years, only some of them have dealt with comprehensive understanding of CN modelling taking into account the above described issues. In the years 2000-2006 a number of studies have been conducted in Chemnitz (Germany) and Saint Petersburg (Russia) with several industrial and academic partners. This paper has partially resulted from those projects.

This paper is organized as follows. We start the paper with the state-of-the-art research analysis to the modeling techniques for CN. Section 3 presents basics of the proposed research methodology *DIMA (Decentralized Integrated Modeling Approach)*. In section 4, the DIMA is illustrated on the problem of collaborative network (CN) dynamical synthesis and reconfiguration. We conclude the paper with summarizing the most important features of the obtained results.

2 Modeling collaborative networks: state-of-the-art

In production and logistics, the issue of CN modeling has attracted increased attention and interest in recent years. Recent research (Camarihna-Matos et al., 2005, Ivanov et al., 2004, 2005, 2006) has dealt with forming of CN modeling methodology. According to these works and the system theory basics, the large variety of the issues can be classified into the subclasses of CN analysis and synthesis. The models of CN analysis can be

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divided into CN design analysis as well as CN operative monitoring. The models of CN synthesis are composed of CN configuration (static models) and CN reconfiguration (dynamic models). The most of the CN problems are cross-linked (i.e., models of CN monitoring and reconfiguration, static and dynamic models of the CN (re)-configuration, CN synthesis and analysis models). When reviewing the literature on CN, it is apparent that three major research streams exist. One contains conceptual research, the other one is mathematical modelling, and the other deals with software engineering and information tools.

[Insert Table 1 here]

In recent years, the concepts for business networks are being increasingly developed. A large number of concepts of network organisation and management, such as Extended Enterprise, Agile Enterprise, Virtual Enterprise have been proposed. There have been also developed some concepts and strategies for SCM such as CPFR (Collaborative Planning, Forecasting and Replenishment), VMI (Vendor-Managed Inventory), SCMo (Supply Chain Monitoring). In this stream researches try to grasp and structure managerial issues related to business networking. The studies give extensive guidelines to deeper understanding of basic principles and advantages of new organisational forms. Conceptual research to the CN synthesis is much grounded. However, it shows significant limitations regarding the problems of CN design analysis as well as CN operative re- (synthesis) and operative analysis.

As for the CN analysis, the two main categories are subject to research – complexity and uncertainty. The research on *CN complexity* is divided in different approaches. One the most popular is the Complexity Management (Blecker&Kersten, 2006). According to this approach, the CN complexity relates to numerousness, variety, connectivity of elements, opacity of the relations between elements, and dynamics that act on the system. Based on the complexity analysis the CN complexity management framework offers 4 strategies: accept-

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ing complexity, controlling complexity, reducing complexity, and avoiding complexity. In other approaches, CN complexity has been described from various points of view: structural, organizational, and functional, product and production system complexity, enterprise and market complexity. Complexity analysis is usually applied to the stage of the CN design. In practice, we always come across various deviations from plan states caused by uncertainty of the CN execution.

CN functioning is challenged by high uncertainty. This leads to perturbations and deviations from planned states during the CN execution. Uncertainty is a category which is mostly used in relation to risk management. In literature on production and logistics, various terms such as billwhip-effect, vulnerability, robustness etc. have been used to analyse the problem of CN execution under the terms of uncertainty. Risk management is a methodological approach to the management of outcome uncertainty. Few studies have integrated uncertainty into models of networking (Hallikas et al., 2004). These conceptual researches try to classify types of risk and uncertainty, and to develop some suggestions how to plan and control the networks taking into account risk factors. (Sorensen 2004) provides an overview of main streams of such a research.

A disadvantage of the conceptual research is that the concepts are mostly not provided with any formal models and software implementation. So it leads to ambiguous understanding of some basic terms, lack of unified methodical basis for the solving of various management problems, and to misleading of possible application fields of the developed approaches.

Mathematical research to the CN can be divided into three primary approaches to conducting CN modeling analysis. These are: optimization, simulation, and heuristics.

[Insert Table 2 here]

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Optimization is an analysis method that determines the best possible method of designing a particular supply chain. The mathematical model has some objective that is maximized or minimized, such as total system cost (minimize) or profit (maximize). Analytical methods are based on the Operations Research (OR) approach. CN has been a very visible and influential topic in the field of *operations research*. (Tayur et al. 1999, de Kok and Graves 2004, Simchi-Levi et al. 2004) provide a systematic summary of operations research on quantitative models of the SCM, especially for inventory management, tactical planning decisions and supply contracts. A closely related topic to the problem addressed in this paper is research on *vendor evaluation and selection* (Abdel-Malek and Areeratchakul, 2004). The other research stream deals with mathematical formulation of the CN execution under the terms of risk. As a rule, three uncertainty drivers – demand deviations, supply delays, and behaviour of participants – were considered. There were elaborated valuable approaches using deterministic or stochastic models and game theory (Tayur et al. 1999, de Kok and Graves 2004, Simchi-Levi et al. 2004).

The drawback of using optimization is the difficulty in developing a model that is sufficient detailed and accurate in representing the complexity and uncertainty of the CN, while keeping the model simple enough to be solved. Further, optimization models tend to require more data than other approaches. However, when the problem is not too complex to solve, optimization produces the best possible insights into questions related to the CN management.

Simulation is imitating the behaviour of one system with another. By making changes to the simulated CN, one expects to gain understanding of the dynamics of the physical CN. Simulation is an ideal tool for further analyzing the performance of a proposed design derived from an optimization model. One promising area is the study of combining simulation methods with optimization methods in an iterative way. Regarding the CN, agent-based paradigms, such as complex adaptive systems (CAS) and multi agent systems (MAS) are the most popular simulation technique (Tilebein 2006, Shen et al. 2001). A number of researchers have attempted

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3 to apply agent technology to manufacturing enterprise integration, supply chain management, manufacturing
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5 planning, scheduling and control, materials handling, etc. Regarding the CN complexity simulation analysis,
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7 agent-based paradigms, such as complex adaptive systems (CAS) and multi agent systems (MAS) are the
8
9 most popular simulation technique.
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12 The past research on utilization of the MAS to the SCM and VE problems (Swaminathan et al. 1998, Fox et
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14 al. 2000, Rabelo et al. 2002) have been mostly dealing with agent based frameworks and software architec-
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16 tures, where agents are autonomous, goal-oriented software processes. Though the techniques of how to solve
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18 large-scale problems in a decentralized way were developed, the most of them are based on weak-grounded
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20 heuristic principles. The theoretical background of the MAS is very poor and does not let to consider the MAS
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22 as a general CN modelling framework. Current applications of agent-based paradigms are limited to software.
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24 It is mostly underestimated that these paradigms offer a valuable theoretical perspective on decentralized net-
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26 work management. Besides the MAS, a number of other approaches such as System Dynamics (Sterman
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28 2000) and Petri Nets (Kulba et al. 2006) are often applied for the CN investigations.
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34 *Heuristics* are intelligent rules that often lead to good, but not necessarily the best solutions. Heuristic ap-
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36 proaches typically are easier to implement and require less data. However, the quality of the solution is usu-
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38 ally unknown. Unless there is a reason that optimization cannot be used, heuristics are an inferior approach. In
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40 the CN settings the nature based heuristics such as genetic algorithms and ACO (Ant Colony Optimization)
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42 (Corne et al. 1999) are mostly used.
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46 Besides the above-described approaches, the Systems Science and Control theory can be also used for the CN
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48 modelling (Ivanov et al. 2004, 2005). They can serve as a general methodological basis of the CN synthesis
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50 and analysis. However, the disadvantage of the research grounded in modern *systems and control theories* re-
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52 garding complex business systems is that the system elements are being controlled from a central decision-
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54 maker and cannot change their states and interactions on their own free will (the system elements are passive.
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In complex business systems, the elements are *active* (they can compete and have conflicting aims, interests, and strategies). The classic methods do not allow developing practical comprehensive models taking into account the *goal-oriented (active) behaviour* of enterprises.

The review of the conventional modelling approaches highlighted their common disadvantages and serious limitations regarding the CN. First of all, they do not take into account system elements activity. Besides, synthesis of structures and functions in the CN as well as planning and execution phases are considered separately without interlinking each other. Most of elaborated models consider CN as a static and deterministic system, focus on a single or limited number of objectives without balancing goals of the CN partners, and can not represent ever changing nature of the CN. One promising area is the study of combining various modelling approaches.

The above-described analysis of the research to modeling collaborative networks let to conclude, that the comprehensive CN modelling methodology requires the following components:

Multi-disciplinary mathematical modelling. The data for modeling different CN management issues have different nature and fullness, and they change in dynamics. Furthermore, the CN elements are *active*. They act based on their own interests and goals. Active elements cause the necessity of models elaboration with interactive decision making mechanisms. This complicates the problem solution using one of the conventional solution concepts and requires elaboration of flexible frameworks which allow transiting between various approaches for problem solution (so called multiple-model complexes are needed),

- **Interlinking planning and control models.** Due to attempt to form project-oriented supply chains by flexible project structuring, combining centralized and decentralized project coordination, and concentration on very specialized competencies, the vulnerability of the CN increases. In practice, we always come across various deviations from plan states of the CN caused by uncertainty of the CN execution. The literature analysis shows that the complexity and uncertainty analysis are mostly considered separately so as to CN design

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and execution stages. However, the CN design is efficient only in combination with taking into account uncertainty factors. On the other hand, operative decision making at the stage of the CN execution is efficient based on the reflections to the CN planning models and permanent CN adaptation to a current execution environment. These ideas are reflected in modern research, but still very limited.

- **Amplifying the risk management concept.** Some of uncertainty factors are known to the planning moment (we can estimate the probability of their occurrence by means of risk management), some of uncertainty factors are unknown to the planning moment (we can only assume uncertainty existence), and some of uncertainty factors emerge while CN execution caused by changing CN itself and its environment. To take into account the second and the third factor groups, the stability analysis and CN adaptation concepts must be elaborated.

These were the release points to start developing of the DIMA (Decentralized Integrated Modeling Approach).

3 Research methodology: DIMA (Decentralized Integrated Modeling Approach): basics

This section presents general principles of the DIMA (Decentralized Integrated Modeling Approach). The main goal of the DIMA is to establish a methodological basis for comprehensive CN modelling. Based on the DIMA, partial models and algorithms of the CN planning and control as well as conceptual business models, mathematical models, and software architectures should be considered as interlinked and can be matched with each other taking into account the specific CN features.

The two main principles of the DIMA are *integration and decentralization*. Integration is considered from the following prospects: integration of various modeling approaches and frameworks, integration of planning and

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execution models, integration of decision making levels, and implementing principle of throughout modeling “conceptual model → mathematical model → software” (s. Figure 1).

[Insert Figure 1 here]

Under *decentralization* we understand in this concept the main principle of management and decision making in CN. It means that all the models contain elements of decentralized decision making and CN elements’ activity. The decisions about the CN planning and control are not set up and optimized “from above” but are a product of iterative coordinating activities of the enterprises (agents) in the CN and the CN coordinator (if necessary).

In the DIMA-methodology, various modeling approaches are not set off with each other, but considered as a united modelling framework. E.g., the multi-agent ideology is considered as a basis for the *active elements modelling*. The control theory serves as a *theoretical background* of systems analysis and synthesis. The general scheme of the DIMA-methodology was presented in (Ivanov et al., 2006, Ivanov, 2007). *The main parts of the DIMA-methodology* are: the general systems framework (*GSF*), the integrated modelling framework (*IMF*), and the computing framework (Ivanov, 2006).

[Insert Figure 2 here]

The GSF defines conceptualized business models, meta-methodologies, and set of categories, definitions, specifications, indicators of the CN synthesis and analysis (Ivanov et al., 2005, 2006). *The IMF* defines rules of the integrated multi-disciplinary mathematical models building. It proposes constructive methods and techniques of (i) how to combine various model classes and (ii) how to model interconnected different CN prob-

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3 lems. *The computing framework* integrates building of mathematical models and algorithms, and their imple-
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5 mentation as software. The DIMA-methodology represents a multi-disciplinary modeling framework, which
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7 meets the CN modeling particular features. The approach creates a unified methodological basis of the CN
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9 integrated modeling, from the conceptual level, mathematical modeling up to algorithms and simulation tools.
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11 In our opinion, the best way to explain the main aspects of the DIMA is to bring an example. One of the com-
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13 plex problems elaborated on the DIMA basis is *the problem of the CN dynamical synthesis and execution* that
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15 will be discussed in the next section.
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24 **4 CN dynamical synthesis and execution**

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29 The CN must be configured according to the project goals and reconfigured in dynamics according to the *cur-*
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31 *rent execution environment*. In practice, the CN design decisions are rarely focused on “green Field” situation.
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33 More typically questions are centred on rationalizing the supply chains in response to permanent changes of
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35 SC itself and its environment (Harrison et al., 2005). That is why we will consider the problem of CN dy-
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37 namical synthesis and reconfiguration for illustration of the *DIMA*.
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41 Modeling this problem has significant practical importance. This problem is one of the most critical in a num-
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43 ber of CN strategies such as Mass Customization (Chandra and Kamrani 2002, CPFR (Aviv 2004), SMEs
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45 networks (Wirth and Baumann 2001, Teich 2003, Camarinho-Matos et al. 2005). CN design is a critical
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47 source of competitive advantage given that as much as 80% of total product cost may be fixed by these deci-
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49 sions (Harrison et al. 2005). 75% of operative costs in value chains are caused by supply chains (Wann-
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4.1. General Systems Framework (GSF) - conceptual problem description

Supply chains in CN *emerge* based on dynamic selection of partners from a pool of available suppliers. Remarkable is an existence of alternative suppliers for various project operations, which differ from each other by operations parameter (costs, delivery time, etc.). The collaboration is formed in a decentralized way. Partners manage collaboration to their suppliers and customers. There is no general management unit in CN. The project are co-ordinated by an external or internal unit (a coordinator), who is responsible for the project success (customer side) and coordinating of network participant activities (supply side). The CN management is composed of network planning (network configuration and supply chain scheduling) and control (performance management, monitoring, regulations / change management). The network design aims at forming supply chains through a partner selection from a pool of available suppliers based on the bid parameters of the enterprises (e.g. lead time, costs etc.) and customer requirements (delivery time, desired quantity, product technological structure etc.). The control phase refers to monitoring of supply chain execution and supply chain adjustment (reconfiguration) in case of impermissible deviations from the plan state (Ivanov et al. 2007).

To conceptualize this management concept, the following complex of interlinked models is introduced:

[Insert Figure 3 here]

These principle models, called also as macro-models, can be divided into sub-models to achieve a necessary description degree. Based on the elaborated complex of conceptualized business-models, requirements to the mathematical models and to software functional architectures can be elaborated. It ensures reflections of the conceptual business-process models, the mathematical models (conceptual models are the input of the

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3 mathematical models), and software functional architectures (systematic and reflected description of the busi-
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10 11 12 **4.2.2. Basics terms and definitions**

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17 At this stage, the basics definitions are elaborated. An enterprise networks can be classified under the CN, if:
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19 network and enterprise collaboration are organized project-oriented, each network participant specialises on
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21 certain functional competencies, network participants are independent and act autonomously and self-goal-
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23 oriented, for each project a coordinator exists, who is responsible for the project success (customer side) and
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25 coordinating of network participant activities (supply side). According to the existing definitions of complex
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27 systems the CN qualify for being a complex system. A collaborative network can be defined as a *complex*
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29 *open decentralized system with active independent elements*. Here are some other definitions:
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34 CN synthesis can be defined as a process of iterative matching, coordinating and balancing of partner interests
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36 to build a stable CN for a concrete project.
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39 CN control can be defined as a set of activities for business continuity supporting and continuous adjustment
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41 of collaborative networks in accordance with permanent changes of project execution environment.
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44 CN reconfiguration is a process of the CN structure alteration with a view to increase, to keep, or to restore
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46 the level of CN operability, or with a view to compensate the loss of CN efficiency as caused by the devia-
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48 tions of its functioning.
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51 CN monitoring is a process of continuous analyzing of current CN execution parameters and the CN states
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53 regarding the planned values. Monitoring is interconnected to the reconfiguration and adaptation.
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CN adaptation is set of activities to change a current CN state based on the information about the past, the current CN execution environment, and the forecast in order to get the CN state which let to achieve the final CN goals.

Other definitions were elaborated for: Complexity, Uncertainty, Risk, Stability, Reliability, Structure, Macro-State, Disturbances, Perturbation impacts, etc.

4.2.3. Meta-Methodologies

As an example the meta-methodology of integrated CN complexity and uncertainty analysis can be brought. We proposed the following classification of the main CN complexity and uncertainty drivers for complexity and uncertainty analysis: structures, dynamics, and modelling. If we consider the structural and dynamical aspects of the CN complexity and uncertainty analysis, we come to conclusion, that they can be described in terms of structure dynamics and adaptive control. One of the CN main features is the changeability of their parameters and structures due to objective and subjective causes at different stages of the CN life cycle. In other words we always come across the CN structure dynamics in practice. The main result of the CN modelling complexity and uncertainty analysis is to find out the modelling methods for various problems of the CN management. As a rule, the CN management issues do not allow their solution by means of a one single method. To answer the problem complexity, a combination of various modelling approaches should be applied. We considered uncertainty and complexity as driver of each other. We proposed a systematic approach to classify sources of CN uncertainty. From these classifications we derived the main aspects of the CN complexity. Practice-oriented the framework offers i.e. methodical guidelines of systematic CN complexity and uncertainty analysis. So, the business processes can be designed more goal-oriented and stable avoiding un-

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3 productive redundancies in the CN. In the meta-methodologies are elaborated the principles, which will be
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5 used in all the CN models in order to achieve the comprehensiveness and unification.
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10 **4.3. Integrated Modeling and Computing Frameworks (IMF and CF) - Mathematical modelling and** 11 **software implementation**

12 **4.3.1. Basics**

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20 This section illustrates the methodical principles of the IMF (Ivanov et al. 2007). Based on the requirements
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22 defined in the GSF the rules of building multi-disciplinary mathematical models can be elaborated. The guide-
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24 lines of this building are the following: elements and processes of decision making are described as active
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26 ones by means of agents; modeling flexibility and adequacy is ensured by means of defining various methods
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28 (or combinations of methods) for problem solution as well as of linking interrelated problems; CN planning
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30 and execution models are interconnected in an adaptive way based on information update and adaptation prin-
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32 ciples. Main parts of the proposed integrated modelling framework are: *multi-agent conceptual modeling*
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34 *framework, multiple-model complexes, and system of adaptive planning and control.*
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43 Based on the agent integration with other frameworks we elaborated (i) functional agent model for describing
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45 active elements (i.e., in an analytical graph-model), (ii) general schema of agents interactions for the customer
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47 order execution (integrated with optimization techniques of the linear dynamical systems), (iii) model of CN
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49 stability analysis based on the interests balancing of the CN coordinator and agents, as well as (iii) conceptual
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51 model of decision making in the CN based on the combined using of multi-agent, operations research, and
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53 control theory frameworks (Ivanov et al. 2004, 2005, 2006, 2007).
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Modeling adequacy cannot be ensured within a single model, thus multiple-model complexes were introduced (Ivanov 2007). Each class of models can be applied to the objects for analysis of their particular aspects. The interconnection between different models is ensured by means of *functors* (F). Coordinated application of different models improves modeling quality, as disadvantages of one model class are compensated with advantages of other classes, which enable examining of the determined classes of modeling tasks. The multiple-model complexes allow problem examining and solution in different classes of models. Result representation is performed in the desired class of models.

The elaborated approach of *adaptive planning and control* aims at business continuity supporting and continuous CN adjustment in accordance with permanent changes of project execution environment. It makes it possible to increase the quality of decision-making about the CN reconfiguration and adjustment based on planning under the terms of uncertainty, execution under the terms of adaptation, and reflections of planning and execution phases of the CN control on the adaptation principles. It also allows comprehensive taking into account three main types of uncertainty regarding a decision maker: factors known to the planning moment (i.e., by means of stochastic models), factors unknown to the planning moment, and uncertainty factors emerging while CN execution.

The general modeling structure of the CN dynamical structural-functional synthesis and reconfiguration is shown in Figure 4.

[Insert Figure 4 here]

In the next section, this scheme is considered detailed.

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4.3.2. Network description and synthesis

This stage consists of project structuring, executors structuring, and CN synthesis from a pool of structured executors according to the various project stages.

4.3.2.1. Integration of analytical and agent-based approaches.

The modelling starts with the static graph-theoretical network description. The CN can be described graph-theoretically as a directed graph – a digraph. Then, the elements of the organizational graph (enterprises) are described as active agents in terms of multi-agent theory. So the model of enterprise interactions can be constructed. In this stage, we combine graph-theoretical modeling with agents to describe active elements of the graph as well as to implement modeling dynamics of the CN objects collaboration. We introduced the specific description of these active objects in terms of multi agent theory (Ivanov et al., 2007). The agents try to fill up their capacities of each competence so as to maximize the discrepancy between price and costs. In this stage, we combine graph-theoretical modeling with agents to describe active elements of the graph as well as to implement modeling dynamics of the CN objects collaboration.

4.3.2.2. Integration of static and dynamic models.

Let us discuss an example of how to use the multiple-model complexes applied to the integration of static and dynamic models. The problem of the CN analyzing and synthesizing is mostly formalized using either graph (network) models or models of linear and integral programming. As a rule, the problem of analyzing and synthesizing programs for supply chain execution is formalized with the help of dynamic models. However, the problems of coordination and consistency of the results remain open. To obtain a construc-

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tive solution of these problems, we propose to use a functorial transition from the category of digraphs, that specifies the models of execution of operations, 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 investigations have shown that, in the framework of the considered polymodel description, not only functionality conditions hold, but also the conditions of the general position of the adjacency mapping (Sokolov and Yusupov, 2004). The full formalization of the functorial transition from the category of digraphs in the category of dynamic models was given in (Ivanov et al. 2007).

4.3.2.3. Integration of planning and execution models by means of structure dynamics control.

The next step is *dynamic network description*. In this stage, a set of interlinked dynamic models is formed to link “ideal” planning results and CN execution programmes under uncertainty. These models are: model of order dynamics management, models of operations dynamic management, models of flows management, model of resource dynamics management, model of structure dynamics management, model of CN macro-structural macro states management.

The planned CN is characterized by a set of structures, which is formed during supply chain synthesis (organizational, informational, topological, technological structures). Let us introduce, in terms of the control theory, a *dynamic alternative multi-graph (DAMG)* to relate the above-named sets and structures. The DAMG is characterized by *macro-structural macro states (MSMS)* (Sokolov and Yusupov 2004, Ivanov et. al. 2004). The DAMG and the MSMS are developed to answer structure dynamics in CN and to link planning and execution models taking into account the structure dynamics.

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3 **4.3.2.4. Integration of the IMF and the CF.**

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5 At the last stage, models and algorithms for the CN synthesis can be elaborated. They are based on the model-
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8 ing rules, defined in the IMF. There were developed mathematical models and algorithms for the CN synthe-
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10 sis, CN adaptation, CN reconfiguration, CN stability analysis etc. We worked with analytical models, simula-
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12 tion (MAS and linear dynamical systems), heuristics (genetic algorithms, ACO algorithms), fuzzy modes,
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14 petri nets etc. considered within the multiple-model complexes. Result of the planning stage is the CN con-
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16 figuration (structural-functional-informational CN design, CN execution plans, and CN execution adjustment
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18 scenario).
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24 **4.3.3. CN plan analysis**

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29 This stage aims at CN configuration analysis to generate a stable plan. Uncertainty analysis on this stage is
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31 comprised of two phases: taking into account factors known to the planning moment (i.e., by means of sto-
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33 chastic models) and factors unknown to the planning moment. For the first phase we apply the elaborated gen-
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35 eral scheme of CN modeling under the terms of risk. For the second phase, stability analysis is applied. Our
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37 main contribution is elaboration of a framework for comprehensive stability analysis in the CN, which con-
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39 sists of parametrical stability analysis (known as BIBO-Stability), collaboration stability as well as CN execu-
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41 tion stability combined with the CN adaptation (Ivanov et al., 2006). The stability analysis allows proofing exe-
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43 cution plan feasibility, selecting a plan with the sufficient stability degree from a set of alternative plans, de-
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45 termining CN execution bottle-necks and steps for their strengthening, and scenario elaborating for decision
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47 making about the CN reconfiguration based on indicating permissible CN execution parameters oscillations.
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4.3.4. CN control (execution)

The models of the CN control are comprised of the CN analysis and CN regulation (reconfiguration).

4.3.4.1. CN execution analysis

In our approach, CN *monitoring* is based on the monitoring of the CN *macro-structural macro states*. Monitoring a plan execution consists of determining diagnostics moments (critical control points), when the analysis of planned and factual parameters of the *supply chain execution* (demand, inventories, jobs starting end ending, and stability) is carried out. The particular feature of the CN *monitoring in the terms of macro states* is that at the each monitoring stage, the control parameters are extracted from the parameter vector of the DAMG. The extracting rules depend on the management goals at the stage monitored. It makes it possible to consider all of the CN execution parameters described in the DAMG, and to extract the necessary control parameters in the current execution situation. The other particular feature of the CN monitoring is the analysis of CN *perceptivity and stability*.

Stability in dynamics expresses the ability of a system to return to the initial (planned) state and (or) to remain within bounds of operation under the presence of perturbation factors. The stability analysis is performed regarding all of the states S_i that lie within the control horizon considered. This is an important part of the CN *operative diagnosis and forecasting*. The methodology of the CN comprehensive tactical decision making and operative diagnosis and forecasting taking into account decision stability is tight related to the CN adaptation issues. Stability is an important indicator to fulfil beforehand adaptation of the CN for predicted situation of the state S_i .

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4.3.4.2. CN re-synthesis

The CN *reconfiguration* (real-time re-planning) is comprised of deviations analyzing, elaboration of compensating control actions and construction of a new plan and producing of appropriate correcting actions for transition from the actual supply chain state trajectory to the planned one at the time interval $(t', t''] \in (T_0, T_f]$ or by the final time. The model of supply chain reconfiguration is interconnected to the planning model. It is also based on the dynamical alternative multi graph (Ivanov 2007). While selecting new supply chain it is also essential to take into account a number of specific requirements (preferences of the CN center and CN members). The essence of decision making about a CN reconfiguration, that is to say about a CN plan transition from S_i state to S_{i+1} state is to coordinate agents' interests and interests of a CN center.

Figure 5 presents the dynamic of the CN execution in case of deviations. To take into account particular features of the CN stability analysis (system elements' activity and structure dynamics), the CN execution is described in terms of multi-structural macro states S (Ivanov 2007) and the decision making about the CN reconfiguration are based on the concept of decision making in the CN based on the combined using of multi-agent and control theory frameworks.

[Insert Figure 5 here]

The Figure 5 depicts various variants of system behaviour changing in case of any disturbances at the system state $S_j^{(u)}$ of the initial execution plan. The perturbation impacts may cause various execution parameters deviations Δp_i and corresponded stability decrease regarding the final goals $C(t=end) = \{c_1, \dots, c_c\}$ of a supply chain or project. To match the system stability analysis and taking steps to recover the system stability, we elaborated a concept of the complex CN adaptation is built as a five-level structure. Each level characterizes

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3 certain control loop in accordance with the oscillations and deviations appeared. Each adaptation level corre-
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6 sponds to certain management actions. We distinguished parametric adaptation (i.e., rush orders), structural-
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8 functional adaptation (i.e., supplier structure changing), project goals adaptation (i.e., delivery delay), CN
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10 goals adaptation (i.e., network profit changing) as well as CN models adaptation (Ivanov et al. 2006). It
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12 makes it possible to match the results of stability analysis and actual execution analysis. It also provides a de-
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14 cision-maker with a tool what decisions about the CN adjustment must be taken in a current situation. The
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17 Figure 6 depicts this idea.

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22 [Insert Figure 6 here]
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27 The operative decision making about CN reconfiguration and adjustment are based both on the execution in-
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29 formation and planning results (i.e., selection of adaptation level in case of certain parameter deviations is re-
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31 lated to the stability analysis). In case of deviations (both in future – preventive reconfiguration, and during
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33 the current operation - reactive reconfiguration), the decision maker can timely take necessary steps for the
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35 CN adjustment. It is ensured by that the system of CN performance indicators is methodically and practically
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37 interconnected to the framework of stability analysis (planning stage) and the five-level adaptation framework
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39 (execution stage).
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43 The above-named concepts and models are partially implemented as software, i.e. VERP (Virtual Enterprise
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45 Resource Planning System) and EVCM (Extended Value Chain Management) applications, which provide IT-
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47 support for automatic network design and control, and simulation tool SNDC (Supply Network Dynamic Con-
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49 trol) intended for simultaneous CN structural-functional design and supply chain scheduling.
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53 The VERP and EVCM tools represent web-based environments for the network design based on interaction
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55 between enterprises, and enterprises and customers. To enable the participation in a network for a manufactur-
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ing or measurement agents, software was developed which enables or at least supports the submission of a offer on an automated basis by providing suitable algorithms. The web server is the “core” of that implemented operating concept and provides the web-services. It makes available all the necessary functionalities via the web. Each enterprise might use them if necessary. The web service coordinates all the necessary communication processes between the enterprises for finally determining those enterprises that can best fulfil the customer order.

The tool SNDC facilitates simulation of the CN design and control processes. Let us consider briefly *a case* modelled in the SNDC. There exist n enterprises in the CN, each one of them has a number of competencies. There are m orders to be planned. The planning task is formulated in multi criteria positing. Criteria are maximally even workload of all enterprises and maximal number of orders, which may be executed in the CN. Agreed weight coefficients of these criteria make 1 as a whole. For each client’s order the technology of its execution is determined (the sequence of technological operations – competencies). Each operation of each order is characterized by definite volume standards and admissible delays.

The configuration process consists of 7 stages. Therefore, for instance, at the stage 2 the synthesis of heuristic plan is carried out, and at the stage 5 – its optimization. The results of the configuration process are the structural-functional-informational CN design and CN execution plans. The special feature of the approach, implemented in the SDNC is the possibility to analyze the compiled plan on the base of the methodology of multi structural macro states. An application of the methodology of multi structural macro states makes it possible to represent and valuate CN configuration as well as CN execution plans on the aggregated detailed level. We determined three main macro states: plan, deviation from plan and reconfiguration necessity; and six transitional macro states. This lets managers get a complex presentation of dynamical order execution in the CN. This dynamics may be represented as a chart also. Results of the CN simulation make it possible to analyze complex the dynamics of order execution in the CN and form necessary managing adjustments

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6. Results summarizing

In the Table 3, the main results, obtained in the DIMA methodology are summarized.

[Insert Table 3 here]

The DIMA-methodology represents a multi-disciplinary modeling framework, which meets the CN modeling particular features. The approach creates the unified methodological basis of the CN integrated modeling, from the conceptual level, mathematical modeling up to algorithms and simulation tools. The DIMA also allows interlinking of planning and execution models as well as CN synthesis and analysis models. The proposed models and methods of the CN management have significant practical importance. They let managers plan stable networks and form a complex notion of order execution dynamics in the CN as well as elaborate necessary management adjustments (e.g., to change net structure, introduce additional resources, reject some orders, determine the CN bottlenecks, etc.). The other aspect of practical relevance of this research lies in the development of the new generation of information technologies for the CN management support, which would make up the deficiencies of the conventional APS, SCEN, LES and SCMo systems.

7 Conclusions

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3 In this paper, the basics of the multi-disciplinary methodology DIMA (Decentralized Integrated Modeling
4 Approach) for modelling production and logistics networks were presented. Based on the literature analysis
5 and our experiences, we revealed the shortcomings of the research to the CN modelling, and set up our re-
6 search goal – to develop a research methodology for comprehensive modelling production and logistics net-
7 works. The DIMA elaborated a unified methodological basis for multi-disciplinary CN modeling. The DIMA
8 allows implementing principle of throughout modeling “conceptual model → mathematical model → soft-
9 ware” based on the three interlinked frameworks: GSF, IMF, CF. We also presented concepts and construc-
10 tive tools how to interlink the CN synthesis and analysis models at the planning and control stages. It is the
11 first in the literature that reports an approach of multi-disciplinary modeling complex open business systems
12 with active elements.
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27 The DIMA provides general basics of the CN synthesis and analysis as well as constructive techniques how to
28 implement these basic principles. Based on the DIMA, various applied problems of CN synthesis and analysis
29 can be solved. In the paper, using of the DIMA is illustrated on the problem of network dynamical synthesis
30 and reconfiguration taking into account system elements’ activity, uncertainty factors, structure dynamics,
31 interlinking of conceptual and mathematical models, as well as reflections of planning and execution models.
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39 In general, the application of the DIMA is reasonable to complex problems with high uncertainty level, struc-
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The further development of the DIMA is directed towards elaborating special modelling language for CN. We
also concentrate on the development of modeling „stencils” for various CN management problems. We also
work at simplifying model constructing and at the refining some methodological aspects on the basis of the
results obtained through new algorithms elaboration. The improvement and extension of the software for the
DIMA implementation is also needed. The development of vast model constructions for the CN planning and

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3 execution contributes to advancing of theoretical foundations as well as to developing of the CN interoperabil-
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10 11 12 **Acknowledgements**

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Figure Caption

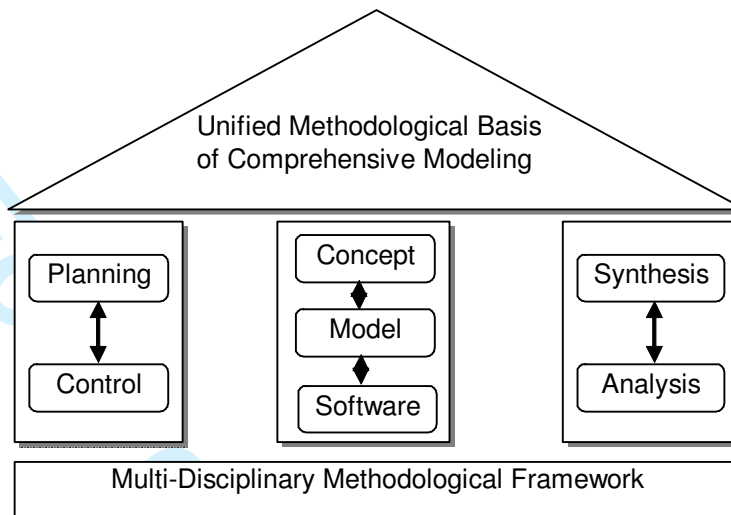


Figure 1. Integrated CN modelling

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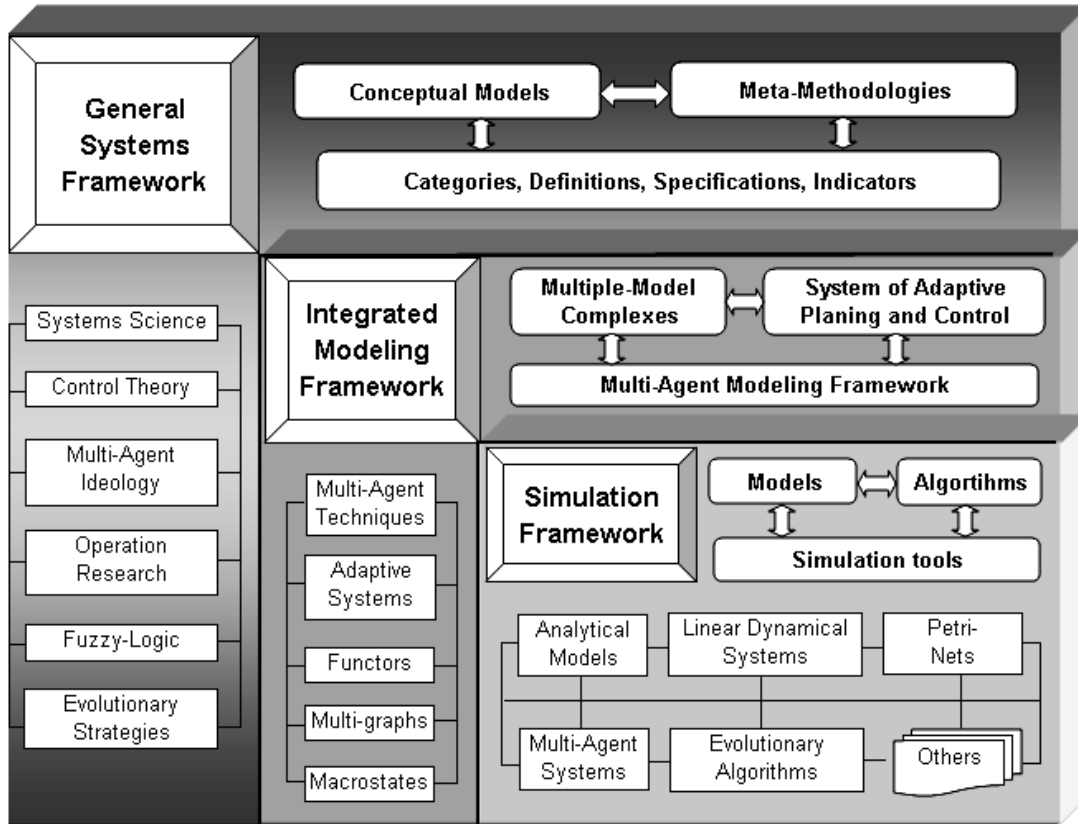


Figure 2. The general scheme of the DIMA-methodology

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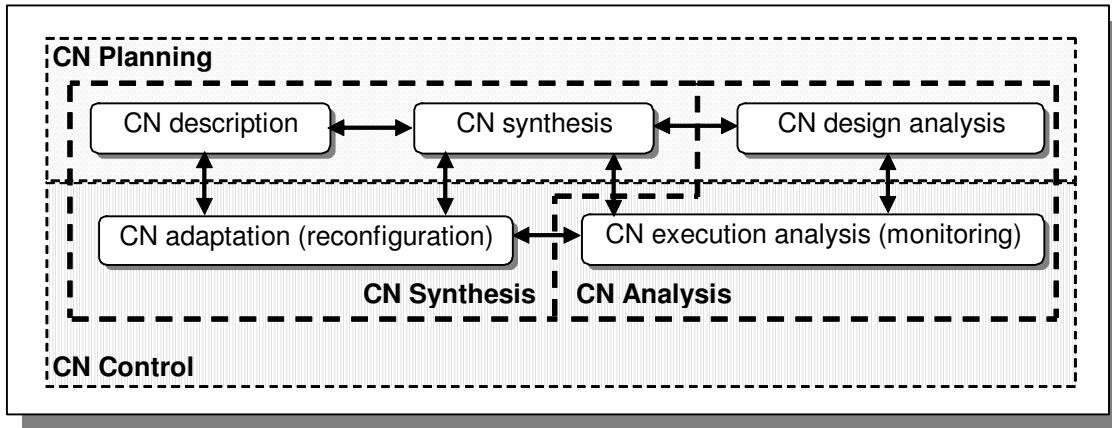


Figure 3. Complex of conceptualized models for the problem of the CN dynamical structural-functional synthesis and reconfiguration

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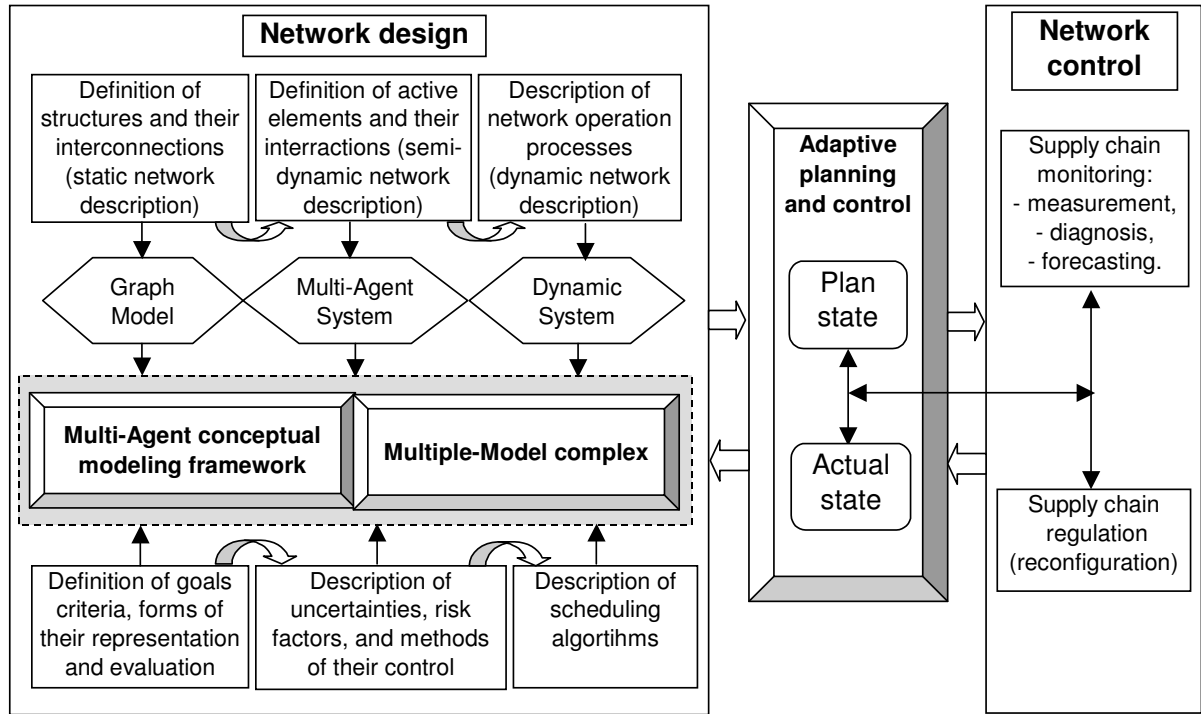


Figure 4. The general structure of the CN integrated modeling

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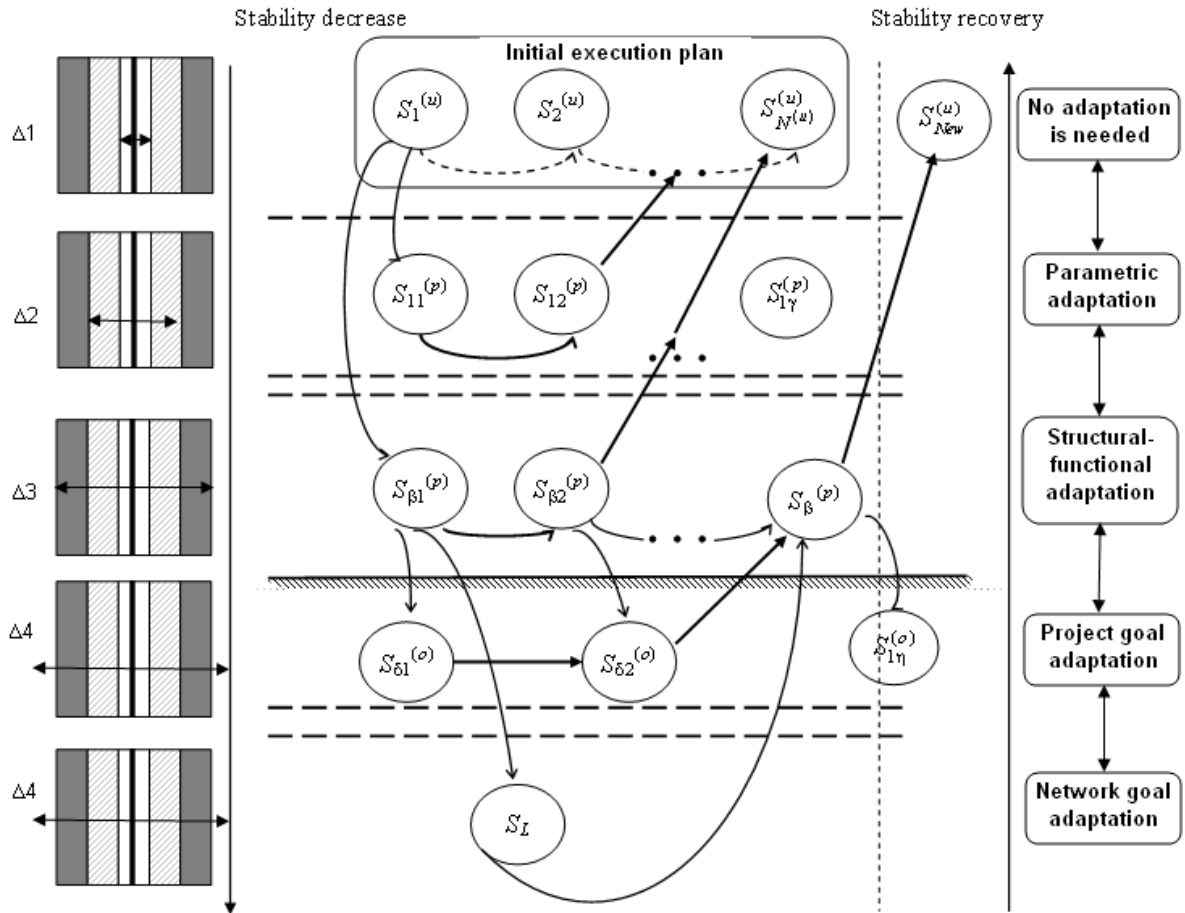


Figure 5: Dynamic of the CN execution and stability recovery

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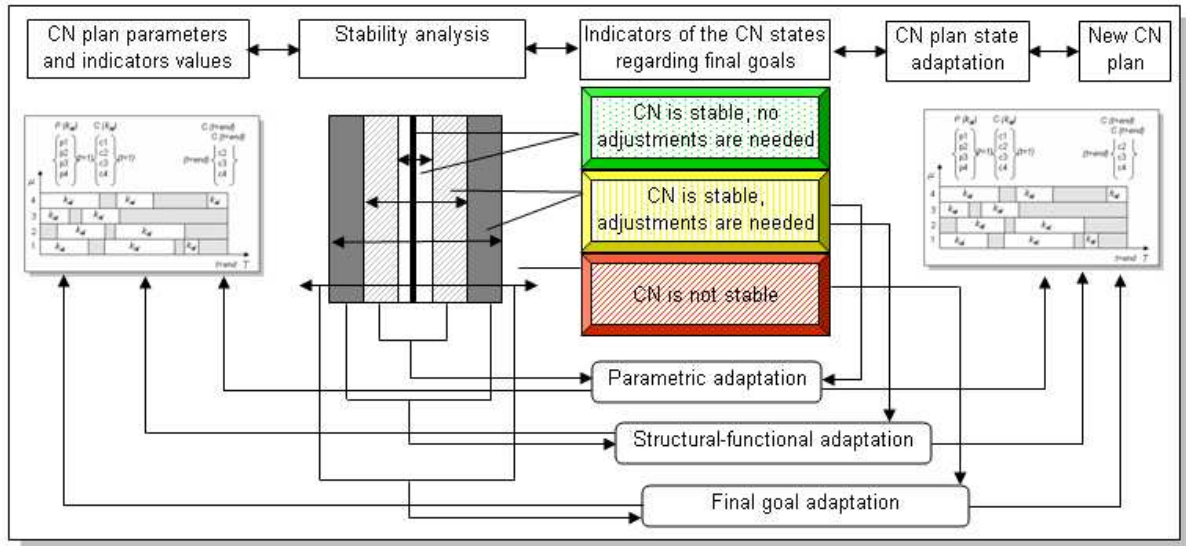


Figure 6: Matching the CN stability analysis and adaptation

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Table Caption

Table 1. Analysis of the CN modeling approaches

| Approach | Application areas | Advantages | Disadvantages |
|----------------------------------|---|---|---|
| Systems Science & Control Theory | General methodological basics of complex systems synthesis and analysis | Well-elaborated basis of complex systems synthesis and analysis | Elaborated for technical and biological systems; for CN modeling an extension is required |
| Analytical methods | Simple problems of CN design and vendor selection | Clarity; Optimal solutions | Not flexible enough; Modeling dynamics is not sufficient enough |
| Heuristics | Complex problems, i.e. dynamical CN structuring | Complex problems solution, also with incomplete information | Do not guarantee optimal solutions |
| Simulation | System investigations in dynamics | Modeling complex dynamic systems; graphics | Complicated elaboration; Complicated results interpretation; Do not guarantee optimal solutions |

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Table 2 - The main streams of research to CN modeling

| | Planning | | Control | |
|--------------------|--|---|---|--|
| | Synthesis | Analysis | Synthesis | Analysis |
| Conceptual level | CN structuring CN scheduling Partners integration and interactions | Uncertainty analysis: risk management, stability analysis; Complexity analysis | CN reconfiguration CN adaptation Real-time scheduling | Performance Management CN Monitoring |
| Mathematical level | Mathematical methods and models to solve the conceptual problems: <ul style="list-style-type: none"> - Analytical methods: (Operations Research) - Simulation (MAS/CAS, Petri Nets, System Dynamics, etc.) - Heuristics: (ACO, genetic algorithms etc.) | | | |
| Software level | CN information space design | CN information space analysis to proof the fullness and non-redundancies | Operative improvement of the CN information space | Analysis of the CN information space correspondence with a current execution environment |

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Table 3 - Main results, obtained in the DIMA methodology

| | Synthesis | Analysis | Practical application | Theoretical application |
|-----|---|--|---|---|
| GSF | Complex of inter-linked conceptualized business-models | Framework of integrated CN complexity and uncertainty analysis | Guidelines for goal-oriented and stable CN synthesis and comprehensive analysis | Unified Methodological basis of the CN synthesis and analysis Guidelines for requirements elaboration on the modelling techniques |
| | Definition of general terms and categories of the CN synthesis and analysis | | Guidelines for matching CN concepts and IT architectures | |
| IMF | General principles and constructive tools for building CN integrated models, i.e. - multiple-model complexes, - DAMG - MSMS - multi-agent | General principles and constructive tools for comprehensive CN analysis, i.e. - stability analysis, - risk management concept - CN monitoring concept | Guidelines for modeling complex problems of CN planning and control Guidelines for matching mathematical models and IT architectures | Guidelines of the integrated multi-disciplinary mathematical models building Constructive methods and techniques of (i) how to combine various model classes and (ii) how to model the |

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|----|--|--|---|--|
| | conceptual model- ing framework - CN adaptation framework | | | partial CN problems interconnected. |
| CF | CN synthesis mod- els and algorithms Software for the CN synthesis (EVCM, SNDC, VERP) | CN analysis models and algorithms Software for the CN analysis (SNDC) | Guidelines for match- ing mathematical models, algorithms and IT architectures Prototypes of the in- formation systems | Reference multi- disciplinary models and algorithms of the CN synthesis and analysis |