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QUANTITATIVE MODELS OF COLLABORATIVE NETWORKS

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The paper deals with issues on mathematical modeling of collaborative networks (CN) caused by complexity and uncertainty of CN due to interactions of active elements (enterprises), high dynamics as well as external and internal disturbances. This paper introduces an integrated approach for CN complex modeling, and illustrates it on the example of production network design and control. The goal of this research is to develop generic model constructions for design and control of CN, and contribute to advancing of theoretical foundations of CN.

1. INTRODUCTION

The greater evolution of *production* concepts, based on advanced organizational principles and modern information technologies (IT), takes place. Collaborative networks (CN) can be classified under these conceptions. In recent years, the concepts and IT tools for CN have been strongly developed (Chandra and Kamrani, 2004, Kuhn, 2002, Virtual Enterprises, 2004). However, the research on quantitative modelling of CN is still very limited. In this paper we consider a concept of production networks, which are based on customer-oriented, temporary networking of core competences enterprises (Teich, 2003, Wirth, 2001). In such temporary networks, the special feature of *supply chain management (SCM)* lies in flexible configurable supply chains, conditioned by an enlargement of alternatives to search suitable partners for the cooperation. This paper introduces in a systematic way an *integrated approach for modeling and optimization of CN* based on combination of control theory, systems theory and operation research with multi agent theory, and illustrates it on the example of production network design and control.

2. RELATED WORKS

Development of quantitative models for CN is complicated by high degree of complexity and uncertainty in CN caused by interactions of *active elements* (enterprises), structure dynamics as well as processes oscillations as due to external and internal disturbances. Some of the issues on fundamental models for SCM can be found in (Tayur, 1999). The book seems to be the first attempt to provide a systematic summary of OR quantitative models of SCM, especially for inventory management and supply contracts.

The most researches on *vendor evaluation and selection* consider the vendor selecting separate for each product part (not from the point of view of the network as a whole). The researches predetermine a focal enterprise (centre), which selects the vendors, and the elaborated analytical approaches are suitable only when a number of product parts and vendors are limited. Few research deals with the methods and algorithms for value chain scheduling.

One of the highlights of past researches has been the application of *multi-agent approach* to SCM and VE (Fox et al., 2000, Shen et al., 2001, Swaminathan et al., 1998, Rabelo et al., 2002). A number of researchers have attempted to apply agent technology to manufacturing enterprise integration, supply chain management, manufacturing planning, scheduling and control, materials handling, etc. However, these researches was mostly concentrated on the software engineering and computer science rather than on the methodological problems of utilization of MAS to CN.

Few studies have integrated *risk management* into models of networking (Sorensen, 2005, Hallikas et al., 2004, Zschorn et al., 2004). The 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.

Some recent research papers (Camarinha-Matos and Afsarmanesh, 2004) emphasise, that the proper methods of CN quantitative modeling have to combine elements drawn from various theories such as Systems Science, Control Theory, Operation Research, Distributed Artificial Intelligence etc. The combination of elements of various methods has been developed applied to complex technical systems for the last 30 years (Mesarovic and Takahara, 1975, Casti, 1979, Sokolov and Yusupov, 2004). In recent years, these ideas have been also used for development of generic models for information management in integrated enterprise systems (Chandra and Kamrani, 2004, Teich, 2003). Another approach to development of fundamental basis for SCM is being developed in the theory of system dynamics (Sterman, 2000). These researches are grounded in modern systems and control theories, which give extensive approaches to design and control of complex systems. However, their disadvantage regarding complex business systems is that the system elements are being controlled from a centre and cannot change their states and interactions of their own free will (the system elements are passive. In complex business systems the elements are active (their can compete and have contradictive aims, interests etc.) The classic methods do not allow developing of practicable complex quantitative models of open decentralized systems with active goal-oriented elements. That is why it is sensible to draw the elements from the multi agent theory, and construct the new techniques of CN modelling.

3. MODELING OF COLLABORATIVE NETWORKS

CN are described by various models. Besides, the CN operation is accompanied by perturbation impacts (*disturbances*), which influence the plan execution and the network environment. Moreover, additional uncertainty and requirements on models arise from the *activity of network elements* and their free-will interactions. The above-mentioned factors do not let produce an adequate description of design and control processes on a basis of single-class models. Consequently, the design and control of CN are to be considered interconnected, and the *adaptation* of models to the current execution environment is to be ensured. The other important feature of CN modeling is that the property of enterprise activity has to be taken into account.

The production CN management is composed of network design (network configuration and supply chain scheduling) and control (performance management, monitoring, regulations/change management) (Ivanov et al., 2004, Zschorn et al., 2005). 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 targets at monitoring of supply chain execution and supply chain regulation (reconfiguration) in case of any deviations from the plan state.

The main parts of the proposed integrated modelling approach are:

- *multi-agent conceptual modeling framework* for the representation of active elements (enterprises) in graph-theoretical modeling,
- *multiple-model complexes* based for combination of various models (e.g. dynamical and static models, analytical and simulation models),
- *adaptive planning and control* for interconnecting of planning and control models.

The complexity and uncertainty of CN arise from the interactions of active elements (enterprises). The past researches on utilization of MAS to CN problems have been mostly dealing with agent based software architectures, where agents are autonomous, goal-oriented software processes. We propose to consider the agents *as not only software entities for negotiation support, but also as conceptual modeling entities*. We consider the agents as a part of the generic model constructions. It means that the agents are used not only on the stage of software simulation, but also at the levels of *the conceptual modeling, formalization and mathematical modelling.*

Due to complexity and uncertainty of CN modeling adequacy cannot be ensured within a single model, thus *multiple-model complexes* should be used. Each class of models can be applied to the objects for analysis of their particular aspects at a given level of detail. The interconnection between different models is ensured by means of functors (*F*) (see Figure 1).

The multiple-model complexes allow problem examining and solution in different classes of models, and result representation in the wishful class of models (concept of *"virtual" modelling*). It becomes possible under the terms of collective application of structural mathematical and categorical functoral conceptions. Paper (Sokolov and Yusupov, 2004) demonstrates the capabilities of the categorical-functoral approach to qualimetry of models.

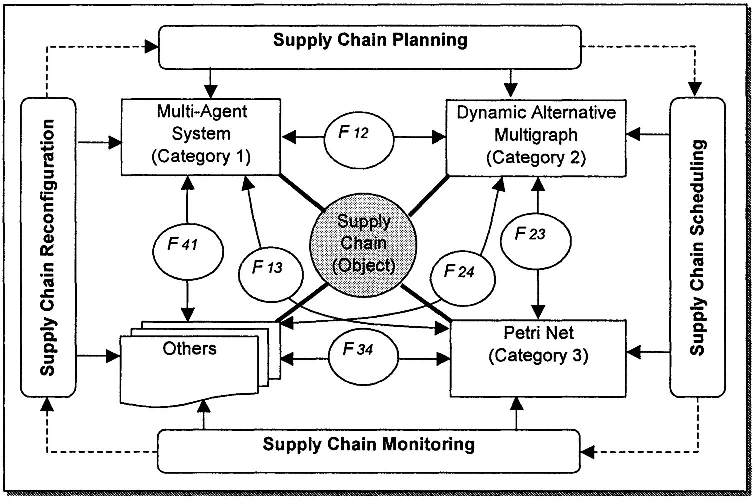

Figure 1. Example of a multiple-model complex

The adaptive planning and control is based on the system planning approach, which lets interpret planning not as discrete operations, but as continuous adaptive process. The concept of adaptive planning and control *incorporates* the phases of planning, monitoring and regulation, and makes it possible to adapt the models of planning and control in accordance with the actual execution environment by means of change of partner selection principles, change of selection algorithms, change of model parameters and criteria, etc.

The *general structure of quantitative models of collaborative networks* is shown in Figure 2.

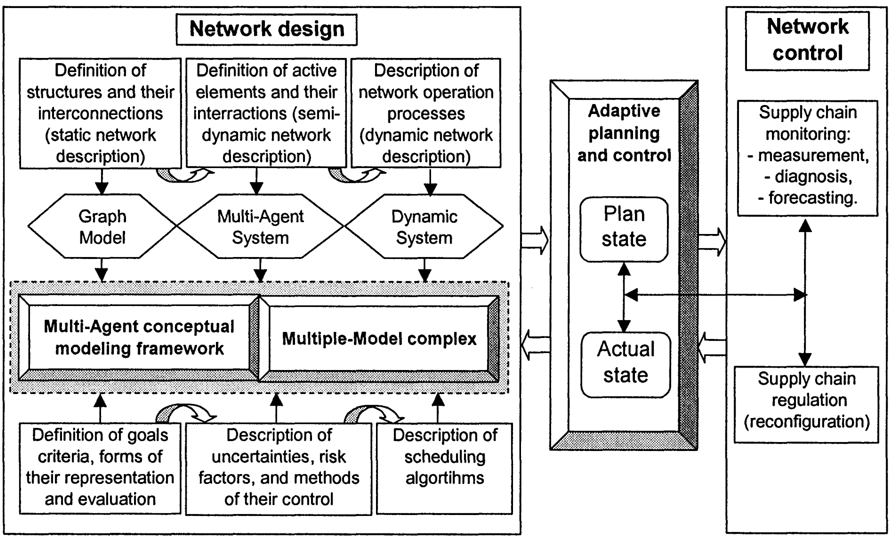

Figure 2. The general structure of quantitative models of collaborative networks

The modelling starts with the static graph-theoretical network description. 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. The next step consists of dynamic network description, which is composed of structure dynamics description and dynamic network operation description. Then the environment description is needed. By the definition of goal criteria it is essential, first, to define methods how to balance the global network criteria (from customers' orders) and local goals of the agents, and secondly, to elaborate forms of multi-criteria selection procedure. The next step of the environment description consists of uncertainty analyzing and integration of risk factors in the models. Then the scheduling algorithms can be elaborated.

The models of network control are comprised of supply chain monitoring and supply chain regulation (reconfiguration) models. Supply chain execution is a highly dynamic process complicated by structure dynamics, changes of network properties and parameters while decision-making, goal-oriented behaviour of enterprises. That is why it is necessary to formulate the models of monitoring and regulations of supply chains complex with the network design models in order to ensure the adequacy of models to the *current execution environment.*

Now let us illustrate the above-described principles. We consider dynamic supply chain building through partner selection from a pool of available suppliers in a CN. The network design is composed of: (i) selecting offers for each operation (formation of a set of alternative supply chains) and (ii) evaluating of alternative supply chains and selecting the best one. Let the number of initial data be denoted in the following way. CN is a set $B = \{B_\mu, \mu \in M\}$ of participant enterprises, which can fulfil a number of operations (jobs) $O = \{O_j, j \in L\}$. A pair (B_μ, O_j) is called *competence,* so that if the μ-enterprise can do the j-operation, so it posses competence $k_{\mu j}$. Each offer of the competence is characterized by available capacity $x_{\mu j}(t)$, costs $c_{\mu j}$, risk $q_{\mu j}$. So the offer network can be modeled graph-theoretically as a *directed graph (digraph).* The competences and their offers represent the nodes, and the edges between the nodes represent the corresponding allowed predecessor-successor-relations between the competences in the offer network.

Then we introduce the specific description of the *active objects in terms of multi agent theory.* For formal representations of agents three main functions are usually used (Kaihara, 2004): production function, profit function and bidding function. The agents try to fill up their capacities of each competence $x_{\mu j}(t) - \tau_j^\nu(\lambda_{\nu j}^\mu) \to \min, \lambda_{\nu j}^\mu \in \Delta, \lambda_{\nu j}^\mu \in \{0;1\}$, so as to maximize the discrepancy between price and costs $p_j^\nu - c_{\mu j}(\lambda_{\nu j}^\mu) \to \max$, where Δ - set of alternatives of resource allocation. For the set of orders, the profit function can be formulated as

$$J_1^\mu = \sum_{j=1}^{L} x_{\mu j}(t) - \sum_{j=1}^{l}\sum_{\nu=1}^{N} \tau_j^\nu(\lambda_{\nu j}^\mu) \to \min \qquad J_2^\mu = \sum_{j=1}^{l}\sum_{\nu=1}^{N} p_j^\nu - \sum_{j=1}^{l}\sum_{\nu=1}^{N} c_{\mu j}^\nu(\lambda_{\nu j}^\mu) \to \max$$

In order to take into account so called soft-factors (e.g., reputation, trust etc.), we consider also a reputation function of agents $r_{\mu j} = r_{\mu j}(W_{\mu j}, V_j)$, where $W_{\mu j}$ – knowledge about the agent B_μ, to competence $k_{\mu j}$, V_j – importance of the job O_j. The bidding function of an agent B_μ, to competence $k_{\mu j}$ at the instant of time t can be formulated as $BF_{\mu j} = f(x_{\mu j}(t), c_{\mu j}, q_{\mu j}, r_{\mu j})$.

Now the *dynamic network operation models* have to be constructed. We propose to use a functorial transition from the category of digraphs that specifies the static network models, 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 (Sokolov and Yusupov, 2004).

The supply chain is characterized by a set of structures which are formed while supply chain synthesis (organizational, informational, topological, technological structures etc.). Let us introduce in terms of the control theory a *dynamic alternative multi-graph* (DAMG) to relate these structures (Ivanov et al., 2004). The usage of DAMG allows representation of the graph-theoretical model in terms of dynamic linear system. It also allows forming of multi-structural macro states, and makes it possible to obtain a complex view on the network operation in dynamics.

Then we elaborate a complex of *dynamic network operation models* to describe the functioning of the supply chains (they will be discussed in one of our future papers). The dynamic network operation models let to describe the functioning of the supply chains (changing of order's states, changing of enterprise states with each operation to reflect the consumption of resources, as well as external operations to supply these resources from outside, etc.).

After the network description the goal criteria definition is needed. A set of orders to be planned is described as $A=\{A_\nu, \nu \in N\}$. Each order has a technology, which contains sequence of operations O_j $(j=1,2,\dots,j_\nu)$. Realization of customer's orders is to finish in accordance with such parameters as desired delivery time, price limit, and accepted risk level (*reliability level* of a supply chain). The measure *supply chain reliability* is introduced in order to form and constrict set of Pareto optimal supply chains. It is also important to take into account some additional organizational constraints. For the optimal supply chain selecting is to define a principle of multi-criteria decision making, e.g based on the AHP-method. In our approach, the goal criteria (desired delivery date, costs, etc.) are represented as a multi-criteria selection structure. The optimal supply chain is selected with a scheduling algorithm, for example, an ACO-algorithm.

After the scheduling is finished, the *sensitivity analysis* takes place in order to analyze supply chain perceptivity and stability. Sensitivity theory lets analyze complex the uncertainty factors and integrate them in the models. The evaluation of *supply chain stability* is meant for the final decision making about the network design, and is the last step in the network design process. Special tools such as Workflow-systems support the sensitivity analysis. So the plan network state is generated.

However, the system and the environment can change during the operation, therefore it is necessary to correct plans periodically. In our approach, *monitoring of supply chain* is based on the monitoring of macro-structural states of the supply chains (Ivanov et al., 2004) as well on the *supply chain stability monitoring*. The particular feature of the SC monitoring in the terms of *macro states* is that at the each monitoring stage the parameters controlled are extracted from the parameter vector of the DAMG. The extracting rules depend on the management goals at the stage monitored. It makes it possible to consider all the parameters of supply chain execution described as the DAMG, and on the other hand to extract the necessary parameters to be controlled in a current execution situation. The other particular feature of the SC monitoring is analyzing of supply chain stability. Analysis of SC execution with the use of stability indicator lets determine the moment when reconfiguring of SC is needed.

Supply chain 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 to the planned one. The model of supply chain reconfiguration is interconnected to the network design model. At the first phase of reconfiguration forming (generation) of allowable multi-structural macro-states is being performed. In other words a structure-functional synthesis of a new supply chain should be fulfilled in accordance with an actual or forecasted situation. At the second phase a single multi-structural macro-state is being selected, and adaptive plans of supply chain transition to the selected macro-state are constructed.

The above-named concepts and models are realized as software, e.g. EVCM (Extended Value Chain Management) (Teich, 2003, Zschorn et al., 2005), which provide IT-support for automatic network design, simulation tool SNDC (Supply Network Dynamic Control) intended for network design and supply chain scheduling, and computer-aided monitoring system (CMS). The EVCM-tool represents a web-based environment for the network design based on interaction between enterprises, and enterprises and customers. Software SNDC facilitates real-time planning and control of the processes and states of supply chains in CN. The obtained numerical results are satisfactory. The further direction of our researches is to provide the software SNDC with the agent oriented technologies.

4. CONCLUSIONS

The elaborated methodology provides the comprehensive quantitative modeling of CN. It allows taking into account activity of system elements (goal-oriented behaviour of enterprises) by their describing as agents. So the decentralized scheduling by means of agent negotiations is enhanced by the usage of control theory allows generating the ideal control programs for evaluating of the plans found by agents. The utilization of MAS to conceptual modelling framework also allows interconnecting the decentralized scheduling algorithms and learning algorithms. The usage of of multi-structural macro states makes it possible to obtain a complex view on the network operation in dynamics. The other advantage of the proposed approach is that the design process as well as the monitoring and reconfiguration of supply chains in CN are considered complex based on the unified methodological principles and systematic integrating factors of uncertainty in CN design and control models. It allows interconnecting of planning and control models as well as adaptation of supply chains and their models to the current execution environment. The presented approach allows development of vast model constructions for planning and execution in CN contributes to advancing of *theoretical foundations* of CN as well as to providing new advanced techniques for *practical management* in the areas of strategic planning, forecasting, and operative system management.

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