OPTIMAL STRUCTURE COORDINATION IN SUPPLY CHAIN (SC): PRINCIPLES, MODELS, METHODS AND ALGORITHMS FOR THE SC STRUCTURE DYNAMICS CONTROL

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ABSTRACT
One of the main features of modern supply chains (SC) is the variability of their parameters and structures caused by objective and subjective factors at different stages of the SC life cycle. In other words, we always come across the SC structure dynamics in practice. Under the existing conditions the SC potentialities increment (stabilization) or degradation reducing makes it necessary to perform the SC structure control and management (including the control of structures coordination). The aim of this investigation is to develop a generalized description of models, methods and algorithms for the SC structure dynamics control.

Keywords: supply chains, control of structures coordination, decision support system

1. INTRODUCTION

Analysis of the main trends for modern complex technical systems (SC) indicates their peculiarities such as: multiple aspects and uncertainty of behavior, hierarchy, structure similarity and surplus for main elements and subsystems of SC, interrelations, variety of control functions relevant to each SC level, territory distribution of SC components.

One of the main features of modern SC is the variability of their parameters and structures caused by objective and subjective factors at different stages of the SC life cycle (Okhtilev, Sokolov, and Yusupov 2006; Peregudov and Tarrasenko 1989; Ivanov and Sokolov 2010; Ivanov and Sokolov 2012). In other words, we always come across the SC structure dynamics in practice. Under the existing conditions the SC potentialities increment (stabilization) or degradation reducing makes it necessary to perform the SC structure control (including the control of structures coordination). There are many possible variants of SC structure dynamics control. For example, they are: alteration of SC functioning means and objectives; alteration of the order of observation tasks and control tasks solving; redistribution of functions, problems and control algorithms between SC levels; reserve resources control; control of motion of SC elements and subsystems; coordination of SC different structures.

According to the contents of the structure dynamics control problems they belong under the class of the SC structure — functional synthesis problems and the problems of program construction, providing for the SC development.

The main feature and the difficulty of the problems, belonging under the above mentioned class is a follows: optimal programs, providing for the SC main elements and subsystems control can be implemented only when the lists of functions and control and information-processing algorithms for these elements and subsystems are known.

In its turn, the distribution of the functions and algorithms among the SC elements and subsystems depends upon the structure and parameters of the control rules, valid for these elements and subsystems. The described contradictory situation is complicated by the changes of SC parameters and structures, occurring due to different causes during the SC life cycle.

Coordination is one of the central issues in supply chain management (SCM) that is applied by companies with the aim to successfully meet the customer needs while improving the performance efficiency (Chen and Hall 2007). The study by Hall and Potts (2003) introduced the consideration of benefits challenges of coordinated decision-making within SC scheduling. Most recently, Agnetis et al. (2006) and Disney et al. (2008) investigated the impacts of schedule coordination on SC performance. Chung et al. (2011) considered minimization of order tardiness through collaboration strategy in a multi-factory production system. In SC schedule coordination, two or more processes are typically considered subject to their mutual coordination. This coordination may be subject to coordinating schedules of different suppliers with some planned schedule changes by one of them, or simultaneous consideration of different interlinked flows (e.g., material and information flows). In practice, due to some re-scheduling activities (i.e., new rush customer orders) at one of the companies, the schedule coordination should be performed again. In this study, we consider two synchronized schedules in the supply chain (e.g., an assembly line schedule at a production company and a supply schedule for a module). This problem is a dynamic scheduling problem where machine capacities are constrained (Ivanov and Sokolov 2012) and a schedule recovery is needed. The body of literature on this issue is limited. Recently, schedule recovery has been considered for situations where one of the suppliers is disturbed (Xiao et al. 2007; Xiao TJ, Qi XT and Yu G 2007). Chen and Xiao 2009 studied an assembly system where suppliers provide parts to a manufacturer. Hall and Liu (2011) investigated the capacity allocation by a manufacturer who faces the challenge of limited resources subject to orders from distribution centers. Similar problems can be found in regard to maintenance scheduling and adjustable machines. The goal of this study is to develop an approach in order to ensure an explicit inclusion of schedule changes in the SC coordinated decisions. The peculiarity of the proposed approach is the dynamic interpretation of scheduling based on a natural dynamic decomposition of the problem and its solution with the help of a modified form of continuous maximum principle blended with combinatorial optimization.

At present, the class of problems under review is not examined quite thoroughly. The new theoretical and practical results have been obtained in the following lines of investigation: the synthesis of the SC technical structure for the known laws of SC functioning (the first direction — Peregudov and Tarrasenko 1989; Ackoff 1978; Aframchuk 1998; Peschel 1978); the synthesis of the SC functional structure, in other words, the synthesis of the control programs for the SC main elements and subsystems under the condition that the SC technical structure is known (the second direction - Okhtilev, Sokolov, and Yusupov 2006; Ivanov 2010; Ivanov and Sokolov 2010; Skurikhin, Zabrodskii, and Kopeichenko 1989); the synthesis of programs for SC construction and development without taking into account the periods of parallel functioning of the existing and the new SC (the third direction — Ivanov 2010; Ivanov and Sokolov 2010; Arnott 2004); the parallel synthesis of the SC technical structure and the functional one (the fourth direction — Ivanov and Sokolov 2010; Okhtilev, Sokolov, and Yusupov 2006).

Several iterative procedures to solve the joint problems, concerning the first and the second directions, are known currently. Some particular results were obtained within the third and the fourth directions of investigation. All the existing models and methods for the SC structure — functional synthesis and for the construction of the SC development programs can be applied during the period of the internal and external design when the time factor is not very important.

The problem of SC structure dynamics control consists of the following groups of tasks: the tasks of structure dynamics analysis of SC; the tasks of evaluation (observation) of structural states and SC structure dynamics; the problems of optimal program synthesis for structure dynamics control in different situations. Therefore, the development of new theoretical bases for SC structure dynamics control is currently very important. From our point of view, the theory of structure dynamics control will be interdisciplinary and will accumulate the results of classical control theory, operations research, artificial intelligence, systems theory, and systems analysis. The two last scientific directions will provide a structured definition of the structure dynamics control problem instead of a weakly structured definition. These ideas are summarized in Figure 1. Here, as the first step to the new theory, we introduce a conceptual and formal description of SC structure dynamics.

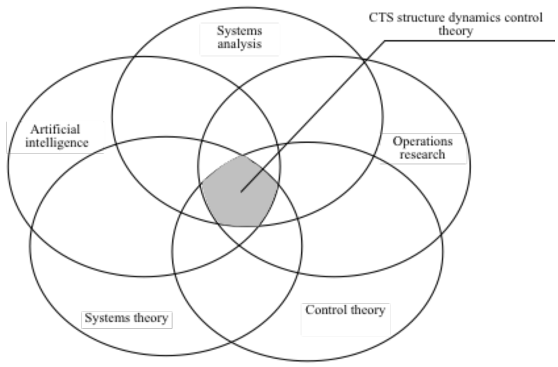

Figure 1: The theory of structure dynamics control as a scope of interdisciplinary investigations

2. CONCEPTUAL AND MULTIPLE-MODEL DESCRIPTION OF SC STRUCTURE DYNAMICS CONTROL

The preliminary investigations have confirmed that the most convenient concept for the formalization of SC control processes is the concept of an active mobile object (AMO). In the general case, it is an artificial object (a complex of devices) moving in space and interacting (by means of information, energy, or material flows) with other AMO and objects-in-service (OS) (Kalinin and Sokolov 1985; Kalinin and Sokolov 1987; Kalinin 2015). Figure 2 shows a general structure of AMO as an object being controlled. AMO consists of four subsystems relating to four processes (functioning forms): moving, interaction with OS and other AMO, functioning of the main (goal-oriented) and auxiliary facilities, resources consumption (replenishment).

The four functions of AMO are quite different, though the joint execution of these functions, the interaction being the main one, provides for SC new characteristics. Thus, it becomes a specific object of investigation, and SC control problems are strictly different from classical problems of mechanical-motion control. The notion of "Active Mobile Object" generalizes features of mobile elements dealing with different SC types. Depending on the type of Active Mobile Objects, they can move and interact in space, in air, on the ground, in water, or on the water surface. The Active Mobile Object (AMO) can be also regarded as a multi-agent system. We distinguish two classes of AMO: AMO – one, namely AMO of the first type. This type of AMO fulfills AMO principal tasks; and AMO – two, which supports functioning of AMO – one. Objects-in-service can be regarded as external AMO.

For example, on the one hand, distribution centers, factories, warehouses can be interpreted as AMO – two, on the other hand, various types of production at different stages of their life cycles may be regarded as AMO – one.

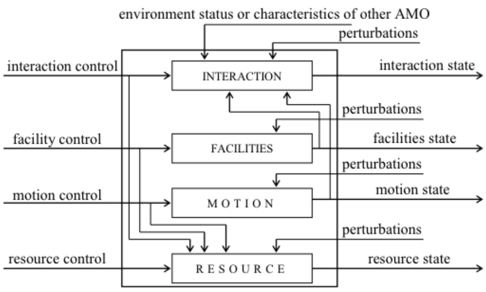

Figure 2: General block diagram of AMO

Thus, at the conceptual level, the process of SC functioning can be described as a process of SC operation execution, while each operation can be regarded as a transition from one state to another. Meanwhile, it is convenient to characterize the SC state by the parameters of operations.

The particular control models are based on the dynamic interpretation of operations and the previously developed particular dynamic models of SC functioning.

In accordance with the proposed conceptual model of SC control, let us introduce the following basic sets and structures: B is a set of objects (subsystems, elements) that are embodied in SC and are necessary for its functioning. $\overline{B}$ is a set of external objects (subsystems, elements) interacting with SC (the interaction may be informational, energy or material). $\widetilde{B} = B \cup \overline{B}$ is a set of the considered objects. $\widetilde{C} = C \cup \overline{C}$ is a set of channels (hardware facilities) that are used by SC and OS for interaction. D is a set of SC operations. Φ is a set of SC resources. P is a set of SC flows. $G = \{G_\chi, \chi \in NS\}$ is a set of SC structural types, where the main types of structures are the topologic (spatial) structure, the technology (functional) structure, the technical structure, the structures of mathematical and software tools, and the organizational structure.

To interconnect the structures let us consider the following dynamic alternative multi-graph (DAMG):

$$G^t_\chi = \left\langle X^t_\chi, F^t_\chi, Z^t_\chi \right\rangle, \quad (1)$$

where the subscript χ characterizes the SC structure type, $\chi \in NS = \{1,2,3,4,5,6\}$ (here 1 indicates the topologic structure, 2 indicates the functional structure, 3 indicates the technical structure, 4 and 5 indicate the structures of mathematical and software tools, 6 indicates the organizational structure, the time point t belongs to a given set T; $X^t_\chi = \{x^t_{\chi l}, l \in L_\chi\}$ is a set of elements of the structure G^t_χ (the set of DAMG vertices) at the time point t; $F^t_\chi = \{f^t_{<\chi,l,l'>}, l, l' \in L_\chi\}$ is a set of arcs of the DAMG G^t_χ; the arcs represent relations between the DAMG elements at time t; $Z^t_\chi = \{f^t_{<\chi,l,l'>}, l, l' \in L_\chi\}$ is a set of parameters that characterize relations numerically.

The graphs of different types are interdependent, thus, for each particular task of SC structure–dynamics control the following maps should be constructed:

$$M^t_{<\chi,\chi'>} : F^t_\chi \to F^t_{\chi'}, \quad (2)$$

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

$$M^t_{<\chi,\chi'>} = M^t_{<\chi,\chi_1>} \circ M^t_{<\chi,\chi_2>} \circ \ldots \circ M^t_{<\chi'',\chi'>}. \quad (3)$$

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

$$\begin{aligned} S_\delta &\subseteq X^t_1 \times X^t_2 \times X^t_3 \times X^t_4 \times \\ &\times X^t_5 \times X^t_6, \quad \delta = 1,\ldots,K_\Delta \end{aligned}. \quad (4)$$

Thus we obtain the set of SC multi-structural states:

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

Allowable transitions from one multi-structural state to another can be expressed via the maps:

$$\Pi^t_{<\delta,\delta'>} : S_\delta \to S_{\delta'}. \quad (6)$$

Here we assume that each multi-structural state at time $t \in T$ is defined by a composition (3).

Now the problems of SC structure dynamics control can be regarded as a selection of a multi-structural state $S^*_\delta \in \{S_1, S_2, \ldots, S_{K_\Delta}\}$ and of a transition sequence (composition) $\Pi^{t_1}_{<\delta_1,\delta_2>} \circ \Pi^{t_2}_{<\delta_2,\delta_3>} \circ \Pi^{t_f}_{<\delta',\delta>}$ ($t_1 < t_2 < t_f$), under some criterion of effectiveness. The results of the selection can be presented as the optimal program for SC structure dynamics control. This

program guides the system from a given multi-structural state to the specified one.
Figure 3 presents the interpretation of structure dynamics processes for SC functioning problems.
Here: $\Gamma_{\chi}^{t_1}$ is the functional structure of SC at moment t_1, $\Gamma_{\chi_1}^{t_1}$ is the technical structure of SC at moment t_1. The dynamic alternative multi-graphs $G_{\chi}^{t_1}$, $G_{\chi_1}^{t_1}$ describe functional and technical structure dynamics. Next figure describes the graphical interpretation of a particular problem of SC structure dynamics control. In this case, the main point of the problem is that a flexible distribution of tasks between the main elements of SC control system (CS) is to be established. This problem is strictly interrelated with a problem of optimal dynamic allocation of limited resources in SC CS. These two problems should be solved jointly. In this case, the problem of SC structure dynamics control can be stated as a problem of an optimal path search in the dynamic alternative multi-graph (Figure 4). Today, different methods and models are used to solve these problems.

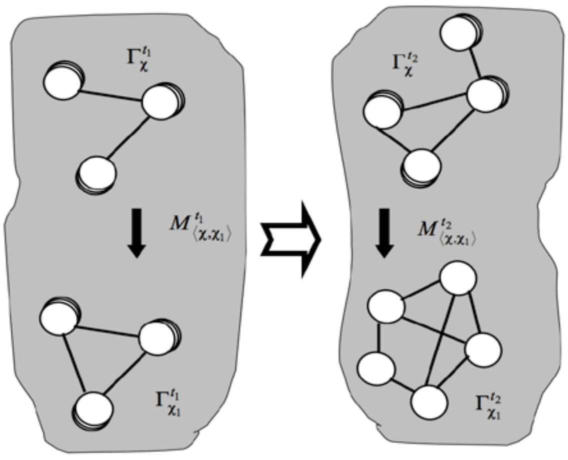

Figure 3: Structure dynamics process for SC functioning problems

The known approaches to these problems are based on the PERT description of scheduling and control problems and traditional dynamic interpretation. The realization of these dynamic approaches produces algorithmic and computational difficulties caused by high dimensionality, non-linearity, non-stationarity, and uncertainty of the appropriate models.
We proposed modifying the dynamic interpretation of operations control processes. The main idea of model simplification is to implement non-linear technological constraints in sets of allowable control inputs rather than in the right parts of differential equations. In this case, Lagrangian coefficients, keeping the information about technical and technological constraints, are defined via the local-sections method. Furthermore, we proposed that interval constraints are used instead of relay ones. Nevertheless, the control inputs take on Boolean values as caused by the linearity of differential equations and convexity of the set of alternatives. The proposed substitution allows using fundamental scientific results of the modern control theory in various SC control problems (including scheduling theory problems).

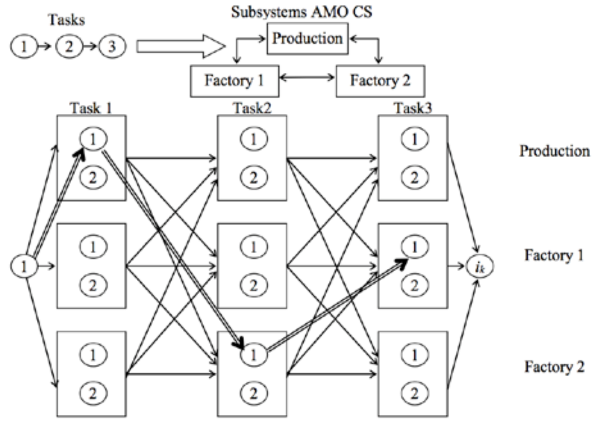

Figure 4: Graphical interpretation for particular problem of SC structure dynamics control

As provided by the concept of SC multiple-model description, the proposed general model includes the particular dynamic model: dynamic model of SC motion control (Mg model); dynamic model of SC channel control (Mk model); dynamic model of SC operations control (Mo model); dynamic model of SC flows control (Mn model); dynamic model of SC resource control (Mp model); dynamic model of SC operation parameters control (Me model); dynamic model of SC structure dynamic control (Mc model); dynamic model of SC auxiliary operation control (Mv model) (Okhtilev, Sokolov and Yusupov 2006; Ivanov 2010; Ivanov and Sokolov 2010).
Figure 5 illustrates a possible interconnection of the models.
Procedures of structure dynamics problem solution depend on the variants of transition and output functions (operators) implementation. Various approaches, methods, algorithms and procedures of the coordinated choice through complexes of heterogeneous models have been developed by now.
SC structure-dynamic control problem has some specific features in comparison with classic optimal control problems. The first feature is that the right parts of the differential equations undergo discontinuity at the beginning of interaction zones. The considered problems can be regarded as control problems with intermediate conditions. The second feature is the multi-criteria nature of the problems. The third feature concerns the influence of uncertainty factors. The fourth feature is the form of time-spatial, technical, and technological non-linear conditions that are mainly considered in control constraints and boundary conditions. On the whole, the constructed model is a non-linear, non-stationary, finite-dimensional

differential system with a re-configurable structure. Different variants of model aggregation were proposed.

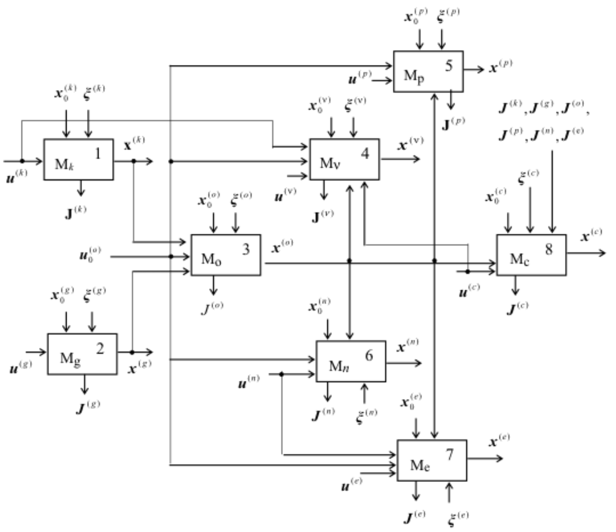

Figure 5: The scheme of model interconnection

These variants produce a task of model quality selection that is the task of model complexity reduction. Decision-makers can select an appropriate level of model thoroughness in the interactive mode. The level of thoroughness depends on: input data, external conditions, and the required level of solution validity.

The proposed interpretation of SC structure dynamics control processes provides advantages of modern optimal control theory for SC analysis and synthesis. During the investigations we described the main classes of SC structure dynamics problems. These problems include: SC structure dynamics analysis problems; SC structure dynamics diagnosis, observation, multi-layer control problems; problems of SC generalized structural states synthesis and the choice problems of optimal transition programs providing the transition from a given SC structural state to an allowable (optimal) structural state. Methodological and methodical bases for the theory of structure dynamics control were developed. Methodological bases include the methodologies of the generalized system analysis and the modern optimal control theory for SC with re-configurable structures. The methodologies find their concrete reflection in the corresponding principles. The main principles are: the principle of goal programmed control; the principle of external complement; the principle of necessary variety; the principles of multiple-model and multi-criteria approaches; the principle of new problems. The dynamic interpretation of structure dynamics control processes allows for the application of the results, previously received in the theory of dynamic systems stability and sensitivity, for SC analysis problems.

During our investigations the main stages and steps of a program-construction procedure for optimal structure dynamics control in SC were proposed.

At the first stage, the formation (generation) of allowable multi-structural macro-states is performed. In other words, a structure-functional synthesis of a new SC make-up should be fulfilled in accordance with the current or a forecasted situation. Here, the first-stage problems come to SC structure-functional synthesis.

The general algorithm of the SC structure-functional synthesis includes the following main steps.

Step 1. Gathering, analysis, and interrelation of input data for the synthesis of SC multi-structural macro-states. Construction or correction of the appropriate models.

Step 2. Planning the solution process for the problem of the SC macro-states synthesis. Estimation of time and other resources needed for the problem.

Step 3. Construction and approximation of an attainability set (AS) for the dynamic system (1). This set contains an indirect description of different variants of SC make-up (variants of SC multi-structural macro-states).

Step 4. Orthogonal projection of a set defining macro-state requirements to AS.

Step 5. Interpretation of output results and their transformation to a convenient form for future use (for example, the output data can be used for the construction of adaptive plans of SC development).

At the second stage, a single multi-structural macro-state is selected, and adaptive plans (programs) of SC transition to the selected macro-state are constructed. These plans should specify transition programs, as well as programs of stable SC operation in intermediate multi-structural macro-states. The second stage of program construction is aimed at the solution of multi-level multi-stage optimization problems. The general algorithm of problem solving should include the following steps.

Step 1. Input data for the problem are prepared and analyzed in an interactive mode. During this step, the structural and parametric adaptation of models, algorithms, and special software tools of simulation system (SIS) is fulfilled to the past states and to the current states of the environment, object-in-service, and control subsystems embodied in existing and developing SC. For missing data simulation experiments with SIS models or expert inquest can be used.

Step 2. Planning the comprehensive modeling of adaptive SC control and development for the current and forecasted situation; planning of simulation experiments in SS; selection of models, selection of model structure; determination of methods and algorithms for particular modeling problems, selection of models and model structure for this problems; estimation of the necessary time.

Step 3. Generating, via comprehensive modeling, the feasible variants of SC functioning in initial, intermediate, and required multi-structural macro-states; introducing the results to a decision-maker; preliminary interactive structure-functional analysis of modeling results; producing equivalent classes of SC multi-structural macro-states.

Step 4. Automatic putting into operation of data of SC functioning variants; analysis of constraints correctness; final selection of aggregation level for SC SDC models, and for computation experiments aimed at SC SDC program construction.

Step 5. Search for optimal SC SDC programs for the transition from a given multi-structural macro-state to a synthesized one and for stable SC operation in intermediate multi-structural macro-states.

Step 6. Simulation of program execution under perturbation impacts for different variants of compensation control inputs received via methods and algorithms of real-time control.

Step 7. Structural and parametric adaptation of the plan and of SIS software to possible (forecasted through simulation models) states of SO, CS, and of the environment.

Here, SC structural redundancy should be provided to compensate for extra perturbation impacts. After reiterative computation experiments the stability of constructed SC SDC plan is estimated.

Step 8. Introducing comprehensive adaptive planning results to a decision-maker; interpretation and correction of these results.

One of the main opportunities of the proposed method of SC SDC program construction is that besides the vector of program control we receive a preferable multi-structural macro-state of SC at the end point of control interval. This is the state of SC reliable operation in the current (forecasted) situation.

The combined methods and algorithms of optimal program construction for structure dynamics control in centralized and non-centralized modes of SC operation were developed too.

The main combined method was based on the joint use of the successive approximations method and the “branch and bounds” method. A theorem characterizing properties of the relaxed problem of SC SDC optimal program construction was proved for a theoretical approval of the proposed method. Different examples (Okhtilev, Sokolov, and Yusupov 2006; Yusupov et al. 2011; Ivanov 2010; Ivanov and Sokolov 2010; Ivanov and Sokolov 2012; Ivanov and Sokolov 2013) illustrated the main aspects of the implementation of the proposed combined method.

3. CONCLUSION

The methodological and methodical basis of the theory of SC structure dynamics control and coordination has been developed by now. This theory can be widely used in practice. It has an interdisciplinary character provided by the classic control theory, operations research, artificial intelligence, systems theory, and systems analysis. The dynamic interpretation of SC coordination process provides a strict mathematical basis for complex technical-organizational problems that were never formalized before and have a high practical importance.

The proposed approach to the problem of SC structure coordination control in terms of general context of SC structural dynamics control enables: common goals of SC functioning to be directly linked with those implemented (realized) in SC control process, a reasonable decision and selection (choice) of adequate consequence of problems solved and operations fulfilled related to structural dynamics to be made (in other words to synthesize and develop the SC control method), a compromise distribution (trade-off) of a restricted resources appropriated for a structural dynamics control to be found voluntary (Okhtilev, Sokolov, and Yusupov 2006; Ivanov 2010; Ivanov and Sokolov 2010).

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