Application of the Hybrid Agents Technology for Control of the Construction Company

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Abstract—**Planning the project duration together with separate works is an essential element of managing the construction. The final duration depends on multiple factors, including the funds, customer requests, and capabilities of the construction company. In order to avoid additional costs in penalties or additional expenses, the management needs to estimate the real construction duration in advance, before the contract is signed. Further on, these terms need to be monitored both in whole and for the specific jobs in order to be able to edit further stagers with regard of the remaining time, resources and used resources ratio. The development of a decision support system for the construction company is a pressing problem due to the growing demand in decision making persons' labor automation in planning and monitoring the construction processes. The paper presents the model and the application experience for such a system.**

Keywords—control; construction; planning; multi-agent simulation; decision support; subcontract

I. Introduction

In management and decision-making in the sphere of construction problem-oriented network planning systems (such as MS Project and TimeLine) are used, as well as simulation modelling systems (SMS), with the model being adjusted to the specific needs or with ready-made templates for formalizing problem areas (ARIS with eM-Plant module, Arena, AnyLogic, BPsim). The automation of decision-making in construction management based on situational network planning models is described in [1].

Construction work management implies performing two subtasks: 1) scheduling work and allocating resources for specific tasks (labor - your own and your subcontractor's - resources, material and technical – your own and leased - resources, financial resources – your own and invested funds); 2) monitoring internal and external environment changes, rapidly adjusting the work schedule to achieve effective performance taking into account temporal, financial and resource constraints [2].

The completion of the two tasks identified above can be considered from different angles. Traditionally, decision-makers use PERT (Project Evaluation and Review Technique), a technique for project evaluation and analysis, when planning. Within the framework of this method the decision-maker, using specialized tools (e.g., MS Project, TimeLine), plots on a diagram the relationship of events and work activities, characterized by duration, cost and resources required. Examples of such diagrams are network diagrams and Gantt charts. Based on the critical path method, the decision-maker, using network diagrams, identifies "bottlenecks" in construction work planning and generates alternative options for work changes in order to eliminate such "bottlenecks" as overloading their own resources, and exceeding the cost limit for specific work, caused, among other things, by the use of extensive subcontracting. Subsequently, the planning options are implemented in a number of network diagrams showing the relationship between work and events for the decision-maker to analyze and identify the most efficient solution taking into account the existing constraints [2].

The disadvantage of this approach to construction work planning is only partial automation of decision-makers' work on the construction of network graphs/Gantt charts and on identifying "bottlenecks" in planning, with a significant amount of work on generating planning alternatives and selecting the most effective options carried out manually on the basis of qualifications, experience and heuristics of taking into account various environmental factors. In view of this, we are considering a different approach to solving construction management problems - the use of multi-agent simulation modelling.

The construction management processes are formalized in a model of multi-agent resource conversion processes (MRCP) [3] which allows evaluating the dynamics of process implementation and cost indicators (implementation time, the presence of duplicate functions, the process cost, staff salaries expenditure, etc.), as well as evaluating the process efficiency indicators (cost-effectiveness, working time and waiting time ratio, and the actual execution time and the planned execution time ratio). The application of multi-agent modelling allows formalizing, by means of the agents' knowledge base, the decision-making model and the accumulated scenarios for solving problems in the field of construction management.

The use of MRCP hybrid agents' technology to formalize the construction work management processes allows automating the decision-makers' functions of generating alternative solutions for various tasks: searching for investors and materials suppliers, selecting subcontractors, detecting and eliminating "bottlenecks" in planning. The use of hybrid agent technology involves describing the subject area with the aid of software products of varying functionality, integrated into a single decision-making support system: dynamic situations modeling system BPsim.MAS system and the system for

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technical engineering and commercial design BPsim.MSN [4]. The BPsim.MSN system implements the technology of intelligent agents (IA) providing the user with a tool to develop intelligent systems. The IA technology allows automating the decision-makers' work of analyzing and synthesizing business systems, such as business process reengineering [5], project management, construction management.

The basis for the dynamic model of design and construction processes implemented in BPsim.MAS is the MRCP model which provides support for work planning and for evaluating various projects of independent property development. The search for solutions model implemented in BPsim.MSN underlies the search for effective solutions for multi-criteria construction management tasks. As a result of integrating the proposed models, complex automation of decision-makers' work in the sphere of construction management is achieved.

II. Developing Models For «Wan Bao» Construction Holding

As a result of examining the subject area the following construction work management steps were identified: drawing up a business plan reflecting the expected economic performance indicators of the holding's activities under certain initial conditions; obtaining a loan for construction; participating in the tender for the construction; planning design and construction work; carrying out design and construction work; selling/renting the constructed objects.

The BPsim.MSN tool was applied to describe the main classes that reflect the holding's database information on materials suppliers, on land characteristics, on subcontractors, on the holding structure, on credit institutions, etc. On the basis of the developed class diagram the business planning agent was designed, providing an automated way to generate alternative business-plans for construction work. The decision maker evaluates the proposed plans and selects a more economically advantageous one.

The initial conditions of the selected business-plan are input in the developed BPsim.MAS MRCP simulation model of design and construction. The model is designed to evaluate the effect of management decisions on the dynamic characteristics of the processes in «Wan Bao» holding. These include: the actual cost of the processes, reallocating resources between processes, downtime, individual processes overload, identified processes that require subcontracting resources, the actual total amount of labor and materials, and the actual duration of the processes. The characteristics evaluation is performed by the model agents.

Let us consider the description of the knowledge base (KB) of the following agents: operations agent *AOp* responsible for identifying operations that require subcontracting; distribution agent *AD* implementing the capture of the application for the operation and the distribution of holding *Rhold* resources and subcontracting resources when performing operation *Op*. The attributes of application *z* to perform operations described above are presented in Table 1.

Table 1: Defining attributes of application *z* to perform operation *Op*

Symbol	Description
z_p	The required labor to perform operation *Op*
z_s	The subcontracted labor required to perform operation *Op*
z_time	The remaining time of operation *Op* performance
z_pr	The mark of subcontracting operation *Op*: 0 – no subcontracting used; 1 – subcontracting used
z_owner	Owner-node of application *z* (agent *AOp* or *AD*, operation *Op*, next model node *NextNode*)
z_d	The date of operation *Op* start
z_m	The month of operation *Op* start

During the development of the agents' knowledge base the following operators working with applications were used: *Select (z, Node)* - application *z* captured by node *Node*; *Select (z, Node) <> 1* - application *z* not captured by node *Node*. When describing the KB the variables comparing simulation time and calendar time were also used: *iRes43* - current day, *iRes44* - current month. The description of KB for agents *AOp* and *AD* and operation *Op* is presented in Table 2.

Table 2: Operation and distribution agents' KB and the description of the operation node

Operation Op agent's knowledge base		
Situation description	**IF Condition**	**THEN Condition**
No subcontracting needed, internal resources are sufficient	*Select(z,AOp)*	*Rhold:= Rhold-z_p*
	(iRes43=z_d)&(iRes44=z_m)	*z_pr:=0*
	z_p≤Rhold	*z_owner:="Op"*
Subcontracting needed, internal resources are insufficient	*Select(z,AOp)*	*z_s:=z_p - Rhold*
	(iRes43=z_d)&(iRes44=z_m)	*Rhold:=0*
	z_p>Rhold	*z_pr:=1*
		z_owner:="Op"
Operation Op launch conditions and exit resources		
Duration	**Launch conditions**	**Output resources**
z_time	*Select(z,Op)*	*Rhold:=Rhold+z_p*
	z_pr=0	*z_owner:="NextNode"*
Distribution agent AD knowledge base		
Situation description	**IF Condition**	**THEN Condition**
Application capture by agent AD with subcontracting required, provided the agent is available	*Select(z,AP)<> 1*	*z_owner:="AP"*
	Select(z,Op)	
	z_pr=1	
The operation time has finished	*Select(z,AP)*	*Rhold:= Rhold+z_p - z_s*
	z_time=0	*z_owner:= "NextNode"*
The operation time has not finished and subcontracting is not needed anymore	*Select(z,AP)*	*z_pr:=0*
	z_time>0	*Rhold:= Rhold-z_s*
	Romд ≥z_s	*z_owner:="Op"*
The operation time has not finished and subcontracting is still needed	*Select(z,AP)*	*z_time:= z_time-1*
	z_time>0	
	Rhold<z_s	

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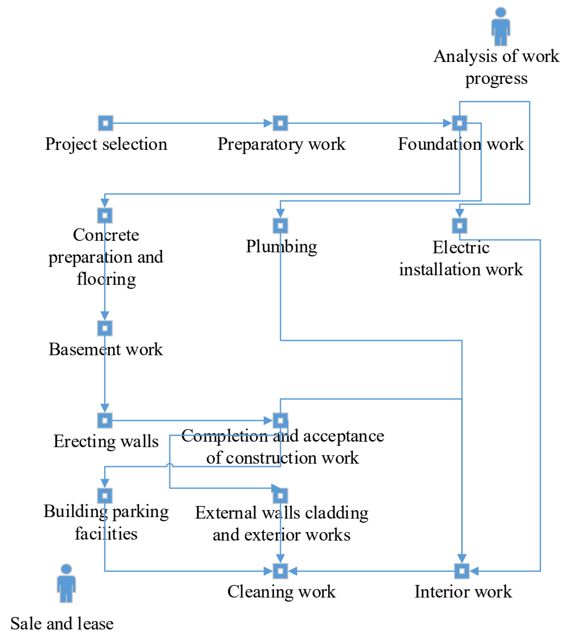
Figure 1 shows the decomposition for the "Construction of a building" node in the MRCP model of construction processes in BPsim.MAS.



Figures 1: BPsim.MAS simulation model of construction work processes

III. Reengineering The Simulation Model Of A Construction Holding

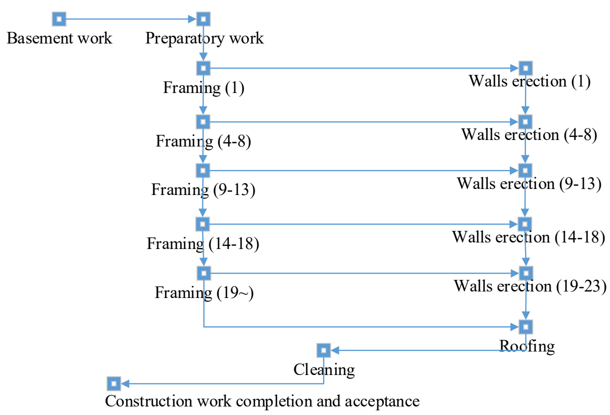
The experiments with the simulation model of the «Wan Bao» Construction Holding revealed that the proposed detalization of the construction work (more than 120 operations, around 90 resources) entails an increase in the amount of computing resources and computing time required for the experiment. In addition, in case of simulating construction of two or more objects, certain operation chains are overloaded (the initially created model allows simulating 1 construction project concurrently), which leads to an increase in the queue for applications and downtime. To eliminate the "bottlenecks", the MRCP model was improved using IA reengineering and roll-out/roll-in procedures. The description of the individual stages of construction work is shown in Figure 2.

The use of intelligent agent reengineering enabled the analysis of operation chains load and plotting branches of operations parallel to chains with excessive load (and the resulting queues). The operations reengineering allowed eliminating overload and reducing the overall execution time. The statistics on the rules of reengineering applied to the construction holding model is presented in Table 3.

IV. Integrating PERT Method With Multi-Agent Simulation Modelling

In order to assess the mathematical expectation and the dispersion of the entire project implementation time, taking into account the impact of various external and internal factors on the construction work, PERT method was used. The method is designed to analyze projects for which the execution time of all or some of the work cannot be determined accurately. The application of the method allows obtaining estimates for [6]:

1) the expected work execution time;
2) the expected project execution time;
3) the probability of the project completion within the time specified.



Figures 2: Detailing the «Walls erection» stage

Table 3: Statistics on applying reengineering rules to the «Wan Bao» construction holding simulation model

Roll-in rule name	Number of changes
Two and more consecutive operations	41 operations rolled-in
Auxiliary (unused) operations	101 operations rolled-in
Independent resource	4 resources withdrawn
Adding parallel chains of operations	32 operation added

To determine the abovementioned numerical characteristics of a work stage (work *j*) three time estimates were identified by carrying out simulation experiments with two subcontracting models [3]:

t_o - an optimistic estimate of work *j* execution time, calculated for the case when work conditions are most favorable [6]. In the context of construction model this estimate is obtained with the aid of simulation model "Subcontracting 2" (in this model the possibility to do without subcontracting is considered at each subsequent step [3]), in the conditions of medium load of the construction holding company;

t_p – a pessimistic estimate of work *j* execution time, calculated for the case when the process develops in the most unfavorable way [6]. This estimate is obtained by means of “Subcontracting” simulation model (in this model external resources are attracted if internal resources are insufficient to carry out the operation from the beginning to completion [3]),

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in the conditions of the maximum load of the construction holding company;

t_{mp} – the most probable estimate of work j execution time, which takes account of the normal course of events [6]. This estimate is obtained by means of "Subcontracting" simulation model [3], in the conditions of the medium load of the construction holding company.

The distribution of the actual work execution time is described by β-distribution. For a subset of critical works S, confidence limits of the project duration are calculated by means of the following formula:

$$T_{C,S} = \sum_{j \in S} (t_e)_j \pm K \sqrt{\sum_{j \in S} (v_e)_j},$$

where t_e is mathematical expectation for β-distribution $t_e = (t_o + 4t_{нв} + t_n)/6$; K – constant that depends on the degree of reliability (K = 3 for 99,7% reliability, K = 2 for 95% reliability); v_e – dispersion for β-distribution $v_e = [(t_n - t_o)/6]^2$.

V. Planning Experiments To Assess The Possibility Of Building An Additional Object

The working conditions and resource potential of the company in question impose limitations on the number of simultaneously constructed buildings – as a rule, 4 projects are implemented concurrently. The objective is to model, to analyze the results and to decide whether it is possible and reasonable to start constructing the fifth object. To achieve this, it is necessary to take into account the possible stages of the projects that are already under implementation, their scale and the replacement of projects near completion with those being launched.

Taking into account the specifics of the projects, the following three construction stages are essential for the analysis: site preparation and foundation work, erecting walls and roofing, exterior and interior finishing work. The company specializes in the construction of two types of buildings - business centers and residential buildings. Let us consider possible situations at the moment when the need arises to make a decision on the construction of the new fifth object.

To determine the total number of possible situations the formulas of combinatory will be used. There are 4 projects; each of them can be in one of the three identified stages, referred to as 1, 2, 3 (i - initial stage, m - middle stage, f - final stage). Therefore, the elements of the space of elementary outcomes in this experiment are the following combinations; 1 1 1 1 (all the objects are in the initial implementation stage); 1 1 1 2 (three objects are in the initial implementation stage, one object is in the second stage), and so on. The outcomes of 1 1 1 2, 1 1 2 1, 1 2 1 1, 2 1 1 1 are identical, as they describe the same situation - three objects are in the initial implementation stage, one object is in the second stage, i.e., the order in the sets is not important. This means that the choice is made out of three elements (stages) four times (to describe the 4 objects) without ordering, with repetition (in the 1 1 1 2 outcome the first stage "repeats" 3 times). To calculate the total number of outcomes let us use the formula of combinations with repetitions:

$$\overline{C}_3^4 = C_{3+4-1}^4 = C_6^4 = \frac{6!}{4!2!} = 15 .$$

The outcomes are given below.

1 1 1 1 All projects are in the initial construction stage
1 1 1 2
1 1 1 3
1 1 2 2
1 1 2 3
1 1 3 3
1 2 2 2
1 2 2 3
1 2 3 3
1 3 3 3
2 2 2 2
2 2 2 3
2 2 3 3
2 3 3 3
3 3 3 3 All projects are in the final construction stage

This approach considers only the project implementation stage. Let us introduce another parameter that reflects the realities of the analyzed company operation - the type of construction projects. To do this, let us expand the set describing the construction stages of individual objects by specifying the type of building (a business center or a residential building):

1b, 2b, 3b – a business center building which is in its first, second or third construction stage respectively;

1r, 2r, 3r – a residential building in its first, second or third construction stage respectively.

A business center construction requires more time and resources compared to a residential building construction. The outcome in this experiment will be, for example, the combination 1b 2b 3r 3r - one of the business centers is in the first stage of construction, another business center is in the second stage, the two residential buildings are in the third stage. In this case, the total number of outcomes is

$$\overline{C}_6^4 = C_{6+4-1}^4 = C_9^4 = \frac{9!}{4!5!} = 126 .$$

Carrying out the obtained number of experiments requires investing substantial time and resources. In order to identify the most realistic situations the additional analysis of the holding operations was carried out, which showed that out of the total number of simultaneously constructed objects no more than two are business centers, i.e. the outcomes of type 1b 1b 1b 1b, 2r 1b 1b 1b, and so on, are impossible. In this case, to calculate the total number of outcomes, the following subsets are singled out:

1) all four objects are residential buildings. Since in this case the outcomes differ only in stages, the total number of outcomes was described above $\overline{C}_3^4 = 15$;

2) one of the objects is a business center and three are residential buildings. So, for the same situation concerning

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three residential buildings, there are three possible combinations taking into account the fourth object - business center - stages. For example, 1r 1r 1r (3 residential buildings are in the first stage of construction); the resulting combinations will be: 1r 1r 1r 1b, 1r 1r 1r 2b, 1r1r1r3b. All the possible combinations for three medium-rise buildings are:

$$\overline{C}_3^3 = C_{3+3-1}^3 = C_5^3 = 10 \ .$$

Each part is expanded with 3 options (stages) for the fourth high-rise object. The result is the number of outcomes that equals $10 \cdot 3 = 30$.

3) 2 objects are business centers and 2 are residential buildings. In this case, for the two pairs of medium and high-rise objects various combinations of stages are possible. Thus, the quantity is

$$\overline{C}_3^2 \cdot \overline{C}_3^2 = \left(C_4^2\right)^2 = \left(\frac{4!}{2!2!}\right)^2 = 36 \cdot$$

Consequently, the total number of combinations in case of no more than two high-rise buildings under construction equals 15 + 30 + 36 = 81.

Another aspect of the company operation, which affects the project execution time and its rate of return, is outsourcing part of the work to companies and individual entrepreneurs. Two subcontracting models were identified on the basis of the analysis [3]. When applying each of the models 81 combinations are possible for the project stages and scale, thus, their total number increases twofold: $81 \cdot 2 = 162$.

The new fifth object can also be of two types - high or mid-rise, and can be implemented under one of the two sub-contracting models. Thus, the total number of possible situations is $162 \cdot 2 = 324$.

To make the experiment reliable it must be taken into account that those projects that are near completion merge with the new ones. Otherwise, all the resources would be used for the decreasing number of objects, which is not the case in reality - besides the new facility, 4 other buildings need to be under construction at the same time.

VI. Experimenting With The Construction Holding Model

The simulation experiment with the construction holding model was conducted with the following initial conditions and simplifications: 1) building 11 objects with the subsequent sale of the constructed area; 2) carrying out the entire construction using loans from credit institutions, taking into account the payment of an interest-free loan; 3) availability of officially owned land suitable for construction; 4) availability of the stock of all the necessary construction materials; 5) calculating pre-tax profit.

Let us estimate the dynamics of the following output characteristics of the model: 1) operating costs of the loan and the workers' wages *fRes93*; 2) income from selling the constructed area *fRes96*; 3) account balance *fRes1 = fRes96-fRes93*, including pre-tax profit, interest on the loan, the cost of land and materials.

The results of the experiments with MRCP model are saved in MS Project and MS Excel.

According to the experiment, the account balance growth trend is associated with the completion of individual objects construction and a substantial increase in the facilities for sale.

The experimental data are consistent with the statistical data of «Wan Bao» construction holding operation for the period of 5 years (from June 2005 to August 2010). Therefore, a conclusion can be made about the adequacy of the developed simulation MRCP model for the management object.

Applying the re-engineering method to analyze "bottlenecks" at the stage of "Framing and erecting walls" is presented in Table 4.

Table 4: Applying the re-engineering method to analyze the «Framing and erecting walls» stage

Initial model At the framing and wall erection stages there are not enough trucks and there is downtime. The reengineering agent suggests: 1) increase the number of trucks; 2) roll-in the parallel operation chains.	Trucks – 50 Trucks load – 18.07% Project duration – **2078** d. Revenue – **8, 15** bn. yuan Experiment – 7hrs. 19 min.
Initial model contracted Model roll-in performed (3 parallel chains removed). The experiment results remained unchanged, the experiment time decreased. Increasing the number of trucks is required.	Trucks– 50 Trucks load- 18.07% Project duration – **2078** d. Revenue – **8, 15** bn. yuan Experiment – 2 hrs. 40 min.
Initial model 2 Increasing the number of trucks by 30 led to queues. The model was rolled-out (parallel chain of operations added). This did not result in a significant decrease of project duration. Trucks load increased to 24.28%:	Trucks– 80 Trucks load- 24,28% Project duration – **1865** d. Revenue – **8, 04** bn. yuan Experiment – 3 hrs. 17 min.
Subcontracting model Alternative solution – subcontracting and reducing the number of company own trucks.	Trucks– 30 Trucks load- 71.21% Project duration – **1363** d. Revenue – **10, 99** bn. yuan Experiment – 5 hrs. 26 min.
Subcontracting model 2 Improving the algorithm of the subcontracting agent (allows using internal resources more efficiently).	Trucks– 30 Trucks load - 78.96% Project duration – **1282** d. Revenue – **15, 66** bn. yuan Experiment – 3 hrs. 38 min.

The initial model (row 1): there is a shortage of trucks and downtime at the framing and walls erection stages. The agent proposes to increase the number of trucks and to roll-in parallel chains.

Row 2 - model roll-in performed (3 parallel chains removed). The experiment results remained unchanged, the experiment time decreased. Increasing the number of trucks is required.

Initial model 2 (row 3): increasing the number of trucks by 30 led to queues. The second step was rolling out the model. This resulted in a decrease of the project execution time by 213 days.

An alternative solution - subcontracting and reducing the internal fleet of trucks (row 4) - significantly improved the model characteristics, reducing the project execution time by another 502 days.

Subcontracting model 2 (row 4) - by improving the subcontract agent's model the project execution time was reduced by another 81 days.

The data of the initial model experiments correlate with the work statistics of «Wan Bao» holding.

In the "Subcontracting" model external resources are attracted if the amount of internal resources is insufficient to implement all the work from beginning to completion. In the "Subcontracting 2" model the possibility of doing without subcontracting is considered at every subsequent step.

The financial analysis of the profiles of different model variants showed that the most effective model is "Subcontracting 2" with the revenue indicator of 16 billion yuan.

A software module was designed for planning experiments and analyzing their results for the system of dynamic situation modelling BPsim.MAS.

VII. Conclusion

The application of the dynamic situations modeling system based on MRCP hybrid agents technology when managing construction holdings provides decision-makers with an automated solution of the following tasks of analyzing and synthesizing complex business systems: drawing up a business-plan by means of business planning developed in BPsim.MSN IA; planning design and construction work on the basis of evaluating the dynamic characteristics of the processes in the experiments with the simulation model developed in BPsim.MAS, including assessing the amount of subcontracting. The integration of dialog expert systems technology and multi-agent simulation modelling provides a continuous comprehensive support for decision-making in construction management. The method application allowed reducing the construction duration by 42% (or 1.6 year / 580 days), increasing the equipment load (compared to purchasing one cargo truck) and raising revenues by 42.4%. The effect of its implementation was increasing revenues by 4.6 billion yuan. The application of multi-agent simulation modelling and PERT method allowed complementing the multi-agent planning method with the estimate of confidence limits of the work execution time.

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References

[1] Startsev, M. A. 1999. Integrated information system for the automated control of construction at an industrial enterprise, based on the hierarchical situational model of network planning. PhD research thesis. Ufa State Aviation Technical University, Ufa, Russia.

[2] Aksyonov, K. A.; A. S. Antonova; Wang Kai; O. P. Aksyonova; and A. A. Lipodaeva. 2011. Development and application of the decision support system for the construction holding. Computer Science: Telecommunications and Control Systems, St. Petersburg State Polytechnical University Journal, vol. 4 (128), 53-61. St. Petersburg, Russia.

[3] Aksyonov, K. A. and N. V. Goncharova. 2006. Dynamic modeling of the multi-agent resource conversion processes. Ural State Technical University, Ekaterinburg, Russia.

[4] Aksyonov, K. A.; I. I. Sholina; and E. M. Sufrygina. 2009. Development and application of the object-oriented system for modeling and decision support for the multi-agent resource conversion processes. Computer Science: Telecommunications and Control Systems, St. Petersburg State Polytechnical University Journal, vol. 80. St. Petersburg, Russia.

[5] Aksyonov, K. A.; A. S. Antonova; and I. A. Spitsina. 2011. Analysis and synthesis of the resource conversion processes based on simulation modeling and intelligent agents. Computer Science: Telecommunications and Control Systems, St. Petersburg State Polytechnical University Journal, vol. 1 (115), 13-19. St. Petersburg, Russia.

[6] Aksyonov, K. A. and Wang Kai. 2011. The problem of roll-in for the simulation model of the multi-agent resource conversion processes. Computer Science: Telecommunications and Control Systems, St. Petersburg State Polytechnical University Journal, vol. 1 (115), 126-132. St. Petersburg, Russia.