Ontology-based Open Multi-agent Systems for Adaptive Resource Management

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Abstract: The paper describes an ontological model of a planning object, which provides flexible configuration of multi-agent resource management systems. The authors propose using the basic ontology of resource planning and then building it up for significantly different domains. The key concept here is “Task”. A relatively universal agent can be created thanks to formalized description of various classes of tasks based on this concept. It can also be customized to a specific domain area. Based on the ontology, an enterprise knowledge base is created. It contains instances of concepts and relations. The paper also introduces new classes of agents for demand and resource networks. The authors then propose a new method of multi-agent planning using this knowledge base. This approach has been already successfully applied in several domain areas through the developed software package. The paper demonstrates that the use of ontologies can improve the quality and efficiency of planning by taking into account multiple factors in real time, thus reducing the cost of creating and maintaining multi-agent systems, as well as development times and risks.

1 INTRODUCTION

With the increasing complexity of tasks, the ability of a business to quickly adapt to changes becomes the most important characteristic that determines economic efficiency of the enterprise (Zhong, R. Y., 2016). We can distinguish adaptability of the first type, in which plans of enterprises change taking into account new unforeseen events, and adaptability of the second type, when changes affect the knowledge underlying decision-making processes for planning activities of enterprises, for example, products, technological processes, capabilities of available resources, etc. The combination of all knowledge and data about the production object and the enterprise itself is increasingly called the “digital twin” of the product and the enterprise (Tao, F., 2017).

In these conditions, enterprise management requires new approaches to automating solution of planning problems, which should gradually become more operational and flexible, rather than strategic and long-term. In fact, production plan becomes the necessary part of the enterprise "digital twin", along with other parameters, such as the state of its warehouses and machines at any given time.

However, high complexity and dynamics of event-driven production processes lead to the fact that traditional batch, centralized and sequential

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computational models, methods and algorithms of combinatorial or heuristic types cannot effectively solve these problems with acceptable quality and within decent time (Leitao, P., 2016). In this regard, the task of searching for rational methods providing for adaptive event-based restructuring of plans in real time becomes extremely relevant and significant.

At the same time, experience in solving practical problems (Rzevski, G., 2014) shows that the key factor affecting the quality and efficiency of planning is the professional knowledge of specialists who determine semantics of the domain area and content-related features of the tasks being solved.

These challenges make digitalization of knowledge relevant and significant, especially in the form that allows for computer processing, in particular, for use in automation systems for planning production resources.

2 PROBLEM STATEMENT

One of the promising approaches to creating automated resource management systems is the use of multi-agent technology (Rzevski, G., 2014).

The proposed approach to creating multi-agent systems (MAS) for resource management is associated with the use of demand and resource networks (DR-networks) (Vittikh, V. A., 2003, Skobelev, P., 2015). This approach allows us to move from the usual "centralized" vision of management, where one single interest and one objective function of the "whole" are dominating - to distributed solution of management problem, where interests of all participants are represented, valued and taken into account.

Moreover, solution to any complex problem is formed evolutionarily, from the roughest and most particular solutions to more complete and accurate ones. In general, this process can be considered as a non-deterministic process of agent self-organization, since each agent itself makes the decision to establish or break the links at a previously unknown time (reviewing decisions made earlier is a typical step in this method). At the same time, all the agents are in the state of continuous identification and resolution of conflicts with other agents. Conflict resolution is implemented through various types of negotiation protocols and mutual concessions with compensations based on satisfaction functions, as well as bonuses and fines (Mayorov, I., 2015). The result of these processes is not a completely globally optimal solution, which is often not possible to obtain, but a rational (locally optimal) one, which has the ability to quickly adapt to events in real time.

The papers (Shoham, Y., 2009, Easley, D., 2009) show a number of important properties of such methods and algorithms for planning and optimization, which not only reduce combinatorial enumeration of options and sometimes provide an optimal solution, but are also intuitive, better parallelized, resistant to changes in the problem statement and have other advantages to become a new tool for solving NP-hard problems.

At the same time, development of MAS still remains more an art than a technology, and requires great efforts from developers both at the design and development stages, and at the implementation and operation stages, as it is necessary to take into account a variety of individual characteristics, preferences and limitations of both participants of the planning process and the actual enterprise objects (products, machines, materials, etc.), which directly affect the quality and efficiency of planning. The principal thing here is that the structure and composition of these requirements is difficult to determine in advance, since they relate to "unconscious" knowledge, and their next change is actually another type of event to be processed by the planning system.

The basic principles for constructing multi-agent systems based on ontologies were previously formulated in the works of G. Rzevski and P.O. Skobelev (Rzevski, G., 2014). In particular, the paper (Skobelev, P. O., 2013) shows the structure of a typical multi-agent system for resource planning, the data model of which is based on ontology.

The proposed research considers the developed principles of creating a basic planning ontology and developing models and methods of decision-making for resource management, as well as implementing a set of software tools in which ontologies can not only expand the set of limitations taken into account, but also reconfigure the planning system for solving new problems.

3 PROPOSED ONTOLOGICAL APPROACH TO PROBLEM SOLVING

3.1 Requirements for Building an Ontology for Resource Planning

In order to solve the problem of formalizing knowledge about individual characteristics of domain objects and processes, it is proposed to create a set of

tools based on the principle of separating the planning logic and describing the domain area of the specific problem to be solved.

Such an approach should make it possible to tune the system to the field of application, describing the enterprise model in a formalized way as an object of planning with the help of a basic set of concepts and relations of the domain ontology. Further, this formalized description, which is an ontological model of the management object (technical object or production enterprise), will be uploaded into the planning MAS for constructing a plan and its further adaptive adjustment based on events. In this case, each order or resource will be associated with its own software agent and a variant of its behavior, which will be adjusted to the specifics of its owner from the knowledge base that describes, for example, qualifications of a worker or specific features of a technological process.

The knowledge base is used for accumulation and formalization in planning of those knowledge quanta, the storage of which in corporate systems is currently not provided. Such a knowledge base that already contains instances of objects instead of classes can be built based on the domain ontology in the form of a semantic network of classes of concepts and relations.

The scheduling tasks have similar features, highlighting which, we can create a basis of concepts and relations sufficient to describe objectives, preferences and limitations of system agents.

Thus, any work plan of an enterprise is built on the basis of orders put into production, each of which is characterized by applicable technological or business processes, preconditions for starting task implementation and the expected result (product or service) for each task, as well as resource preferences, and time standards for performing the work.

The planning task consists in calculating the schedule for executing orders, which determines distribution of resources by tasks and the exact time of their fulfillment from the point of view of the following performance indicators:

• fulfillment of orders as early as possible or in time;

• increasing resource utilization;

• minimizing the average or maximum delays for orders, etc.

The resulting solution must satisfy the performance and resource schedule limitations. For example, an unshared resource can be used by only one operation at a time. If there are several valid schedule options, it is necessary to choose the one that is closest to optimal, since due to dimension of the solution space or completely different criteria used at different stages of planning, obtaining the optimal result can be difficult and unjustified in terms of the time spent.

Compared to the well-known and closest tasks of constructing a schedule for Project Scheduling and Job Shop Scheduling for machines (Shoham, Y., 2009), the described problem statement has a number of additional requirements, the most important of which is growth of the number of individual criteria, preferences and restrictions for each object, as well as the need for adaptive schedule recalculation due to events that change both availability of resources and materials, and technological processes for execution of orders.

3.2 Overview of Existing Ontologies of Production Resources

Creation of ontologies for managing production resources has been the subject of a number of studies.

One of the first known production ontologies was the Process Specification Language (PSL) ontology, which was developed as an independent language of knowledge representation about the production process and used for integration of various applications (Gruninger, M., 2003).

In 2006, the Manufacturing's Semantics Ontology (MASON) was published, designed to simulate the production process and calculate costs associated with it. The main classes of concepts in it were resources (including materials and personnel) and operations (Lemaignan, S., 2006).

Borgo and Leitao (Borgo, S., 2007) proposed their version of production ontology based on one of the top-level public ontologies (DOLCE) and expanding it with domain-dependent concepts. The resulting ontology determines taxonomy of products and components, materials, orders, and production processes.

In the paper (Cândido, G., 2007), the authors were among the first ones to use the ontological approach for automating the assembly line management process, creating a MAS in which resource agents registered their capabilities in the system, while agents of processes selected the necessary resources.

Advantages of using ontologies in agent-based resource management systems have been demonstrated in (Vrba, P., 2009). The described ontology focuses on such concepts as order, product, production process and enterprise structure (grouping of equipment into production cells, description of product movement routes between cells).

The paper (Usman, Z., 2011) proposes a production ontology of the upper level, which can combine the stages of design and production.

In paper (Wautelet, Y., 2012) the authors focused on using ontology to match resources' offer and demand through the concepts of functionality and competency. In (Minhas, S., 2014), application of knowledge bases is considered in the context of assisting dispatchers in planning of the production process. One of the latest works (Sormaz, D., 2019), proposes an ontology based on representation of production process in three dimensions: structural (relationship between processes and the used equipment and tools, etc.), temporal (sequence of operations), variative (ability to choose between alternative processes, equipment and tools). A detailed analysis of the current trends and the future of industrial knowledge bases based on ontologies was published in (Chandrasegaran, K., 2013).

Analysis shows that most ontologies are focused on a specific area of production and mainly serve to integrate knowledge from various information systems or to simulate production processes. Whereas, the aim of this paper is to develop the basic, domain-independent planning ontology that helps apply accumulated knowledge about the production process in automated MAS for planning.

3.3 Structure of Ontology for Resource Management

The main purpose of ontologies and knowledge bases built on their basis is to formalize the domain knowledge in order to more accurately specify requirements that must be taken into account in applied systems, as well as to separate this information from the system source code to enable its editing and expansion. The ontology development process consists in classifying domain concepts and defining the format for knowledge representation in the form of a finite set of concepts and domain relations.

At the first most abstract level, the concepts defined in the RDFS and OWL standards are used. At the next level, it is proposed to use the planning ontology, which consists of the most common and reusable concepts, while details depending on the domain area would be fixed in specialized ontologies that extend the basic one. Thus, a separate manufacturing ontology can be created to describe the domain area of machine-building production. The hierarchy of concepts can be specified in the more specialized ontologies down to the level of a particular enterprise. On the basis of the domain ontology, an ontological model of the enterprise is constructed, consisting of instances of the previously described concepts including the enterprise organization, description of products and technological processes, equipment, people and tools used (Fig. 1).

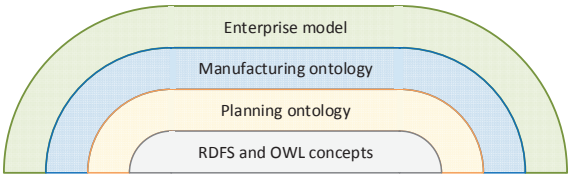

Figure 1: An example of ontology representation with multiple layers.

Advantages of using this approach include:

• creation of a single basis in which knowledge is described. This helps systematize and unify the ways of representing knowledge;

• possibility of making changes to the structure of knowledge representation;

• visibility and accessibility of large volumes of complex structured information for users;

• ability to integrate heterogeneous sources of information.

3.4 Basic Planning Ontology

In order to "explain" to the planning system how to work with the domain area, it is necessary to connect its concepts and relations with the already known ones (interpreted by the system and built into its source code). A set of these concepts and relations forms the "planning ontology", in which all abstractions for operation of the planning system can be collected.

For the basic concepts and relations of the domain ontology, it is advisable to choose those that correspond to the main agents of the demand and resource network, used for adaptive planning based on multi-agent technology. Such concepts are: order, task, resource and product (Fig. 2).

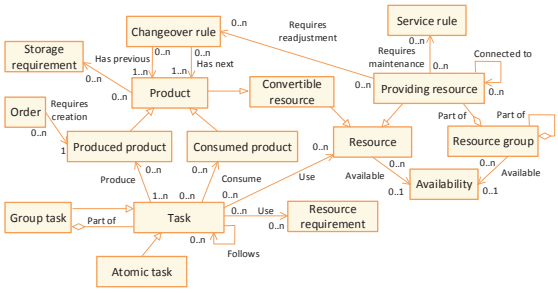

Figure 2: Basic planning ontology.

In general, to form an enterprise model, it is necessary to create instances of the following concepts:

1) Range of products used and manufactured (raw materials, semi-finished products, information products, documents, products, etc.). Description of each type of product can be refined using additional relations and attributes.

2) Composition and structure of used resources (personnel, machines, tools, etc.). The following properties are set for resources: productivity; work calendar; rules for scheduled preventive repairs and maintenance, depending on the operating time or the output volume; readjustment rules determining duration of transition to production of another type of product; additional attributes and relations.

3) Technological processes for obtaining products, which are an ordered list of operations. For operations, standards of lead time are indicated: fixed or depending on the volumes of products involved in the transformation and resources necessary for its implementation (by setting the necessary properties). The time taken to complete the operation may depend on the performance of the selected line.

4) List of orders containing information about the manufactured product, its quantity and deadlines.

3.5 Domain-specific Ontologies

Applied ontologies contain classes of concepts and relations that are specific for this domain, for example, manufacturing ontology describes such classes as “product”, “technological process”, “workshop”, “equipment”, etc. (Fig. 3).

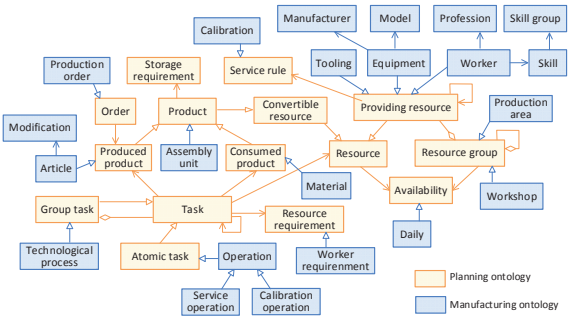

Figure 3: Extension of the planning ontology to the field of manufacturing.

Some of these classes refer to the basic ones given in the planning ontology, for example, the “Providing resource” at the level of ontology of manufacturing is represented by the classes “Tooling” and “Equipment”. Additionally, classes of the general purpose are indicated. These are not inherited from the basic ones, but only participate in relations with them, allowing users to describe properties of the domain area concepts (equipment model, employee competencies, etc.).

4 DEVELOPMENT OF A MULTI-AGENT ONTOLOGY-BASED PLANNING METHOD

To solve the planning problem, it is proposed to use a multi-agent approach, which is based on juxtaposition of ontological entities of domain area and software agents acting on their behalf.

Each agent is able to make decisions and interact with other agents, which altogether form the multi-agent system. Behavior of the MAS is not regulated by any centralized algorithm, but, on the contrary, arises from the local interactions of the agents forming it. Each agent has a set of behaviors that determine its response to messages from other agents, or to changes in external conditions (events).

In the proposed approach, the schedule is built via self-organization of software agents of the demand and resource network with competition and cooperation in the virtual market. The basic types of agents are agents of orders, tasks, resources, products, as well as the scene agent.

Objectives and limitations of these agents are shown in Table 1.

Table 1: Objectives and limitations of agents.

Type	Objectives and preferences	Limitations
Order agent	To be fully completed in the specified time, with minimum cost	Timing, volume, marginal cost
Task agent	To be performed on a suitable resource within the specified timeframe in the shortest time	Characteristics of the required resources and products, start and end dates, relations with other tasks
Resource agent	To be as occupied as possible, minimize downtime and changeovers	Work calendar, unavailability intervals, service and readjustment rules, performance
Product agent	To provide its storage, minimize retention	Storage requirements, delivery or production time, consumption time
Scene agent	Identification of bottlenecks in the schedule, managing activity of system agents, interaction with external systems	Time allocated for planning, depth of permutation chains in the schedule

Objectives and preferences of each agent are determined through the satisfaction function, which is a weighted sum of components that meet various criteria. Depending on the value of satisfaction function, an agent is automatically assigned a bonus (or penalty), the amount of which is determined by the bonus and penalty function set for this agent (Mayorov, I., 2015).

The agent-based planning method is built on the conflict analysis mechanism that provides the ability to rearrange conflicting tasks in the schedule through agent negotiations (by exchanging messages according to specified rules). As a result, an acceptable locally optimal solution is achieved, which is further adaptively corrected in the "sliding mode" on the given planning horizon.

The following is an algorithm for the planning method:

1) In accordance with the current state of the scene, agents of orders, resources and products are created. The scene agent sends a signal about the start of planning to one or more order agents.

2) The order agent reads the technological process for the related product and generates task agents corresponding to the technological process and operations arranged in a hierarchy.

3) The top-level task agent reads the concept of the given task in the knowledge base and checks for the presence of products used in the task, evaluates resource requirements and selects a combination of them based on assessment of its duration. The procedure for finding placement options includes analyzing the required resources, comparing requirements of tasks and capabilities of resources, coordinating times of availability of all resources, and choosing the best combination of performers. Moreover, as resources are selected, the system determines a set of orders interfering with placement on the selected resources (the conflicting set). The procedure for determining a conflicting set of orders depends on the type of resource under consideration: an unshared resource fixes a conflict in case of intersection of time intervals used by two tasks, while the shared resource fixes a conflict if the total amount of the resource used by the tasks exceeds the limit value. After selecting a placement option, the group task agent sends a planning request to the agents of child tasks.

4) Agents of child tasks recursively search for placement options taking into account limitations determined by the parent task. Planning results are reported to the top-level task agent, which clarifies its placement or invites child tasks to schedule at another time.

5) The top-level task agent informs the order agent about parameters of the selected placement.

6) The order agent proposes conflicting orders to find another slot in the schedule, reporting their losses in comparison with the basic (initial for the current thread) version of the schedule. As a result, a chain of permutations of tasks and orders is determined, values of objective functions of those entities affected by changes in the plan are calculated, and based on this, the final value of the objective function of the whole system is refined as the normalized sum of objective functions of its constituent agents. A permutation chain is successful (permissible) if the value of objective function of the system is higher, and the order agent can compensate for the loss of other entities involved in this variant of permutations. If these conditions are met, the changes in the schedule are approved. Otherwise, another placement option is determined.

7) After placement, the order agent checks availability of products related to it by the "Produced" relation and notifies their agents of the delivery time to the warehouse.

8) This process continues until the condition is fixed where no agent can improve its state (satisfaction function).

9) The scene agent determines the agent with the worst criteria for the system as a whole. The selected worst agent is instructed to break ties with related products and resources. The selected agent receives an increased importance coefficient of the worst criterion in the satisfaction function, so that agents choose other options during the next rescheduling.

10) The agent tries to be scheduled again - if successful, the process goes on to the next criterion and the corresponding agent. If not, the agent reports the amount of compensation that it lacks to achieve the new criterion value.

11) The scene agent evaluates availability of the currency in the system and if necessary, adds virtual currency to this agent. As a result, the worst agents iteratively "tighten" their criteria for the new values, compensating for the losses of other agents via virtual budget.

12) The process ends if the time allotted for building the schedule is over, or if there is no more room for improvement.

4.1 Support Tools

To implement the proposed approach, a software package was developed, which includes a management module, a user interface, an editor of

ontologies, models and scenes, as well as a planning module (Fig. 4).

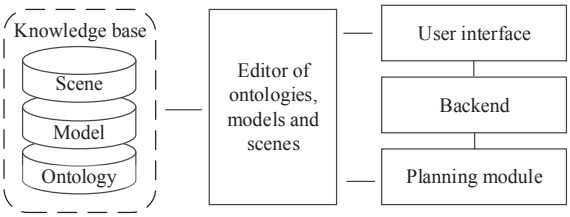

Figure 4: Architecture of the software package.

The management subsystem is the server part of web application that implements its business logic. The editor of models, ontologies and scenes provides creation, editing and storage of a digital model of the planning object, providing a software interface for access to available information. The data warehouse is physically divided into two parts: ontological and relational. The ontological part contains descriptions of all used ontologies and models in the form of triplets, while the relational part contains data about all objects entered into the system (resources, orders, tasks, etc.). This division allows users to combine advantages of rigid, normalized and dynamically extensible data structures stored in various DBMSs: PostgreSQL and Mongo.

The main objective of the planning module is formation and adaptive restructuring of the order execution plan taking into account resource limitations. The module creates and configures instances of system agents based on the ontological description of the planning object, provides a multi-threaded environment for their implementation, determines the order and algorithm of their functioning. The module is built on Akka framework that implements a low-level mechanism for asynchronous messaging and thread-scheduling in a concurrent environment. It allows creating thousands of agent instances on a limited number of threads. All created agents correspond to the base concepts from the planning ontology and can be directly executed without manual code insertion because all communication protocols have been already implemented.

The user interface is the client part of the web application that runs in the browser and implements graphical interface for accessing the object model and planning results.

5 USING THE TOOLS FOR SOLVING APPLIED PROBLEMS

The developed methods and tools were applied to solve the following problems:

- production planning for an aircraft manufacturing enterprise;
- planning for truck assembly;
- planning a well drilling process.

Despite significant differences in the statements, all these problems were solved using one software package with some improvements related, primarily, to visualization of domain-dependent processes. At the same time, all changes in the planning module were not “tied” to a specific domain area and only increased its general capabilities, which allows us to make the conclusion that the product can be gradually stabilized and can later be offered to system integrators as a regular service.

In each case, the basic planning ontology was used, on the basis of which domain-specific ontologies and enterprise models were created. In the case of aggregate assembly of trucks, it was possible to reuse the ontology of manufacturing, expanding it to the specific case of robotic tools. At the same time, based on the needs arising in solving applied problems, the basic planning ontology was being built up and the logic of agents' work was modified. General information about the number of entities in the knowledge base, agents in the planning module, as well as approximate terms of completion of the tool complex is given in Table 2 (the number of agents depends on the number of orders entered, the table shows average values).

Based on the analysis, the following main advantages of the developed approach can be distinguished, since it helps to:

- significantly reduce the complexity and labor intensity of creating a MAS for resource management;
- increase the number of factors for decision making;
- configure the logic of MAS without involvement of programmers;
- reduce the costs of creating and maintaining the described systems;
- use the same source code for different tasks, reducing the number of errors and risks associated with development.

Table 2: Indicators of the use of a set of tools for solving applied problems.

Applied task	Size of basic ontology	Size of domain ontology	Size of enterprise model	Number of agents	Time for completion (man/month)	
					KB	Planning module
Aircraft assembly	61	152	925	> 350	3	5.5
Truck assembly		89	382	> 520	1	2
Well drilling		85	441	> 5000	2	3.5

In practice, it becomes possible to systematize, accumulate, and formalize the specific knowledge of enterprises that could not previously be separated from the source code and which can now receive additional value. In the future, it will enable us to consider the emerging knowledge base as another asset of the enterprise.

6 CONCLUSIONS

The paper proposes the basic ontology of resource planning and possibilities of its expansion in domain areas, making it possible to use the same set of DR-network agents to manage enterprises in significantly different domains. An extension of the multi-agent planning method based on the ontological enterprise model stored in the knowledge base is presented. The paper also presents examples of using this approach to control assembly of aircrafts, robotic assembly of cars and the drilling process.

The proposed approach makes it possible to build formal ontological models of DR-networks of enterprises and flexibly configure multi-agent systems of resource management without labor-intensive reprogramming in order to take into account specific features of their work. The created ontological models of enterprises can be the basis for creating ontological "digital twins" of enterprises, applicable both for operational management and for modeling the processes of development and modernization of enterprises.

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REFERENCES

Zhong, R. Y., Xu, X., Klotz, E., et al., 2016. Intelligent Manufacturing in the Context of Industry 4.0: A Review. In *Frontiers of Mechanical Engineering*. P. 616-630.

Tao, F., Cheng, J., Qi, Q., et al, 2017. Digital twin-driven product design, manufacturing and service with big data. In *International Journal of Advanced Manufacturing Technology*. P. 3563-3576.

Leitao, P., Karnouskos, S., Ribeiro, L., et al, 2016. Smart Agents in Industrial Cyber-Physical Systems. In *Proceedings of the IEEE*. № 104 (5). P. 1086-1101.

Rzevski, G., Skobelev P., 2014. *Managing complexity*. WIT Press. Boston.

Vittikh, V. A., Skobelev, P. O., 2003 Multiagent Interaction Models for Constructing the Needs-and-Means Networks in Open Systems. In *Automation and Remote Control*. 64(1). P. 162-169.

Skobelev, P. Multi-Agent Systems for Real Time Adaptive Resource Management, 2015. In *Industrial Agents: Emerging Applications of Software Agents in Industry*. P. 207-230. Elsevier.

Mayorov, I., Skobelev, P., 2015. Towards thermodynamics of real timescheduling. In *International Journal of Design & Nature and Ecodynamics*. Vol. 10. Is. 3. P. 213-223. WIT Press.

Shoham, Y., Leyton-Brown, K., 2009. *Multi-agent systems: Algorithmic, Game Theoretic and Logical Foundations*. Cambridge University Press.

Easley, D., Kleinberg, J., 2010. *Networks, Crowds, and Markets: Reasoning about a Highly Connected World*. Cambridge University Press.

Skobelev, P. O., 2013. Situational management and multi-agent technology: collective search for coordinated solutions in a dialogue. In *Ontology of Designing*. №2 (8). P. 26-48. (In Russian)

Gruninger, M., Menzel, C., 2003. The process specification language (PSL) theory and applications. In *AI Magazine*. Vol. 24(3). P. 63-74.

Lemaignan, S., Siadat, A., Dantan, J. Y., 2006. MASON: A proposal for an ontology of manufacturing domain. In *Proc.of DIS 2006*. P. 195-200. IEEE.

Borgo, S., Leitão, P., 2007. Foundations for a Core Ontology of Manufacturing. In *Ontologies. Integrated Series in Information Systems*. P. 751-775.

Cândido, G., Barata, J., 2007. A mutliagent control system for shop floor assembly. In *Holonic and Multi-Agent Systems for Manufacturing*. P. 293-302.

Vrba, P., Radakovič, M., Obitko, M., 2009. Semantic Extension of Agent-Based Control. In *The Packing Cell Case Study*. P. 47-60.

Usman, Z., Young, R., Chungoora, N., et al., 2011. A Manufacturing Core Concepts Ontology for Product Lifecycle Interoperability. In *Enterprise*

Interoperability. IWEI 2011. Lecture Notes in Business Information Processing. Vol 76. P. 5-18.

Wautelet, Y., Heng, S., Kolp, M., 2012. A Usage-Based Unified Resource Model. In *The 24th International Conference on Software Engineering and Knowledge Engineering.* P. 299-304.

Minhas, S., Berger, U., 2014. Ontology Based Environmental Knowledge Management - A System to Support Decisions in Manufacturing Planning. In *Proc. of 6th International Conference on Knowledge Engineering and Ontology Development*. P. 397-404.

Sormaz, D., Sarkar, A., 2019. SIMPM – Upper-level ontology for manufacturing process plan network generation. In *Robotics and Computer Integrated Manufacturing*. Vol. 55. P. 183-198.

Chandrasegaran, K., Ramani, K., Sriram, R. D., 2013. The evolution, challenges, and future of knowledge representation in product design systems. In *Computer-Aided Design*. Vol. 45(2). P 204-228.