Ontology-based Design of Batch Manufacturing Enterprises

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***Abstract*—The paper discusses the current, tactical and strategic aspects of increasing the industrial control level and uses batch manufacturing enterprise JSC «Savushkin product» as an example. Proposed ontological approach to the design of such kind of enterprises is based on the hierarchical system of formal ontologies built from a certain standard. In particular, we discuss the principles of formalization of standards on which the enterprise activity is based using the ISA-88 standard as an example.**

***Keywords*—ontology, subject domain, ontology-based design, intelligent system, Ontology of designing intelligent systems, batch manufacturing enterprise, formal ontological model, ISA-88 stadard, enterprise physical model**

I. Introduction

A. Objective and Relevance

This article considers tactical and strategic aspects of improving industrial control on the example of batch manufacturing enterprise JSC «Savushkin product». These studies are relevant due to the fact that without state-of-the-art automation and without its rapid improvement, modern enterprises can not be highly competitive.

The purpose of this article is to build ***an ontological model of batch manufacturing enterprise*** to improve industrial control quality of such enterprises and their ability to adapt to a constantly changing environment.

B. Requirements for Industrial Control Instrumentation of the Modern Enterprise

Automation tools of modern enterprises must quickly adapt to any changes in production itself – to expansion or reduction of product output, changes in the product nomenclature, changes in the equipment used, changes in the production structure, changing relationships with suppliers and customers, changes to the regulatory legal acts (including standards), which the company must comply with, to various emergencies. Adapting industrial control to all types of businesses changes and to changes in its interaction with the outside environment requires change to the business model first. These changes must fully reflect the current status of its activity.

Automation tools of the modern enterprise must be flexible enough not only for rapid adaptation to the reconfiguration of the production lines, but also for prompt changes and continuous improvement of said automation tools. It is essential not only to decrease the laboriousness of improving the industrial control level, but also to maintain a high rate of improvement. Well-thought-out process of transition from one level of automation to the next, during which both old and new version are used, is necessary, as well.

Current industrial control system operation and its continuous improvement process requires a coordinated and efficient cooperation between employees. The basis of such interaction is a well-structured, fairly complete business model, which can be updated on-the-fly. It should reflect all aspects of the current structure and activity of the enterprise, as well as approved and discussed plans for its development. Such kind of integrated model is called enterprise knowledge, which should be managed (produced, stored, updated, distributed, etc.) [38], [18].

Improvement of the industrial control level assumes a significant increase in the number of automatic or automated tasks. This, in turn, calls for automated solutions to intellectual problems, i.e. the use of artificial intelligence technologies. Intellectual problems to be solved in the enterprise include:

- analysis of manufacturing situation (including emergencies);
- decision-making at different levels;
- planning behavior in difficult circumstances;
- creating and maintaining documentation;
- training new and current employees;
- etc.

In order to ensure the widespread use of artificial intelligence technology in factory automation, all the corporate knowledge of the enterprise must be represented using a formal knowledge representation language. At the same time, this language should be useful not only for the intelligent computer systems, but also for employees. This means that the formal language of enterprise knowledge representation must be clear, concise and understandable not only for intelligent computer systems, but also for employees.

C. Problems that Need to be Addressed

- Existing industrial control instrumentation is expensive, difficult to learn and adapt to the specific manufacturing process. Typically, such tools, on the one hand, can only be applied to a limited class of problems, but, on the other hand, developers strive to make these tools as universal as possible, extending them with domain-specific solutions. This leads to the bulkiness and complexity of such systems;
- As a consequence of this approach to extending functionality, existing industrial control instrumentation has low flexibility (limited ability to make changes to it), resulting in a significant overhead in the adaptation of such tools to the new requirements. As a rule, changes in these tools require (often a third-party) developer intervention, which leads to significant costs in both time and money. Due to these problems, not every enterprise can achieve and maintain a high level of automation, even if there are appropriate solutions available in the market;
- The absence of common unified models and tools for building industrial control systems leads to a lot of duplicate solutions, both within industry as a whole, and within company in particular. This situation often arises when some special systems that solve particular problems within an enterprise, are incompatible with each other, which leads to additional implementation costs of coordination mechanisms (e.g., data format conversion);
- The absence of such models prevents further enhancements to the industrial control automation instrumentation, in particular in the field of automation of decision-making in emergency situations and event prediction;
- Industrial control systems are highly dependent on their developers. This leads to adoption and maintenance problems when developer staff changes;
- Lack of formal models of various standards governing industrial control and other enterprise activities leads to possible difficulties in the interpretation of certain regulations, in personnel training, and in business operation. Finding necessary information in a large volume of documentation can be difficult. Besides, this fact makes it difficult to perform compliance testing of the company and its divisions.

D. Analysis of Existing Approaches to the Aforementioned Problems

Currently, there are a number of approaches oriented at improving industrial control systems and their flexibility for various types of enterprises. We will now discuss some of them, in particular those that influenced the development of the approach proposed in this paper.

1) Enterprise Knowledge Management Models: Enterprise knowledge management is a systematic process of identification, use and transfer of information and knowledge, which are created, updated and used by people. During this process, company constantly generates, stores and uses knowledge in order to obtain competitive advantages, thus forming the intellectual capital of the enterprise [29]. In today's economy, difficult to replicate knowledge, represented in any form, should be considered as an important asset, since it is the source of competitive advantage. Thus, the focus is not the creation of knowledge, but their use and their flow within the company [19].

Enterprise knowledge management is currently implemented in the form of knowledge management systems. Methods and technologies of their construction are discussed in [37].

Main challenges in the enterprise intellectual capital management are due to the fact that at present there are no generally accepted models of its structure [34].

Current theories of the intellectual capital management concern particular spheres of management activity and do not structure knowledge in a way that allow for their effective use and transformation. [29].

The most recent trend in the formalization of enterprise knowledge accumulation and management processes is to construct their models using the ontological approach.

2) Enterprise Ontological Models: Ontological models, as the basic approach to designing various systems, is widely used nowadays [17]. In particular, researchers identify a special subject domain called "Enterprise ontologies" [38]. Proposed approaches amount to constructing a number of ontologies that describe the activities of an enterprise or its subdivisions. When necessary, various kinds of knowledge can be included in these ontologies to describe various aspects of the company activities.

Applying an ontological approach to structuring knowledge allows the enterprise to use this knowledge more effectively. It significantly decreases the complexity of updating the knowledge to adapt them to solving new problems, accelerates and simplifies the process of training new staff [20].

A number of studies examined the use of the ontological approach to solving domain-specific problems of some enterprise [25].

However, existing approaches share a number of common disadvantages:

- lack of a unified, universal representation of various classes of enterprise knowledge;
- lack of a unified approach to separation and development of ontologies, which, along with the previous point, often leads to the impossibility of integration and reuse of ontologies developed within an enterprise or even within different subdivisions of the company;
- lack of a unified approach to the construction of ontology hierarchy limits the possibility of constructing a complex interconnected system of ontologies, that is able to describe the enterprise with the necessary amount of detail.

3) Multi-agent Enterprise Models: Currently, multi-agent model is widely used in the design of industrial control systems of various levels. This approach is convenient and widely used because of its similarity to the real processes taking place in the enterprise. Indeed, in the classic multi-agent system for the agent refers to a subject, usally active and capable of interacting with the environment [13], [35]. Being united in groups, such agents are able to solve problems much more complex than could be solved by one agent. The advantages of multiagent approach include the ability to build distributed multi-tier systems on its base.

The most obvious interpretation of this kind of model, as applied to a particular enterprise, is to consider its employees as the agents, each of which is able to solve a certain class of problems and has to internally coordinate their actions in order to achieve a common goal. The hierarchy of structural units of a specific enterprise can determine hierarchy levels of agents belonging to relevant departments or shops. Furthermore, methods of organization and management, designed for multiagent systems can be used in the model of an enterprise built in such a way.

In particular, the [5] has introduced higher-level agents (meta-agents). Their task is to gather information from lower-level agents and coordinate them. Similar ideas are expressed in [14]. In the papers [11], [2], options for automatic selection of the optimum mechanism for the coordination of agents to achieve a common goal are presented. It also offers social and psychological models of coordination of agents activities, for example, based on some general «laws» [15].

Aside from the obvious aforementioned points, there are other areas of the application of multi-agent approach to building enterprise model or some of its parts. In particular, [Baker, 1998] provides an overview of similar solutions in the industrial control. In the [Leitao, 2013] paper the approach to optimize the operation of specific equipment through the integration of various optimization algorithms based on agent systems is shown. A more general overview of the agent-oriented approach in the enterprise is given in [10].

Currently, however, the principles of hierarchical multi-agent systems in which some agents may be included in other agents, which in turn, may also be components of other higher-level agents, are insufficiently investigated. This fact greatly complicates building of a common multi-level hierarchy of agents to describe the enterprise with various levels of detail, from an enterprise-wide model to the equipment and personnel of a specific shop or subdivision.

Another disadvantage of the multi-agent model is the lack of uniformity in the construction of formal models of agents and the orchestration of their interaction that prevents the use of similar solutions at different levels and gives rise to the additional overhead.

4) Situational Control Models: The term "situational control" first appeared in the works of D.A. Pospelov [30]. Then this line developed by him and his students and followers, which is reflected in [26], [31]. The basic idea of situational control is that there is no universal approach to management, in different problem situations it is necessary to take into account various factors influencing their decision-making strategy, thereby achieving effective decision-making.

Currently, this area of science is experiencing a kind of rebirth associated with the relevance of the proposed approach it in the management of various processes in enterprises, both directly in the management of manufacturing processes, and in resolving arising emergency situations. In particular, [28] discusses the possibility of using situational control in the energy sector. A number of papers discuss usage of the ontological approach in the implementation of situational control[33], [36].

Therefore, models and methods of situational control can be used in the construction of the ontological model of the enterprise to increase the efficiency of solutions intended for specific manufacturing situations, including emergencies.

5) Business Process Re-engineering Models: Business process re-engineering is the fundamental rethinking and radical redesign of business processes of enterprises to rapidly improve key indicators of their current activities: cost, quality, services and rates [4].

Re-engineering process is based on two basic concepts: "future corporate identity" and "business model". The future corporate identity is a simplified image of the original, reflecting its main features, and omitting the minor details.

Business model is a presentation of the main business processes of the company in their interaction with the company's business environment. Business models allow to identify the characteristics of the basic processes of the business unit and the need for re-engineering [16].

Thus, the object of re-engineering is not an organization, but the processes occurring in these companies.

To increase the efficiency of re-engineering, it is necessary to:

- allow the construction of formal models that describe the company with different levels of detail, including a description of all the processes taking place in the enterprise;
- ensure unification, integration and hierarchical organization of these models.

The main disadvantage of all of the above models is that none of them are sufficiently complete and comprehensive. Enterprise model should be an amalgamation of all of the aforementioned models to adequately represent all of the aspects of real enterprises.

E. Underlying Principles of the Proposed Approach

At the heart of our proposed approach to problem solution based on the following principles mentioned above:

- The company is viewed as a distributed, intelligent socio-technical system, which is based on well-structured enterprise-wide knowledge base.
- All of the above models (knowledge management, ontological, multi-agent, business process re-engineering) are integrated within the enterprise knowledge base.
- The enterprise is viewed as a hierarchical multi-agent system. Agents of such an enterprise include employees and software agents. Hierarchical organization of multi-agent system means that agents can be non-atomic (represent a group of interacting agents). Such structures can be infinitely nested.
- A complex of informational and physical tools, which ensures functioning of the company is made available as the integrated distributed intelligent system. We call it the ***enterprise intelligent system***. Primary users of this system are company employees;

- Enterprise ontology model design boils down to the design of the ontology-based model of an *enterprise intelligent system*. This ontology-based model of the enterprise is both the object and the result of its design.
- We propose to use the ***OSTIS technology*** [21], [22] to implement enterprise-wide intelligent systems. This means:
  •• Various kinds of knowledge are represented using unified, universal representation language – ***SC-code***;
  •• Developing a system boils down to developing its model in SC-code language (***sc-model***), which is then interpreted by one of the interpretation platforms.
  •• The knowledge base is a hierarchical structure that allows to store knowledge with various levels of detail. It is especially so with a hierarchy of ***subject domains*** and the corresponding ***ontologies***. [24].
  •• Tools for collaborative knowledge base and knowledge processing machine design are included in the technology.
  •• Knowledge processing model is based on multi-agent approach, which allows to build parallel asynchronous knowledge processing machines.It also allows to integrate various specific models of knowledge processing in a single system.
  •• All agents interact solely through the shared sc-memory, which stores SC-code structures. This approach ensures flexibility of the system and makes it possible to solve various problems in a parallel fashion [39].
  •• Agent programs are developed using an internal, inherently parallel language – SCP (Semantic Code Programming). It uses SC-code for representation of its texts. This ensures platform independence of agent programs.

F. Tasks to be Resolved for Proposed Approach Implementation

- Develop a unified structure of the integrated knowledge base of the enterprise intelligent system, represented in the form of a hierarchical system of subject domains and the corresponding ontologies. Subject domains, that are covered by the enterprise-specific standards, are a crucial part of it.
- Develop a knowledge processing machine model [39] of enterprise intelligent system.
- Develop user interface model [27] of enterprise intelligent system.
- Develop an information service model for different categories of users of enterprise intelligent system.
- Develop a model of enterprise intelligent system knowledge base engineering and re-engineering support tools.

At this stage, the work focuses on developing an ontology-based model of knowledge base, in particular, of those subject domains, that are covered by the fundamental standards. This is due to the fact, that the formal representation of those standards is the basis for coordination of all the key aspects of the company activity. Besides, it allows to build an all-encompassing ontological model of an enterprise and of its individual components.

To prove their relevance, we will now take a look at the current state and the history of the industrial control system development of a specific enterprise.

II. History and current industrial control state at JSC «Savushkin product»

In the late '90s, the company faced a need to seriously upgrade itself to become a leader not only inside domestic market but also in Russia. Because of lack of finances and weak state of existing solutions, usage of third-party automation software systems was rejected but decision about own development was made. The goal was to develop a multipurpose framework as base for not only industrial control, but also for accounting, warehouse, etc. A small group of developers thus started to work on a SCADA system, which was later named EasyServer. The first EasyServer-based project performed temperature control of tanks inside the apparatus shop.

After the successful project launch we have confirmed the efficiency of the decisions we made. Some new projects were implemented afterwards – CIP station, milk acceptance shop, dried milk shop. These projects were successfully developed in spite of some difficulties. As a result, the SCADA-system EasyServer became the main development tool.

The automation level is constantly growing with the system development. Data acquisition from different sensors (volume, pressure) was developed first. Technological operation and devices control were implemented next. In the future, the batch production level is to be added.

CODESYS from 3S-Smart Software Solutions for WAGO controllers is also used as development tool . It is a free tool, can be used for the development using engineering languages for programmable logic controller (IEC 61131-3) – IL, LD, FBD, SFC, ST. Automation engineers use this approach to develop quite simple autonomous projects (milk accepting stations) without using help of programmers. Implemented projects are integrated into the system using open MODBUS TCP communication protocol.

Communication between individual projects (own, as well as third-party) also needs to be addressed to ensure effective operation of the shop. But there is no universal approach – some projects use MODBUS TCP, others use additional controller, like a communication gateway. Besides, physical connections for signals exchange are sometimes used. All this further complicates the system. Using in-house design for projects and the whole system has these advantages:

- Fast project development speed. All functionality accumulated during the development becomes part of the system. Now typical project gets done literally by one automation engineer over several hours. This allowed to implement over 200 projects to date.
- The relative cheapness of the in-house developed EasyServer SCADA. Despite the costs of maintaining of the skilled development team, it proved to be much cheaper than a third-party solution. For example, typical Siemens based project (CPU 315-2 PN/DP, software STEP 7 and WinCC Basic, SCADA WinCC) costs nearly 9000€, while solutions from Wago and EasyServer (excluding development costs, PAC PFC200) cost less than 2500€(prices are as of November 2016).
- A comprehensive functionality of the EasyServer system. System features are comparable to commercial counterparts (Simatic Step 7 + Simatic WinCC), despite limited

resources. It is achieved by a very tight integration with the actual production.

Disadvantages of the current industrial control state implementation:

- Data presentation is implemented as a relatively simple reports. At the launch of the first projects the reports have been implemented as separate applications written in Delphi. Table data from the project server were exported to MS Excel via BDE. Later, in 2008, a FastReport Server report generator was purchased. During its usage developers were experiencing problems with insufficient system functionality and the end of support by the developer. At the moment, decision to organize the data processing (and reporting as well) at a higher level was made, and the control system level now only keeps basic projects reports. The question of the upper level platform (enterprise level in general – ERP) for reporting task solutions is therefore open.
- Since priority was given to (and is now given to) the development (and modification) speed, there is a relatively low level of the system-wide documentation, which is true for individual projects, as well. Therefore solutions, which becomes part of the designed system documentation, are required. For example, during the development of the documentation for the project "Hutorki" (2007) resulting MS Word file had a size of about 40 pages, containing picture inserts of various charts, descriptions of operations, etc. The functional automation chart and the layout description of cabinets were made in MS Visio. The IO modules description have been made in an in-house WagoEditor program which is able to export its outuput to MS Excel. The development of the first documentation version took a few days of one developer's time. The project is being upgraded every year, at the same time the process of making changes to the current version of the documentation takes about the same time as the development of the new one. Updating the documentation every time requires redrawing the circuits, developing communications within the projects, etc. The variety of data sources and formats, as well as their need for manual coordination makes matters worse. Thus, now the description of the functional automation chart, electric parts and design specifications are made in the Eplan CAD. Description of the technological process also made in Eplan CAD, but it is kept separately in the form of Lua scripting language script. Description of certain devices (frequency converters, valves) is stored in PDF format, and comes from the manufacturers.
- Limited time for testing and debugging. Current market state and extreme modern design methods are constantly accelerating pace of startup projects, resulting in no debugging time. The newly developed functionality has to work literally yesterday. Therefore, there is a great need for diagnostic and self-test modules for the projects.
- There is a growing enterprise automation coverage. Now it is not only individual shops, but also the whole enterprise. Therefore, the control system has to operate not on the level of "operator" – "human machine interface" – "separated technical process", but on the "production logistics manager" – "Intelligent web interface" – "the whole plant" level.
- Modern production conditions dictate strict rules for continuous reduction of the human involvement, so the introduction of robots (industry robotization) is an essential part of the development. Integrating robots and control systems into the enterprise-wide system as-is is very expensive, both from human and from financial standpoint. Thus, there is the need for solutions that can be integrated in a familiar way. They will allow to implement new manufacturing processes robotization projects, which indicate movement towards what is essentially a human-less industry.

For the successful integration into the world-wide market, it is desirable today, and certainly required in the future, to lead the organization of production in the "Savushkin Product" company in line with international standards (in particular, with the ISA-88 standard). However, standards can be a deterrent – they are bulky, relatively slow to develop, there are problems with their interpretation. Direct implementation attempt may require unreasonably high costs. Therefore, to bring the enterprise processes in line with international standards, it is necessary to use a more flexible production management, as well to more flexibly account for the standards' evolution.

III. Standards governing the company activities, and their formalization

A. General approach to standards formalization

Ontological approach to designing an enterprise is based on the standards formalization. Every standard is considered an *ontology* of a corresponding *subject domain*, which serves as a base to automated solution of a number of tasks, some of which include information services for employees, formal assessment of conformance to the standard, etc.

One of the most important problems when incorporating standard into an enterprise is a possibility of having multiple interpretations of some parts of a standard. Such interpretation has to be constantly adjusted to match the intent of the original document. Besides, there are some peculiarities of implementing standard into any given enterprise. Since every standart evolves constantly, it has to be updated accordingly. This causes changes to the enterprise structure and activity management to ensure standard compliance.

One way to solve such problems is by constructing its formal semantic model, which could be equally interpreted by a computer system and a human alike. Formal semantic model representation of a standard is not a standard itself – it is a subjective interpretation of a standard by a developer of a given model. At the same time, formal semantics-based representation of a standard provides a constructive ground for its mutual approval. Such representation also ensures clarity and unambiguity of its interpretation. Formal semantics-based representation of a standard ensures a substantial simplification of making changes to such representation, as well. These changes may be necessary due to the clarifying of its interpretation or due to the evolution of the standard itself. Given simplification is due to the fact, that in semantics-based representation of any kind of knowledge, including standards, signs of all entities and their relations are represented only once. This means, that changes to them are localized within knowledge base, unlike in the natural-language texts, where such relations are not explicit and therefore are hard to establish and maintain.

Formal semantics-based representation of a standard allows to supplement it with various kinds of didactic information (examples, explanations, analogies) to improve employees' comprehension of a standard, without changing the structure of said representation.

Constructing a formal model of a standard amounts to constructing an *integrated formal ontology*, which specifies the corresponding *subject domain*. It is necessary to translate structure and contents of a source document to a hierarchy of *subject domains* and corresponding *ontologies*. Isolating subject domains allows to localize solutions for tasks and problems within a small subset of a knowledge base. In other words, search for a solution of a task (problem) from a certain subject domain is limited to this subject domain.

Ontological approach to constructing a formal model of a standard allows to build an intelligent help system for this standard by implementing intelligent knowledge processing agents. Such system can provide a wide range of information services to its users, including ability to answer a variety of questions, answers for which may not be explicitly expressed in the text of a standard or are hard to find in such a text. Examples of such questions include:

- What is entity X?
- What is X needed for?
- Which entities are necessary for X?
- How entities X and Y are connected?
- What caused event X?
- What will happen if X?
- etc.

X, Y may be the names of a certain objects, situations, events, etc.

We will now formalize a specific standard using this approach.

B. ISA-88 formalization

Among multitude of standards governing manufacturing activities of enterprises, there is ISA-88 standard [7], which best covers the specifics of a batch manufacturing enterprises, such as JSC «Savushkin product».

The main virtue of ISA-88 is the decomposition of a batch manufacturing subject domain into a set of independent subject domains of recipes, equipment and control [12]. Such decomposition allows company specialists to solve their problems within a strictly defined subject domain, abstracting away from the rest. This fact fundamentally ensures flexibility of batch manufacturing and serves as a basis for constructing an ontology-based model of an enterprise.

ISA-88 consists of four parts, but the first one is particularly valuable for constructing formal ontology, since it provides terminology and a consistent set of concepts and models used in batch control. From now on, we will focus on Part 1 of ISA-88.

ISA-88 Part 1 document structure includes 6 sections

1) Scope of the standard
2) Normative References
3) Definitions
4) Batch Processes and Equipment
5) Batch Control Concepts
6) Batch Control Activities and Functions.

Document structure translates to a hierarchy of *subject domains* and corresponding *ontologies* as described. ISA-88 as whole corresponds to a ***Subject domain of batch manufacturing enterprises***. First two sections specify a document and do not concern the description of a subject domain of batch manufacturing enterprises and, therefore, do not map to any part of the hierarchy of subject domains and ontologies. Section 3 corresponds to a terminological ontology and a logical ontology [24] of ***Subject domain of batch manufacturing enterprises***. Subsection 4.1 corresponds to the ***Subject domain of process models of batch manufacturing enterprises***. Remaining subsections of this section correspond to ***Subject domain of physical models of batch manufacturing enterprises***. Section 5 corresponds to ***Subject domain of procedural control models of batch manufacturing enterprises***. Section 6 corresponds to ***Subject domain of batch control activities***.

Hierarchy of basic subject domains can be formally represented using SCn language [6] as follows:

Subject domain of batch manufacturing enterprises
=> *partial subject domain**:

- *Subject domain of physical models of batch manufacturing enterprises*
- *Subject domain of process models of batch manufacturing enterprises*
- *Subject domain of procedural control models of batch manufacturing enterprises*
- *Subject domain of batch control activities*

Here are the ***structural specifications*** [24] of partial subject domains, represented using SCn language.

Subject domain of physical models of batch manufacturing enterprises
∋ *maximal class of research objects'*:
  equipment entity
∋ *non-maximal class of research objects'*:

- *process cell*
- *unit*
- *equipment module*
- *control module*
- *enterprise*
- *site*
- *area*
- *equipment relation*

∋ *researched relation'*:
  *contains**

Subject domain of process models of batch manufacturing enterprises
∋ *maximal class of research objects'*:
  process element
∋ *non-maximal class of research objects'*:

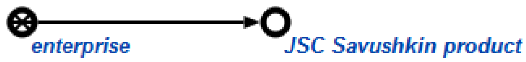

Figure 1. JSC «Savushkin product»

- *process stage*
- *process operation*
- *process action*

∋ *researched relation'*:
*process element link**

Subject domain of procedural control models of batch manufacturing enterprises
∋ *maximal class of research objects'*:
procedural element
∋ *non-maximal class of research objects'*:

- *process cell procedure*
- *unit procedure*
- *operation*
- *phase*
- *recipe procedural element*
- *equipment procedural element*
- *recipe process cell procedure*
- *recipe unit procedure*
- *recipe operation*
- *recipe phase*
- *equipment process cell procedure*
- *unit procedure*
- *equipment operation*
- *equipment phase*

∋ *researched relation'*:
*execution order**

We will now discuss examples of enterprise physical model description of JSC «Savushkin product» based on the terminology introduced in ***Subject domain of physical models of batch manufacturing enterprises***.

IV. Physical model of JSC «Savushkin product»

One can specify an enterprise in various aspects, some of which (processes, procedures, equipment and control) are governed by ISA-88 standard. As was mentioned in the previous section, these aspects correspond to hierarchically organized subject domains. To illustrate this, we will provide a fragment of JSC «Savushkin product» specification within a *Subject domain of physical models of batch manufacturing enterprises*. This specification has seven levels: enterprise, site, area, process cell, unit, equipment module, control module. We will start from the enterprise level.

A. Enterprise level

Enterprise is a largest manufacturing unit, which usually means company as a whole. In our case, we have JSC «Savushkin product» at the enterprise level. Formal representation of this fact is provided in Fig. 1. From now on we will use SCg language [6] for formal representation

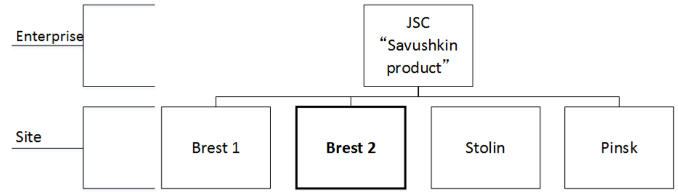

Figure 2. Areas of JSC «Savushkin product»

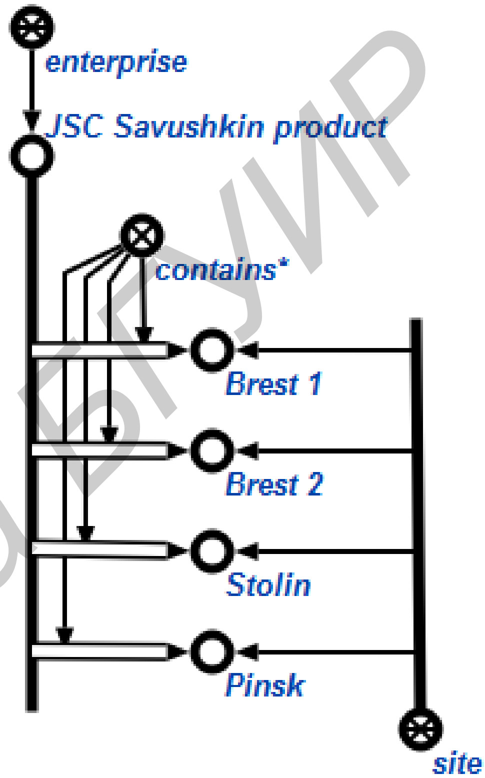

Figure 3. Formal representation of a connection between top two levels of a physical model

B. Area level

Enterprise consists of one or more areas. Area boundaries are usually determined based on geographical approach. Areas of JSC «Savushkin product» are shown in 2. Formal representation of this information is shown in Fig. 3. «Brest 2» area will now be considered (it is emphasized in Fig. 2).

C. Site level

Area contains one or more sites. As per ISA-88, not every part of an area will be a part of a site. Only those directly related to batch manufacturing process will be considered as a part of a site.

Sites of «Brest 2» area are shown in Fig. 4. Formal representation of a given part of enterprise structure is shown in Fig. 5. «Soft cheese and cottage cheese shop» site (emphasized in Fig. 4) will be discussed from this point onwards.

Establishing boundaries of the highest-level entities are beyond the scope of an ISA-88 standard, since there are many

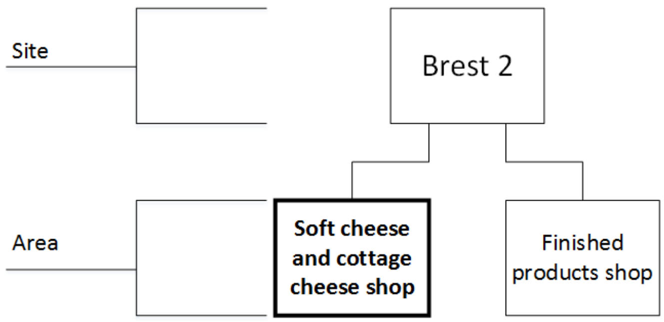

Figure 4. Sites of a «Brest 2» area

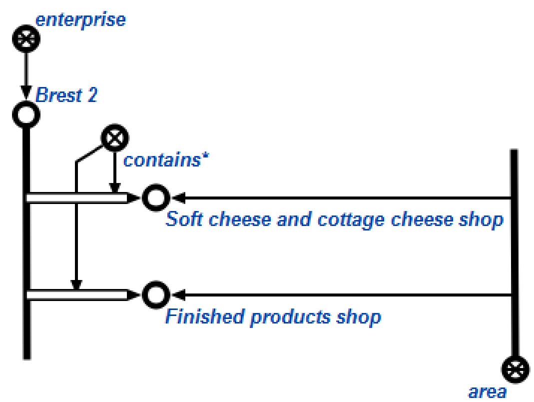

Figure 5. Formal representation of a connection between second and third levels of a physical model

factors that determine them, such as corporate politics or business requirements. And batch manufacturing needs may not be the most important factor [12]. Those entities are discussed in more depth in the ISA-95 standard.

D. Process cell level

Site contains all the equipment necessary to produce a batch. The term «train» is sometimes used to describe the site's equipment needed to produce a batch. Process cell can contain more than one train, and the order of the equipment in it is called a path. Process cell takes raw materials or work-in-progress substances and makes them into a product or into a different work-in-progress substance.

Soft cheese and cottage cheese shop of a «Brest 2» area contains two process cells – one for making cottage cheese and one for shaping and packing of the product (see Fig. 6). Fig. 7 shows the formal representation of this part of the enterprise structure. We will now focus on a process cell, which produces cottage cheese «Khutorok» (emphasized in Fig. 6)

E. Units, equipment modules and control modules

Lowest three levels of a physical model are discussed together, since, according to ISA-88, process cell can directly contain units, equipment modules, as well as control modules, which is shown in Fig. 8. In a similar fashion, unit can contain equipment modules, as well as control modules.

Units are the basic parts of batch manufacturing. Batch manufacturing process actually happens inside units. Units

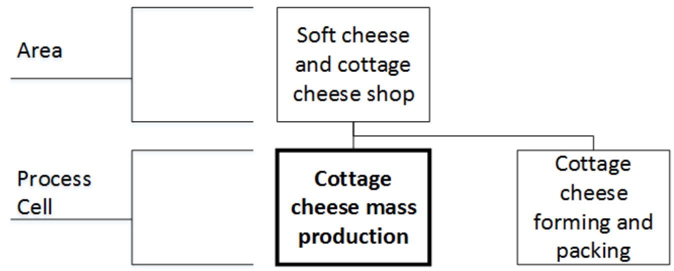

Figure 6. Process cells within a soft cheese and cottage cheese shop

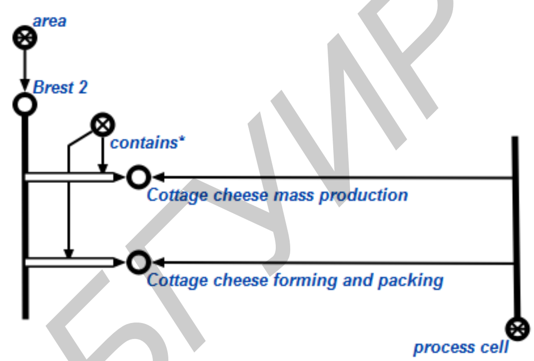

Figure 7. Formal representation of the connections between fourth and fifth levels of a model

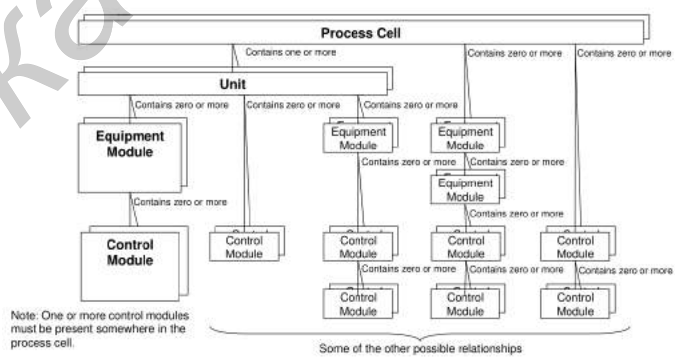

Figure 8. Some of the possible relations between the entities of lowest three levels of an ISA-88 physical model

perform major processing activities, which in some way add value to the final or the work-in-progress product – mixing, chemical reactions, etc. They are usually, but not necessarily, based around some container.

Equipment module is a group of equipment that can carry out a finite number of specific batch manufacturing functions. ISA-88 standard assumes that equipment module can implement decision-based logic. Monitoring pressure or level of liquid, maintaining certain temperature conditions can be used as examples.

Control module is a basic element of a physical model. It represents a connected set of sensors, valves, etc., which can be interpreted as a single entity. It is worth noting that control module does not have to be physically implemented. It can be an instruction or a group of instructions of a programmable microcontroller, or even a device driver.

The process cell we are looking at has 32 coagulators (units), two input trains, eight output trains, eight whey pumping trains and 16 boilers (equipment modules), as we can see in Fig. 9. Formal representation of the lowest levels of a physical model is shown in Fig. 10. Control module list is omitted for the sake of brevity. Some of them will be mentioned in the upcoming example.

F. Practical application of a physical model

Practical applications of a physical model include, in particular, formalization of the enterprise technical documentation, such as functional charts. Fundamental simplicity of mutual translation between a technological chart and its semantics-based representation makes it possible to ask questions about its parts, initiate commands to change physical equipment state, monitor equipment status over time. This functionality is provided by a collective of receptor and effector agents operating on the semantics-based representation of a documentation, stored in shared semantic memory. This allows to «liven up» enterprise technical documentation and to make it multipurpose.

For an example of a practical application we will consider a part of a previously mentioned process cell, which contains two coagulators (units) and a boiler (equipment module). It additionally has a number of sensors, pumps and valves, which are, according to ISA-88, considered control modules, because they are basic devices and implement atomic functions.

Fig. 11 shows a part of enterprise functional chart, which depicts equipment that is used during the cottage cheese heating phase. This chart is implemented using [23] standard. Chart shows two coagulators (№14 and №15) with two temperature sensors each (TE141, TE142, TE151, TE152), circulation tank and a heat exchanger. Temperature sensors monitor water temperature in coagulator shells. Arrows show water circulation through coagulator heating system (coagulator №14, circulation tank, heat exchanger and coagulator №15). Circulation tank has two level sensors – LS41 and LS42, that monitor water level to prevent water overflow or depletion. If water level in the circulation tank drops below LS41 level, the V41 valve is opened. V41 is closed, when water reaches LS42 level. V40 valve manages steam supply to the heat exchanger. This regulates water temperature, which is controlled by the TE4 temperature sensor. Pump N4 pushes water through coagulator heating system. Valves 14V1 and 15V1 manage hot water supply to the shells of coagulators №14 and №15.

We will now discuss a process of transforming a technological chart into its semantics-based representation. Each specific equipment item, such as sensor, pump, pipe or coagulator corresponds to a node in a semantic network. Specific equipment piece is an instance of a certain equipment class. This fact is denoted by a link between nodes, that represent them, as shown in Fig. 12.

Pipes are the special equipment, which interconnects other manufacturing equipment. If, during the manufacturing process, processed substance goes from one piece of equipment to another through a pipe, then there will be two binary links. First one connects a pipe and a source piece of equipment and belongs to a ***source equipment**** relation. The second one connects a pipe and a target piece of equipment and belongs to a ***target equipment**** relation, as shown in Fig. 13.

Pipes can be connected to sensors. However, such connections do not involve a substance movement. They are identified by a ***connection**** link between pipe and sensor instances (see Fig. 14).

Functional chart (see Fig. 11) also depicts constructional parts, such as temperature sensors, as a separate entities. To connect a piece of equipment to its constructional part we use ***part-of**** relation link, which connects corresponding nodes (See Fig. 15).

Such description would be sufficient for a standalone shop. But for a batch manufacturing enterprise with multiple shops, such as JSC «Savushkin product», there is a need to unify its semantics-based representation using a common ontology. Among other reasons, this is needed to simplify shop management and interaction. Ontology of physical models of batch manufacturing enterprises, constructed as a result of ISA-88 formalization, can serve as such ontology. Within ontology-based model of the enterprise, it is situated above an ontology of a specific industry, but below batch manufacturing ontology. Hierarchical organization of ontologies ensures independence between manufacturing recipes and a specific equipment, that implements it. Their link will be established at a higher level of abstraction, which is analogous to a Bridge design pattern used in object-oriented design [3].

To establish a link between the first description and a physical model terms, one needs to match specific pieces of equipment to the appropriate levels of a physical model mentioned before. Merging those descriptions enables better understanding of how are control modules and equipment modules linked. This link is the key to ensure generalization and reuse in batch control [8].

For example, to specify the fact, that a certain piece of equipment (say, a valve) is a control module, one needs to include the corresponding semantic network node in the equipment module set, as shown in Fig. 16.

Other physical levels are assigned to an equipment in a similar fashion. After performing these transformations, we end up with a fragment of a semantic network, which corresponds to the aforementioned technological chart. It is shown in Fig. 18.

Such representation allows to ask various questions about this chart. We will now take a look at two examples.

- «Give an example of equipment module with a heat exchanger». This question is answered by an ***sc-agent for finding constructions, isomporphic to given pattern***. Its single argument is an sc-node, which denotes a search pattern shown in Fig. 17. Natural-language interpretaion of this search query can be constructed as follows: «Find all such structures, that belong to an equipment module set and that contain one or more elements of a heat exchanger set». Answer to this question is shown in Fig.19 as a fragment of a semantic network.
- «Which kinds of equipment are used to heat a cottage cheese mass?» This question is answered by an ***sc-agent for finding subclasses of given class within a given***

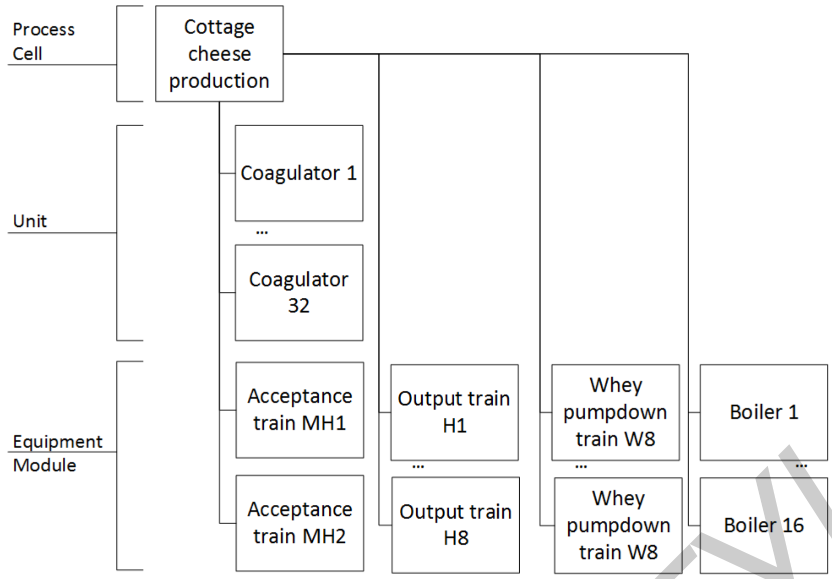

Figure 9. Units and equipment modules in a cottage cheese-making process cell

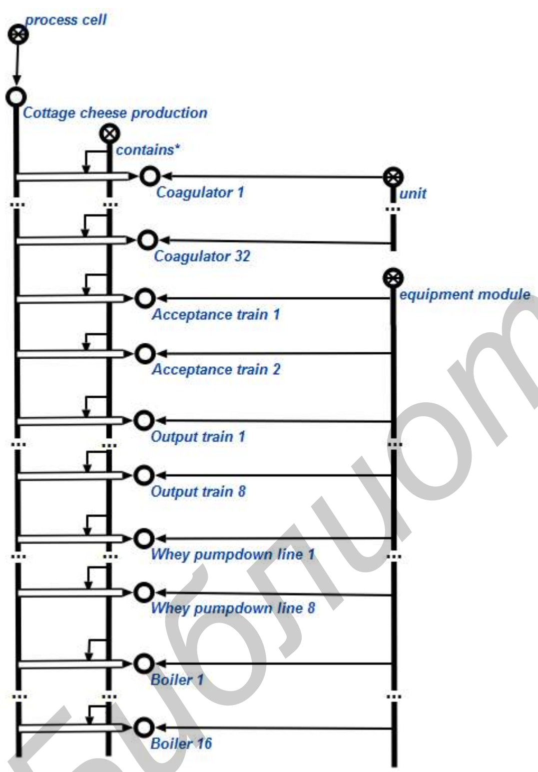

Figure 10. Formal representation of the lowest levels of the physical model

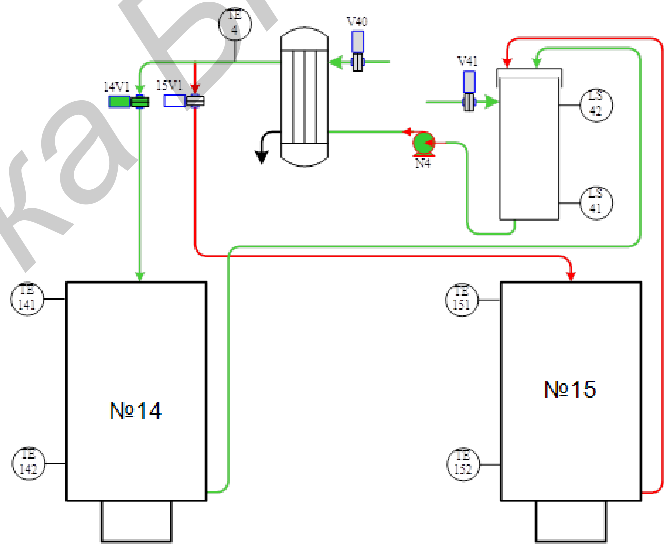

Figure 11. Functional chart implemented using GOST 21.404-85

Figure 12. Example instance of the equipment class

structure. Its accepts two arguments. First one is a node, representing a structure, within which to perform a search. Second one is a node of a class, subclasses of which are to be found. Argument values in this case are: (1) structure in Fig. 18 and (2) equipment node. Answer to this question is a set of classes coagulator, temperature sensor, valve, volume sensor, pipe, circulation tank, heat exchanger, pump. This agent is widely applicable and can answer any question of «Which X is used in Y?» kind.

V. Conclusion

This paper demonstrates basic principles of ontology-based design of batch manufacturing enterprises, using JSC «Savushkin product» as an example.

Key points of this paper:

- Enterprise is viewed as a knowledge-driven ***intelligent multi-agent system***. Knowledge are stored in a memory, shared between all of the agents. Such shared memory is

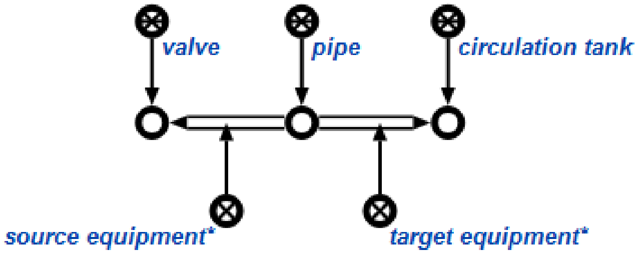

Figure 13. Two pieces of equipment connected with a pipe

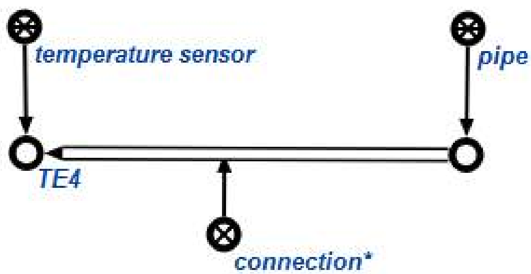

Figure 14. Connection between a pipe and a sensor

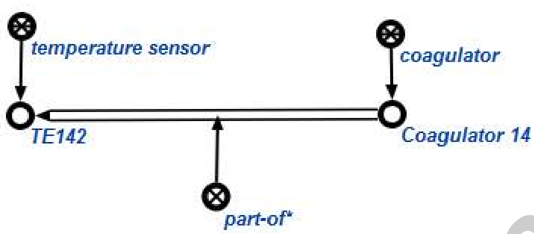

Figure 15. Connection between an equipment item and its constructional part

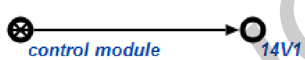

Figure 16. Valve is a control module

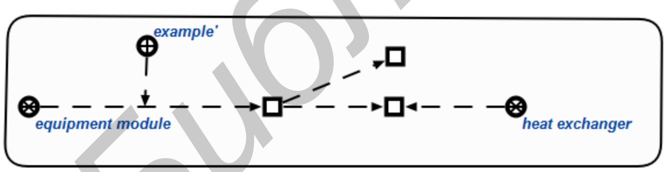

Figure 17. Search pattern example

called corporate memory of an enterprise. Agents of an intelligent enterprise include both programmatic agents, that work with corporate memory, as well as employees, who work and interact through this memory;

- ontology-based design of an enterprise is based on strictly specified, consistent ***system of a formal ontologies***. Each ontology describes principles behind certain aspects of operation management of a certain types of enterprises. Each formal ontology corresponds one-to-one to a ***subject domain***, which formally includes models (specifications) of various enterprises. These specifications describe these enterprises in an aspect, with which the ontology of that subject domain is concerned. ***Integrated ontology-based model of an enterprise being*** designed consists of a number of models, which describe the same enterprise but correspond to different ontologies;
- operation management principles, aimed at ***improving and adapting*** the enterprise to the changing conditions, have to be strictly specified as an ***enterprise improvement ontologies*** for a certain specified class of enterprises. Such ontologies are further subdivided into several partial ontologies, that describe various aspects of improving the structure or operation of the enterprise;
- the primary quality criterion of the produced ***system of formal ontologies*** for a certain specified class of enterprises is an ability to partition an enterprise improvement ontology for this class in such a way, that improvement of a various aspects of an enterprise could be carried out in parallel and relatively independently from one another. This criterion characterizes ***flexibility of enterprises***, built using this system of formal ontologies;
- the system of formal ontologies of ***batch manufacturing enterprises*** is built upon a formalization of the ***ISA-88 standard***, which is represented using the following system of ontologies:
  •• ***Ontologies of physical models of batch manufacturing enterprises***;
  •• ***Ontologies of process models of batch manufacturing enterprises***;
  •• ***Ontologies of procedural control models of batch manufacturing enterprises***;
  •• ***Ontologies of batch control activities***.
- ISA-88 is a remarkably high-quality standard, that facilitates the design of highly flexible batch manufacturing enterprises;
- Formalization of standards simplifies the process of making an enterprise conformant to the standards. It also facilitates the auditing process to ensure its conformance. Formalization of standards allows for a significant improvement of the information service level of an enterprise. It also facilitates employee education on the subject of a standard.

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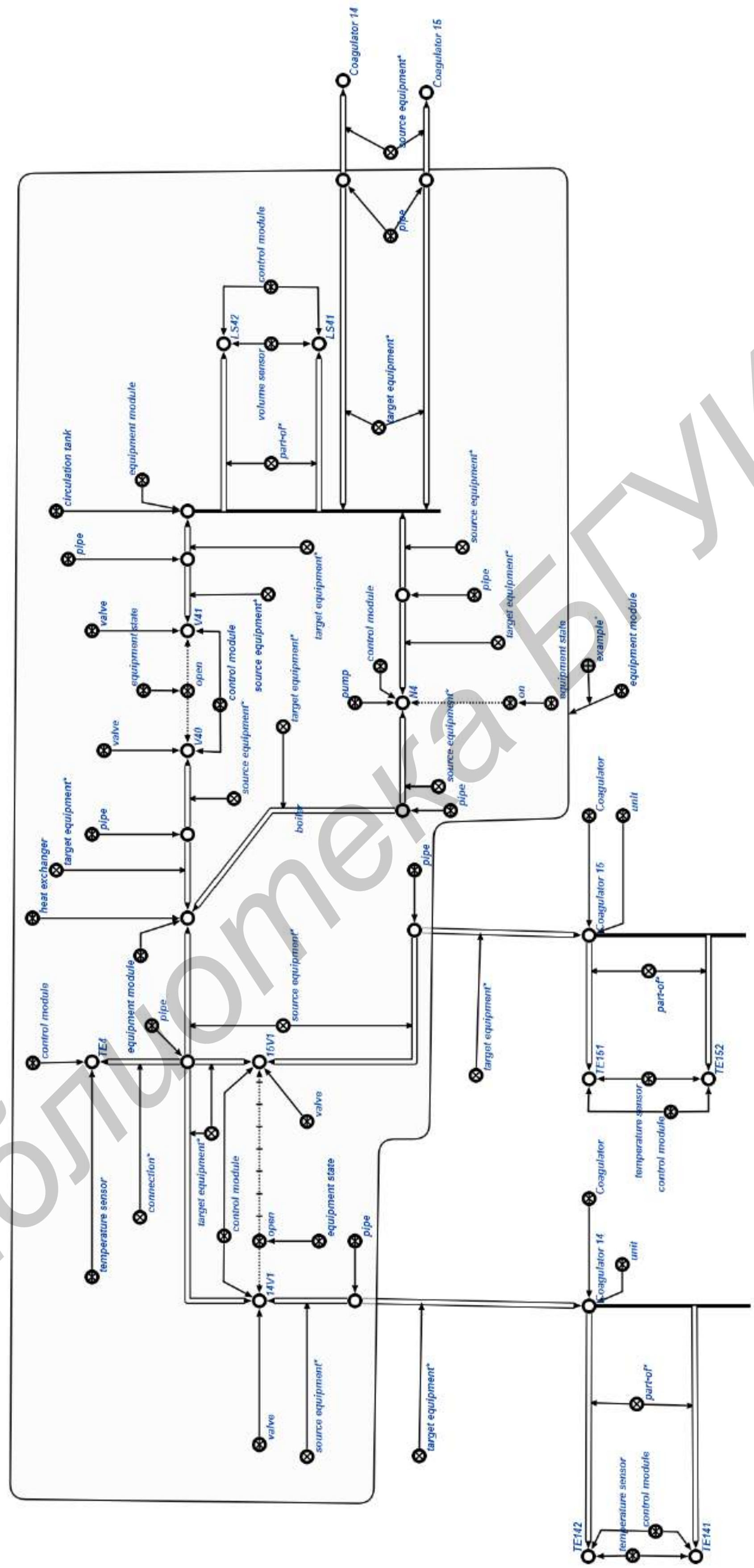

Figure 18. Fragment of semantic network, which corresponds to the technological chart

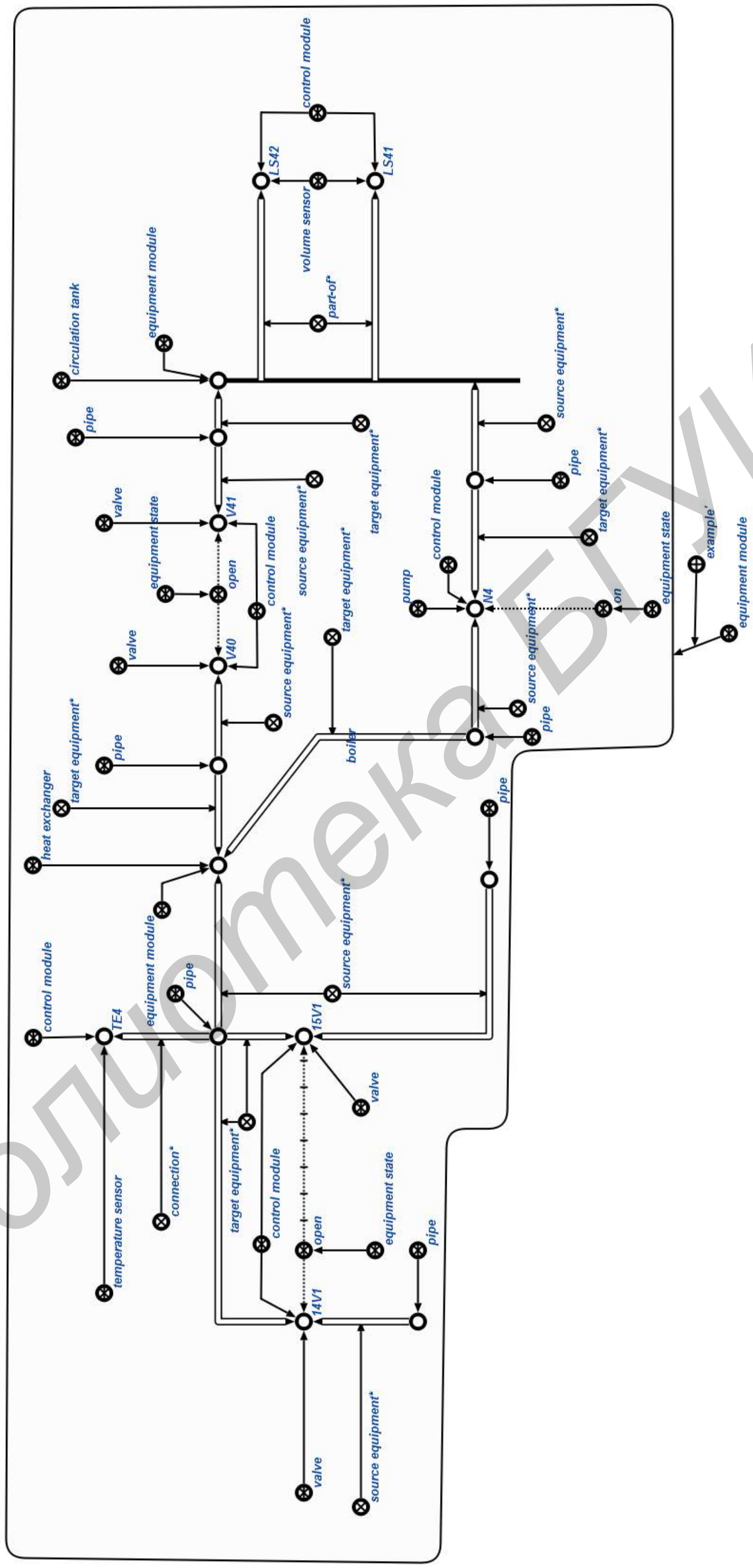

Figure 19. Answer to the question regarding an equipment module containing a heat exchanger

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Онтологическое проектирование предприятий рецептурного производства

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Данная статья посвящена рассмотрению текущих, тактических и стратегических аспектов повышения уровня автоматизации предприятий на примере предприятия рецептурного производства ОАО «Савушкин продукт». Предлагается онтологический подход к проектированию такого рода предприятий, состоящий в построении на основе текстов стандартов иерархической системы предметных областей и соответствующих им формальных онтологий. В его рамках предприятие рассматривается как распределенная, интеллектуальная, иерархическая, многоагентная система, в которой в качестве агентов могут выступать программы обработки знаний, технические устройства и персонал. В частности, обсуждаются принципы формализации стандартов, на которых основана деятельность предприятия, на примере стандарта ISA-88, касающегося предприятий рецептурного производства, каковым является ОАО «Савушкин продукт».

Средства автоматизации современного предприятия

должны оперативно и с минимальными затратами времени сотрудников адаптироваться к любым изменениям самого производства – к расширению или сокращению объемов производства, изменениям номенклатуры производства, изменению используемого оборудования, изменению общей структуры производства, изменению взаимодействия с поставщиками и потребителями, к изменению нормативно-правовых актов (включая стандарты), которым предприятие должно соответствовать, к различного рода непредвиденным обстоятельствам.

Средства автоматизации современного предприятия должны быть гибкими не только для оперативной адаптации к реконфигурации производства, но и для оперативного внесения изменений в сами средства автоматизации в направлении их постоянного совершенствования. Отметим, что здесь существенным является не только снижение трудоемкости повышения уровня автоматизации, но и поддержка высоких темпов повышения уровня автоматизации, а также четко продуманный переходный процесс от одного уровня автоматизации к следующему, в ходе которого одновременно используется и устаревший вариант и новый.

Повышение уровня автоматизации предприятия предполагает существенное расширение числа автоматически или автоматизировано решаемых задач, а это, в свою очередь, приводит к автоматизации решения интеллектуальных задач, т.е. к использованию технологий искусственного интеллекта.

Для того, чтобы обеспечить широкое применение технологий искусственного интеллекта в автоматизации предприятия, все корпоративные знания предприятия должны быть записаны на формальном языке представления знаний. При этом указанный язык должен быть удобен не только для использования в интеллектуальных компьютерных системах, но и для использования всеми сотрудниками предприятия.

Для построения онтологической модели предприятия необходимо решить следующие проблемы:

- Существующие средства автоматизации деятельности предприятия имеют высокую стоимость, трудны в освоении и адаптации к конкретному производству. Разработчики стремятся сделать такого рода средства как можно более функциональными, наращивая их частными решениями, что приводит к сложности и громоздкости таких систем.
- Как следствие подобного подхода к наращиванию функционала, существующие средства автоматизации деятельности предприятия имеют низкий уровень гибкости (возможности внесения изменений), что приводит к существенным накладным расходам при адаптации таких средств к новым требованиям.
- Отсутствие общих унифицированных моделей и средств построения систем автоматизации деятельности предприятия приводит к большому количеству дублирований аналогичных решений как в рамках различных предприятий, так и в рамках разных подразделений одного предприятия.
- Отсутствие такого рода моделей препятствует дальнейшему повышению уровня автоматизации предприятия, в частности, в области автоматизации принятия решений в нештатных ситуациях, прогнозирования дальнейшего развития событий.
- Высокий уровень зависимости системы автоматизации предприятия от разработчиков приводит к проблемам внедрения и сопровождения такой системы при смене разработчика.
- Отсутствие формальных моделей различных стандартов, регламентирующих деятельность предприятия, приводит к возможным трудностям в трактовке тех или иных положений стандарта и обучении персонала. Это также затрудняет процесс проверки предприятия или его подразделений на соответствие необходимым стандартам

В настоящее время существует ряд подходов, ориентированных на повышение уровня автоматизации и гибкости предприятий. Перечислим те их них, что наиболее сильно повлияли на развитие предлагаемого подхода:

- Модели управления знаниями предприятий
- Онтологические модели предприятий
- Многоагентные модели предприятий
- Модели ситуационного управления
- Модели реинжиниринга бизнес-процессов предприятий

Основной недостаток всех приведенных выше моделей заключается в том, что ни одна из них не обладает достаточной полнотой, и для наиболее адекватного соответствия реальному предприятию его модель должна быть результатом интеграции всех этих моделей.

Предлагаемый подход к решению указанных проблем основан на следующих основных принципах:

- Предприятие рассматривается как распределенная, интеллектуальная социотехническая система, в основе которой лежит хорошо структурированная общая база знаний предприятия.
- В рамках базы знаний предприятия интегрируются все вышеуказанные модели (управления знаниями, онтологической, многоагентной, реинжиниринга бизнес процессов).
- Предприятие рассматривается как иерархическая многоагентная система, в которой агентами являются как программно реализованные агенты, так и сотрудники предприятия. Иерархичность заключается в существовании неатомарных агентов (коллективов), включающих как атомарные, так и неатомарные агенты.
- Весь комплекс средств, обеспечивающих деятельность предприятия, оформляется в виде распределенной интеллектуальной корпоративной системы предприятия.
- Проектирование онтологической модели предприятия сводится к проектированию онтологической модели его интеллектуальной корпоративной системы. Онтологическая модель предприятия является одновременно и объектом, и результатом проектирования.

- Для реализации корпоративной системы предприятия предлагается использовать Технологию OSTIS [21],[22].

Чтобы реализовать предложенный подход, необходимо решить следующие задачи:

- Разработать унифицированную структуру общей (интегрированной) базы знаний интеллектуальной корпоративной системы предприятия в виде иерархической системы предметных областей и соответствующих им онтологий.
- Разработать модель машины обработки знаний [39] интеллектуальной корпоративной системы предприятия.
- Разработать модели интерфейсов [27] интеллектуальной корпоративной системы предприятия для разных категорий пользователей.
- Разработать модель средств информационного обслуживания разных категорий пользователей интеллектуальной корпоративной системы предприятия.
- Разработать модель средств поддержки инжиниринга и реинжиниринга базы знаний интеллектуальной корпоративной системы предприятия.

На данном этапе работы основное внимание уделено решению задачи разработки онтологической модели базы знаний, в частности -– построению набора предметных областей, описывающих содержание основных стандартов.

Основой онтологического подхода к проектированию предприятия является формализация стандартов. Каждый стандарт рассматривается как онтология соответствующей ему предметной области.

При внедрении стандарта могут возникать проблемы, связанные с неоднозначной трактовкой некоторых положений стандарта и особенностями применеиния стандарта на конкретном предприятии. Одним из путей решения такого рода проблем является построение его формальной семантической модели, которая могла бы одинаково интерпретироваться как компьютерной системой, так и человеком. Формальное семантическое представление стандарта создает конструктивную почву для его согласования, а также для обеспечения четкости и однозначности его трактовки и обеспечивает упрощение внесения изменений, вызванных как уточнением трактовки, так и эволюцией самого стандарта.

Построение формальной модели стандарта сводится к построению интегрированной формальной онтологии, специфицирующей соответствующую предметную область. Для этого необходимо отобразить структуру и содержание исходного текста документа стандарта на иерархию предметных областей и соответствующих им онтологий.

Использование онтологического подхода к построению формальной модели стандарта позволяет построить интеллектуальную справочную систему, предоставляющую широкий спектр информационных услуг относительно применения стандарта. Такая система способна отвечать на широкий спектр вопросов вида «что такое...?», «для чего необходим...?», «как связаны...?», «что если...?» и другие.

В данной работе формализация стандартов рассматривается на примере предприятия рецептурного производства ОАО «Савушкин продукт». Поскольку специфика рецептурного производство наиболее полно охватывается стандартом ISA-88, то именно он и выбран в качестве объекта формализации. Следует отметить высокое качество стандарта ISA-88, позволяющее проектировать предприятия рецептурного производства, обладающие высокой степенью гибкости.

Содержание первой части стандарта отображается на следующие предметные области в рамках интеллектуальной корпоративной системы предприятия:

- Предметная область предприятий рецептурного производства
- Предметная область физических моделей рецептурных производств
- Предметная область процессных моделей рецептурных производств
- Предметная область моделей процедурного управления оборудованием рецептурных производств
- Предметная область деятельности по управлению рецептурным производством

Здесь также следует отметить, что каждой из этих предметных областей будет соответствовать онтология совершенствования предприятия в соответствующем аспекте его структуры и деятельности, в которой строго описаны принципы организации деятельности, направленной на совершенствование и адаптацию предприятия к изменяющимся условиям. Такая организация системы предметных областей и формальных онтологий обеспечивает параллельное и в достаточной степени независимое совершенствование различных аспектов предприятия, что позволяет говорить о высокой степени гибкости предприятий, строящихся на ее основе.

Данная статья уделяет внимание физической модели предприятия ОАО «Савушкин продукт». Спецификация предприятия в рамках этой предметной области имеет семь уровней: предприятие, производство, производственный участок, ячейка процесса, аппарат, агрегат, блок управления. Предприятие – самая крупная производственная единица, соответствующая компании в целом. Элементы остальных уровней вкладываются в нее по иерархическому принципу. В статье последовательно рассматривается по одному элементу с каждого уровня модели до уровня аппаратов: ОАО «Савушкин продукт» – Производство «Брест 2» – Цех мягких сыров и творога – Ячейка производства творожной массы. Три нижних уровня модели разбираются на примере фрагмента ячейки процесса, иллюстрирующей также использование физической модели при формализации технической документации предприятия. Для каждого из приводимых фрагментов структуры предприятия приводится соответствующий фрагмент семантической сети. Семантическое представление позволяет задавать к документации разнообразные вопросы, обеспечивая тем самым эффективное информационное обслуживание сотрудников предприятия.