Development of Models and Algorithms for Intellectual Support of Life Cycle of Chemical Production Equipment

Evgenii Moshev, Valeriy Meshalkin and Makar Romashkin

Abstract The article gives the statement of tasks necessary for automation of processes of adoption of intellectual decisions on the integrated logistic support of chemical production equipment, the solution of which is aimed at creating a cyber-physical system of the life cycle of the equipment. An example of formalization of this equipment life cycle with the help of functional modeling methods is given. There are given the models of knowledge representation about the equipment in a form of frames, and also—the processes of adoption of intellectual decisions on integrated logistic support of the equipment in a form of production rules. A heuristic-computational algorithm that allows automating the determination of classification characteristics of the equipment according to the degree of danger of the working substance is presented.

Keywords Cyber-physical system · Integrated logistic support · Frame · Production rules · Heuristic-computational algorithm · SADT-model · Functional model

1 Introduction

To ensure the process of continuous improvement of quality of integrated logistics support (ILP) of chemical production equipment under modern reality conditions and the level of technology development, it is necessary to process a significant amount of information arising at all stages of the life cycle of this type of equipment with the

E. Moshev (✉) · M. Romashkin
Perm National Research Polytechnic University, 29 Komsomol prosp., Perm 614990, Russia
e-mail: erm@pstu.ru

M. Romashkin
e-mail: t_romash_63@mail.ru

V. Meshalkin
D. Mendeleev, University of Chemical Technology of Russia, 9 Miusskaya pl., Moscow 125047, Russia
e-mail: clogist@muctr.ru

A. G. Kravets et al. (eds.), *Cyber-Physical Systems: Advances in Design & Modelling*, Studies in Systems, Decision and Control 259,
https://doi.org/10.1007/978-3-030-32579-4_12

usage of promising methods and mechanisms, namely, using cyber-physical systems. Creation of such a system of the life cycle of chemical production equipment for its further application in activities of chemical industry enterprises is inextricably linked with the need to develop models and algorithms with the help of which it is possible to solve actual ILP problems of this industrial equipment arising at various stages of its life cycle.

One of the most important tasks of integrated logistics support [1, 2] of industrial equipment is modeling of engineers', technical, organizational and technological processes for making intelligent decisions as a necessary condition for computerization. In accordance with State Standard of the Russian Federation GOST R 53394-2009, the ILP in the article refers to a set of types of engineering activities carried on through management, engineering and information technologies that provide a high level of performance readiness of industrial equipment (in particular by the features determining readiness of performance, that is, reliability, durability, ability for maintenance, serviceability and repair technological effectiveness, etc.) at a simultaneous reducing operating expenses [3, 4]. ILP of industrial equipment is a complex organizational and technological process that contains not only a large number of system interrelationships between different processes for making intelligent decisions but also special industrial requirements for nomenclature and methods of performing these ones. Among the ILP processes of chemical production equipment that require intellectual decision-making, we can distinguish the following:

- determination of features of equipment classification according to the degree of hazard of the working environment;
- selection and calculation of characteristics of structural elements of the equipment;
- selection and calculation of characteristics of welded and flange joints;
- determination of the characteristics of electric-arc welding and the weight of welding electrodes;
- formation of a structured list with the equipment data;
- calculation of the frequency spectrum of pressure pulsations generated by piston compressors in adjacent pipelines;
- determination of characteristics of structural elements of equipment, not included (missing) in the passport and technical documentation, on the basis of a set of introduced (known) characteristics;
- verification of the values introduced into the passport and technical documentation of equipment of chemical production, and their structural elements on conformity to the requirements of normative and technical documentation.

Currently, the implementation of above processes is carried out mainly manually or with the help of non-specialized software, which requires significant amounts of time and involves a large number of errors, presence of which decreases quality of ILP, and, consequently, leads to reducing profitability indicators and industrial safety of chemical production.

Preliminary analysis of intellectual decision-making processes for ILP equipment of chemical production showed that their formalization is impossible without the use of methods of artificial intellect theory [5, 6] and mathematical modeling.

Analysis of scientific and technical literature, particularly in the field of aircraft industry [7], building [8], studies of dynamic equipment [9], engineering [10], production planning [11, 12], design of systems and databases [13, 14], as well as analysis of current software [15–19] did not reveal the models, the algorithms and the modes of computer program operating that can be used to automation the above processes for making intelligent decisions on ILP of chemical production equipment.

Based on the above, the purpose of this study was to develop the models and the algorithms that allow you to automate the fulfillment of processes of making intelligent decisions on ILP for equipment of chemical production. This article presents only a small part of the results of this work.

To achieve this objective, it was necessary to solve the following tasks:

- to carry out analysis of scientific and technical literature, normative and technical and operational documentation, as well as the life cycle of chemical production equipment as an object of modeling;
- to formalize life cycle (LC) of chemical production equipment as a system of interrelated decision-making processes necessary for effective implementation of ILP;
- to create models of knowledge representation about the equipment of chemical production (digital counterparts of equipment);
- to develop models of knowledge representation about the processes by which decisions are made on ILP equipment of chemical production;
- to develop algorithms that formalize decision-making processes for ILP equipment of chemical production.

2 Analysis of Scientific and Technical Literature, Normative-Technical and Operational Documentation, and Life Cycle of Chemical Production Equipment as an Object of Modeling

In the process of analyzing a significant amount of scientific and technical literature, normative and technical and operational documentation, as well as life cycle processes of equipment of chemical production, the following provisions were established:

- presence of a large number of organizational and technological processes for implementation of which requires intellectual support during each stage of the life cycle of equipment of chemical production;
- containing a considerable amount of routine operations in many organizational and technological processes among which we can note a search of normative and technical data, an implementation of engineering calculations, a fulfillment of geometric representation of the elements that belong to the equipment of chemical production, a formation of technical documentation;

- existence of the dependencies between characteristics of structural elements of equipment of chemical production and working media, which in many cases are discrete in nature and in general can be described by Eq. (1):

$$\langle Y_f \rangle = (k_{f,1}, \ldots, k_{f,i}, \ldots, k_{f,N}) = FP_f, \quad (1)$$

where $\langle Y_f \rangle$—a subset of characteristics of structural elements of equipment of chemical production of *f*-type; $f = \overline{1, N_f}$), N_f—a number of types of structural elements of the equipment; $k_{f,i}$—*i*-characteristic of the *f*-type of the structural element; P_f—a subset of parameters of the equipment of chemical production and working media required to determine characteristics of the structural elements of the *f*-type;

- formalization of many procedures for making intelligent decisions on ILP of equipment of chemical production by means of models and algorithms used in the theory of artificial intellect;
- feasibility of the usage of SADT-models to represent knowledge about organizational and technological component of decision-making processes;
- the relevance of using frame models to represent knowledge about the equipment of chemical production and working environment;
- the advisability of the use of production models or of production rules to represent knowledge about the processes by which decisions on equipment of chemical products are made [20].

3 Formalization of Life Cycle of Chemical Production Equipment

Formalization of life cycle of chemical production equipment as a system of interrelated decision-making processes of ILP was carried out with the help of methodology SADT (Structured Analysis & Design Technique), described by David A. Mark and Clement McGowan in his book "Methodology of the Structures Strength Analysis and Design SADT". This methodology widely used in the development of complex systems is considered in the standards of the IDEF0 family, as an integral part of CALS technologies and is used in many countries, including Russia, where it is also known as methodology of functional modeling.

To simplify the overall formalization task, the complete SADT life cycle model of chemical production equipment was reduced to three conditionally independent models: a model of designed chemical production equipment, the one of the mounted one and that of an operated one (Fig. 1).

All the designed SADT-models differ with taking into account the complex relationships both within the stages of the life cycle of chemical production equipment and between them. With the help of specially developed algorithms, these models make it possible to carry out complex automation of ILP, as well as to ensure the

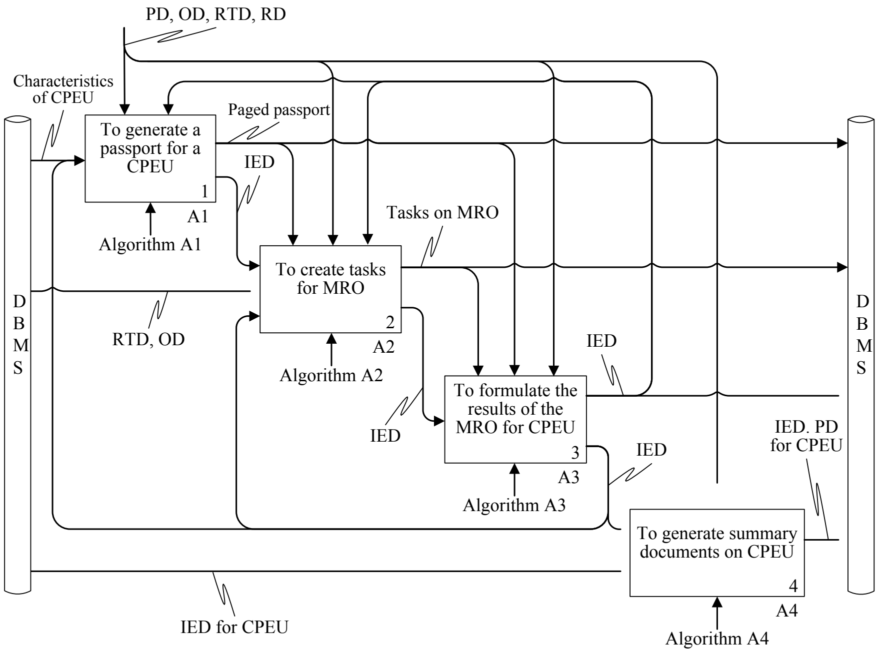

Fig. 1 The diagram of the zero level SADT-model "To execute ILP of the operated chemical production equipment unit" (CPEU): PD—project documentation; OD—operational documentation; RTD—regulatory and technical documentation; RD—repair documentation; IED—interactive electronic documentation; MRO—maintenance and repair; DBMS—database management system

interaction of all the subjects of the life cycle of chemical production equipment in a single information space. At these models usage the fulfillment of duplicate operations is eliminated and the speed of data exchange increases that promote quality improvement and reduction the cost of maintenance and repair of chemical production equipment. A complete description of the model shown in Fig. 1 contains 11 diagrams and about 60 functional blocks.

One of the most complex objects of ILP are piston compressors [21], this is due to physical peculiarities of their work, namely, to the pulsation of the pressure of compressed gas, that can become a source of increased vibration of pipelines adjacent to the compressors. Pressure pulsation is an integral feature of piston compressors' functioning and it is formed due to the periodicity of processes of inlet and outlet of \compressed gases from compressor cylinders. One of the ways to reduce the dynamic impact of gas pressure pulsations on pipelines and on technological equipment that is adjacent to compressors is the use of buffer tanks and smoothing diaphragms. Calculation of buffer tanks is a complex engineering and technical task that requires high qualification of specialists. Based on the above, the authors have also developed models and algorithms which permit to automate the calculation of buffer capacities and diaphragms.

4 Development of Models of Knowledge Representation About Chemical Production Equipment

An analysis of the equipment and the technological structures of chemical production shows that it is logical to present knowledge about the chemical production equipment in a form of interconnected frame models of three types: a general- technical type, a technical and technological one and a structural one.

A general- technical model is a three-level network of frames and contains a set of interrelated characteristics necessary for the description of chemical production equipment as an element of hierarchical structure of an enterprise. A distinction of the model is that it presents the characteristics of chemical production equipment, taking into account global points of the junction for a specific technological installation of coordinate with adjacent equipment and it permits to automate image of technological installations of an enterprise in 3D mode as a single structure. As an example, Fig. 2 presents the first level and a part of the second one of frame-prototype containing the general technical characteristics of the vessel working under pressure as a type of chemical production equipment. A blank field presented in frame-prototype (Fig. 2) (Slot) is provided to enable a decision-maker, if it is necessary, to supply the knowledge about a particular object or expand it.

The model of technical and technological type is a three-level network of frames and contains a set of interrelated characteristics, for example: pressure and temperature of working environment, test pressure, general passport and technical data, records of the results of the repairs and of the audits, chemical composition of the working environment, the group of chemical production equipment according to the class of hazard. A set of the characteristics contained in the model was determined by the analysis of scientific and technical literature, normative and technical and operational documentation, which is formed throughout the life cycle of chemical production equipment. The characteristics used in this model, as a rule, relate to the unit of equipment as a whole, are indicated without correlation to the elements of the structure of chemical production equipment and do not contain information about its structural design and dimensions. The model of technical and technological type differs with its taking into consideration the technological structure of chemical production equipment and also with the requirements of normative and technical documentation that permits to automate ILP of chemical production equipment, and, therefore, to increase its quality.

The model of the structural type is a three-level network of frames and contains a set of characteristics that describe chemical production equipment in a form of an interconnected and purposeful combination of connected together standard structural elements (shells, bottoms, flanges, supports, pipes, fittings, transitions, bends), which is intended to implement the technological processes occurring in chemical production equipment. In addition to topological and geometric characteristics of the structural elements, the model contains regulatory and technical requirements for manufacturing these elements and their weight. The values of the characteristics

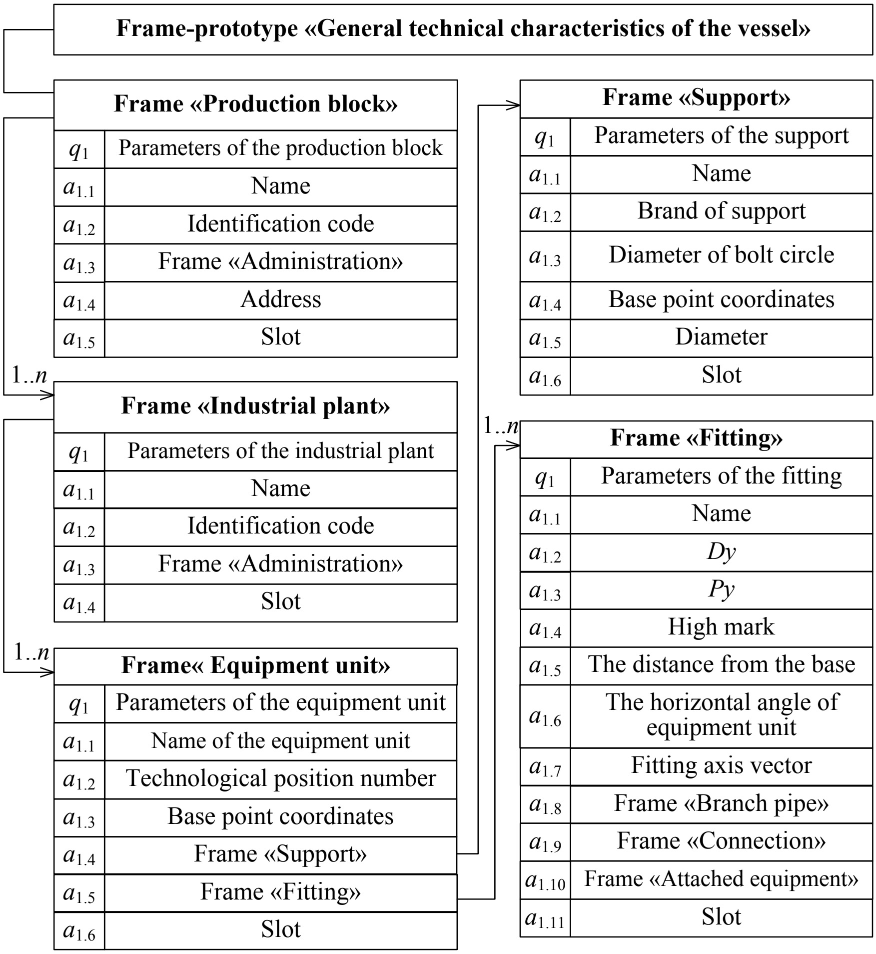

Fig. 2 Frame-prototype "General technical characteristics of the vessel": Dn—nominal diameter; Pn—nominal pressure; 1…n—the relationship between structural components of the model

given in the model are used in the formation of drawings, diagrams, forms and specifications of chemical production equipment throughout all the stages of the life cycle. A distinction of the structural type model is that it permits to automate both the image of the equipment in 3D and 2D modes and the formation of technical documentation throughout all the stages of the life cycle of chemical production equipment.

5 Development of Models of Knowledge Representation About Decision-Making Processes for Integrated Logistics Support of Chemical Production Equipment

As noted above, production models for representation of knowledge on the processes for adoption of intellectual decisions were chosen. These models are widely used to represent knowledge of various objects, including procedural knowledge (heuristics, normative knowledge) [20]. Development of production models of knowledge representation about the processes of intellectual decision-making was carried out by means of analyzing scientific and technical literature; normative-technical, passport, operational and repair documentation, as well as taking into consideration knowledge of experts of applied field and specificity of the stages of the life cycle of chemical production equipment. In total, there have been developed over ten production rules permitting to automate decision-making in determining a group and a category of chemical production equipment according to the requirements of industrial safety, as well as the structural characteristics of the elements of chemical production equipment and pipelines, welded and flange connections, elements of fasteners. Models of representation of knowledge about decision-making processes for integrated logistics support of chemical production equipment differ in display of system relationships between regulatory and technical requirements, various characteristics of chemical production equipment and working environment, which allows to automate selection and calculation of determined characteristics of chemical production equipment in accordance with the requirements of normative documents.

Table 1 shows an example of production rules that allow automating the decision-making processes in determining the characteristics of classification of chemical production equipment, namely, the type of working environment and the group of the vessel by hazard class. The following abbreviations and designations of variables are used in the table: CG, FL, CF—the names of combustible gases, the ones of flammable liquids and those of combustible liquids respectively, adopted in the

Table 1 An example of a production model of knowledge representation about the type of working medium and the group of vessels

I	Working environment: S_I	Type of work environment by hazard class: Ts_I	Conditions of applicability				Group of vessel: G_I
			Operating pressure range, MPa		Operating temperature range, °C		
			P_I^{min}	P_I^{max}	t_I^{min}	t_I^{max}	
1	Benzol	Second class	0.07	320.1	−273	700	1
2	Butane	CG	0.07	320.1	−273	700	1
3	Petrol	FL	0.07	320.1	−273	700	1
4	Fuel oil	CF	0.07	320.1	−273	700	1
5	Water	water	0.07	2.50	−40	400	3

regulatory and technical literature; $P_I^{\min}$, $P_I^{\max}$ и $t_I^{\min}$, $t_I^{\max}$—the boundary standard values of pressure and temperature of the working environment defining the sphere of existence of the characteristics sought in the process.

Determining the type of environment by hazard class is carried out by searching the array of regulatory attitude $R_I = (S_I, Ts_I)$ the relationship that meets the condition $(S_I, Ts_I) \cap S \neq \emptyset$ (2),

$$R_I = \left\{ \frac{1, (S = S_I)}{0} ; if(R_I = 1)then(Ts = Ts_I), \right. \tag{2}$$

where $I = \overline{1, d}$—an identifier of string in an array of regulatory attitude; d—a number of strings in an array of regulatory attitude; S_I, Ts_I—the reference values of component of the working environment and the of working environment by hazard class in I-relation; S, Ts—a given name of the working environment and a sought value of its type.

The definition of the vessel group is carried out similarly by searching the string satisfying the condition in an appropriate array of normative reference relations (3),

$$(Ts_I, (P_I, R_2), (t_I, R_2), G_I) \cap \langle Ts, P, t\rangle \neq \emptyset, \tag{3}$$

where R_2—binary ratio, G_I—a group of a vessel on the hazard class of the working environment.

6 Development of Algorithms Formalizing Decision-Making Processes for Integrated Logistics Support of Chemical Production Equipment

In development of algorithms that formalize the decision-making processes for ILP life cycle of chemical production equipment, the methods of discrete, linear, logical and cyclic programming, the results of system analysis of scientific and technical literature, normative-technical and passport-technical documentation, as well as the knowledge of subject area experts [22] were used. In total, more than twenty necessary algorithms have been developed. The algorithms are differed in displaying the system relationships between heuristic and computational operations within the ILP procedures, as well as in use of frame and production models of knowledge representation, which allows automating intellectual decision-making processes for ILP for chemical industries equipment.

An example of a block diagram of a heuristic-computational algorithm for determining the characteristics of the classification of chemical production equipment by hazard class of the working environment is presented in Fig. 3. Following abbreviations and designations of variables are adopted in the flowchart: PKB—production

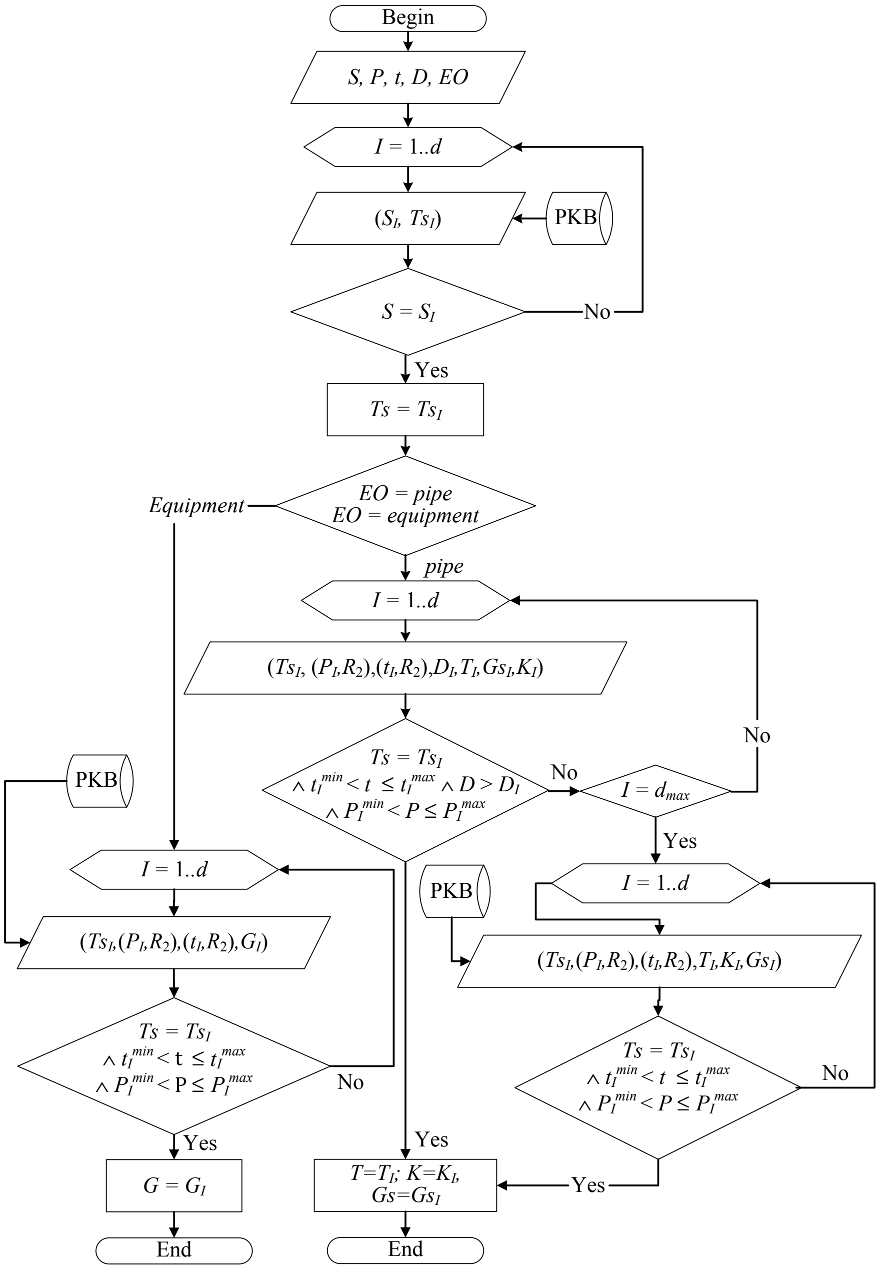

Fig. 3 Block diagram of heuristic-computational algorithm for determining the characteristics of the classification of chemical production equipment according to the degree of danger of the working environment

knowledge base developed with the help of production models of knowledge representation; D—a diameter determining a type of a pipeline; T and K—a type and a category of a pipeline; Gs—working environment group by hazard class. An algorithm differs in that the given values of characteristics of working environment (S), pressure (P) and temperature (t), as well as the diameter (D) of the pipeline with the help of frame and production models of knowledge about the characteristics of chemical production equipment, permits to automate the definition of the working environment group; type, group and category of pipelines, as well as groups of vessels in accordance with the requirements of regulatory and technical documentation.

7 Conclusion

The main scientific contribution of the work is representation of the life cycle and ILP of chemical industries equipment as a single system of interrelated organizational and technological processes. An applied approach allows not only to improve the quality of ILP, as an organizational and technological process, but also eliminate duplication of most processes and the operations performed at all the stages of the life cycle of chemical production equipment.

As a result of the work with the help of the methods of system analysis there were developed:

- SADT-life cycle models of chemical production equipment as a system of interrelated organizational and technological procedures of ILP. The models differ by taking into account the complex relationships between the procedures for making intellectual decisions at different stages of life cycle of chemical production equipment and with the help of special models and algorithms they allow to fulfill the complex automation of ILP, as well as to ensure the interaction of all the subjects of the life cycle of chemical production equipment in a single information space.
- Frame models of knowledge representation about chemical production equipment. The models are distinguished by taking into account the general technical, technological and structural characteristics of chemical production equipment, which allows automating: an image of a process facility as a single structure; an image of equipment units in 3D and 2D modes; making intellectual decisions and formation of technical documentation for ILP of chemical production equipment.
- Production models of knowledge representation on decision-making processes for integrated logistics support of chemical production equipment, which differ by display of system interconnections between regulatory and technical requirements, characteristics of chemical production equipment and working environment that allows to automate selection and calculation of the required characteristics of chemical production equipment, in accordance with the requirements of regulatory documents.
- Heuristic-computational algorithms which enable to automate decision-making processes for integrated logistics support of chemical production equipment. The

algorithms differ by displaying the system relationships between heuristic and computational operations within the ILP procedures, as well as the use of frame and production models of knowledge representation, which allows automating intellectual decision-making processes for ILP of chemical industries equipment.

Developed and described in the article models of knowledge representation, and heuristic-computational algorithms will allow to carry out complex automation of many procedures for making intelligent decisions on ILP of chemical industries equipment. Their inclusion in the system of management of the cyber-physical system of the life cycle of chemical production equipment will ensure high quality of ILP of this equipment, and, consequently, high profitability and industrial safety of the chemical industry enterprises.

References

1. Elena Nenni, M.: A cost model for integrated logistic support activities. Adv. Oper. Res. **2013**, 1–6 (2013)
2. Martin, P., Kolesár, J.: Logistic support and computer aided acquisition. J. Logistics Manag. **1**, 1–5 (2012)
3. Meshalkin, V.P., Moshev, E.R.: Modes of functioning of the automated system "pipeline" with integrated logistical support of pipelines and vessels of industrial enterprises. J. Mach. Manuf. Reliab. **44**(7), 580–592 (2015)
4. Moshev, E.R., Meshalkin, V.P.: Computer based logistics support system for the maintenance of chemical plant equipment. Theor. Found. Chem. Eng. **48**(6), 855–863 (2014)
5. Wu, D., Olson, D.L., Dolgui, A.: Artificial intelligence in engineering risk analytics. Eng. Appl. Artif. Intell. **65**, 433–435 (2017)
6. Russell, S.J., Norvig, P.: Artificial Intelligence: A Modern Approach, 3rd edn. Prentice Hall, New Jersey (2010)
7. Guo, F., Zou, F., Liu, J., Wang, Z.: Working mode in aircraft manufacturing based on digital coordination model. Int. J. Adv. Manuf. Technol. **98**, 1547–1571. http://dx.doi.org/10.1007/s00170-018-2048-0 (2018) (Springer, Cham)
8. Kim, H., Han, S.: Interactive 3D building modeling method using panoramic image sequences and digital map. Multimedia Tools Appl. **77**(20), 27387–27404. http://dx.doi.org/10.1007/s11042-018-5926-4 (2018) (Springer, Cham)
9. Cheng, J., Liu, Z., Yu, X., Feng, Q., Zeng, X.: Research on dynamic modeling and electromagnetic force centering of piston/piston rod system for labyrinth piston compressor. Proc. Inst. Mech. Eng. Part I: J. Syst. Control Eng. **230**(8), 786–798 (2016)
10. Pretorius, P.J.: How integrated is integrated logistics. S. Afr. J. Ind. Eng. **8**(2), 11–16 (1997)
11. Comelli, M., Gourgand, M., Lemoine, D.: A review of tactical planning models. J. Syst. Sci. Syst. Eng. **17**(2), 204–229 (2008)
12. Yevstratov, S.N., Vozhakov, A.V., Stolbov, V.Y.: Automation of production planning within an integrated information system of a multi-field enterprise. Autom. Remote Control **75**(7), 1323–1329 (2014)
13. Khouri, S., Bellatreche, L.: Design life-cycle-driven approach for data warehouse systems configurability. J. Data Semant. **6**(2), 83–111. http://dx.doi.org/ https://doi.org/10.1007/s13740-017-0077-8 (2017) (Springer, Cham)
14. Bertoni, M., Bertoni, A., Isaksson, O.: A value-driven concept selection method for early system design. J. Syst. Sci. Syst. Eng. **27**(1), 46–77 (2018)
15. SAP Software & Solutions. http://go.sap.com/index.html (2015). Accessed 14 Dec 2015

16. Isogen®. Automatic piping isometrics from 3D plant design systems. http://www.alias.ltd.uk/ISOGEN_main.asp (2015). Accessed 21 Jan 2015
17. AVEVA. Software Solutions for the Plant Industries. http://www.aveva.com/en/Products_and_Services/AVEVA_for_Plant.aspx (2015). Accessed 25 Jan 2015
18. CEA Systems. Plant-4D-Plant Engineering Solution. http://www.ceasystems.com/plant-4d-plant-engineering-solution (2014). Accessed 1 Jul 2014
19. iMaint.—CMMS Software—Service Management Software. http://www.imaint.com/en (2014). Accessed 5 Apr 2014
20. Lu, J., Zhu, Q., Wu, Q.: A novel data clustering algorithm using heuristic rules based on k-nearest neighbors' chain. Eng. Appl. Artif. Intell. **72**, 213–227 (2018)
21. Moshev, E.R., Romashkin, M.A.: Development of a conceptual model of a piston compressor for automating the information support of dynamic equipment. Chem. Petrol. Eng. **49**(9–10), 679–685. http://dx.doi.org/10.1007/s10556-014-9818-9 (2014). Springer, Cham
22. Menshikov, V., Meshalkin, V., Obraztsov, A.: Heuristic algorithms for 3D optimal chemical plant layout design. In: Proceedings of 19th International Congress of Chemical and Process Engineering (CHISA-2010), vol. 4, pp. 1425. Prague (2010)