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DEVELOPMENT OF INTELLIGENT SYSTEM FOR STRUCTURAL MODELLING OF COMPLEX SYSTEMS

Summary of Doctoral Thesis

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RIGA TECHNICAL UNIVERSITY
Faculty of Computer Science and Information Technology
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APPROVAL

I confirm that I have developed this thesis submitted for the doctoral degree at Riga Technical University. This thesis has not been submitted for the doctoral degree in any other university.

Ieva Zeltmate……………………………….. (signature)

Date: ……………………………………..

The doctoral thesis is written in Latvian and includes introduction, 4 chapters, and conclusions. The main text is 168 pages and it contains 102 figures. The bibliography contains 153 references. 3 appendixes are added in the separate volume.

TABLE OF CONTENTS

INTRODUCTION

Systems which people face daily are characterized by complex structure and operational principles. Working with the systems, as well as investigating and solving situations related with them, people constantly make choices and decisions. Complexity becomes relevant when people need to understand complex systems and make adequate decisions [HOR 1995, VIC 2002, ASH 2004, JOH 2009]. By understanding here is meant situation when a person (probably in thoughts) has a model of the system, where structure and functioning mechanisms are evident and allow logically and objectively reason about the system [SIM 1987, ASH 2007, SOK 2010]. With the increasing complexity of systems, more significant becomes research of systems, features of related problems and analysis of causal relationships that are essential for decision-making [CAR 2004]. The analysis is accomplished based on individual's knowledge, experience and insight, however, the human ability to perceive and understand is limited, as the average person can simultaneously inspect up to seven independent pieces of information [BAR 1997, YOU 2007]. If the complexity of the system exceeds the perception of the human mind's limits, then investigating the system structure and causal relationships it is not possible to connect (organize) elements of the system, as well as causes with consequences. Consequently, the person isn't able to perceive the system as a whole and to understand it [BAR 1997, RIC 2000, ASH 2007]. The theory of modelling is a direct outgrowth of concept „organization" [KRI 1986]. In order to analyse complex systems appropriate computer modelling and simulation tools are used [JOS 2000, WEA 2004, VAZ 2009], that enable understanding of the research object and support decision-making [RIC 2000].

Nowadays, the information and communication technologies (ICT) provide the fundamental infrastructure for the social and economic processes and are essential to promote innovation in the enterprise and industry. ICT has become a substantial part in the research, development, innovation and technology transfer in different domains [NGU 2010, INF 2011]. With increasing use of ICT and its topicality correspondingly increases the necessity of existing technical solution evaluation and development of new solutions. The research of complex technical systems has a significant role in these processes [INF 2011, PEI 2011]. Requirements for the tool and approach that enable to realize system modelling are determined by characteristics of the complex technical systems and available information [GRU 1997a, KHA 2010]. Main characteristics of complex technical systems are: many, various components and the interactions among them, which are difficult to analyse;

hierarchical structure; and complex behaviour. Knowledge about these systems often belongs to several experts rather than just to one [GRU 2002, KHA 2010].

In Riga Technical University the structural modelling approach that is suitable for complex technical system structural modelling and analysis in normal functional conditions, as well as, under the faults, has been developed. The approach has various advantages: it is suitable for structural modelling in conditions of incomplete information; a graphic notation is used; and it allows the investigation of different system`s morphological and functional aspects. However, the approach is not implemented in an appropriate computer system that enables automatized construction of structure models. In order to perform complex system structural modelling with computer, the approach must be implemented in the intelligent system [GRU 1997a, GRU 2002]. This is an essential precondition to capture, represent and effectively handle with knowledge about complex systems, which different individuals have at different times, and to create system structure models automatically. To create an intelligent system, the relations between complex systems, modelling principles and aspects of the selected approach must be determined.

Motivation of the research

Topicality of the doctoral thesis is related to the increasingly growing complexity of systems and their role in the information and communication technologies. ICT are essential to improve productivity and to contribute the development in industries and science, as well as to meet public demands for public services (such as health, education and transport). Consequently, the ICT research is one of the European Union's Seventh Framework Programme (FP7) priorities in 2013 [EUR 2012]. Complex technical systems are widespread in society, industries and science, using a variety of ICT. In order to build, manage and improve such systems, they must be investigated using appropriate approaches and tools. The model is primary research tool for complex systems [SKY 2006, YOU 2007, SOK 2010]. Complex systems have specific characteristics that limit the choice of modelling approach. Development of ICT expands modelling opportunities. Although many approaches and tools have been developed, the problems with complex system structural, functional, as well as behaviour modelling are not completely solved, in general, for every modelling aspect separate mathematical apparatus is used. To address this shortcoming, in the 70`s of the last century, a structural modelling approach has been developed. In the approach principles of complex system morphological and functional models and methods of structural analysis were developed. Methods and algorithms proposed in structural modelling, deal with the complexity of technical systems with physically heterogeneous elements [GRU 1997b]. However, the capabilities described in structural modelling were not implemented in the tool and there existed no algorithms that enable automatized development of models (models were created manually). In addition, since the development of the structural modelling approach, new aspects of complex systems have emerged, that must be modelled. Mentioned problems are addressed in this thesis.

The goal of the thesis

The goal of the thesis is to develop the knowledge acquisition and representation schema and implement it the intelligent computer system that provides structural modelling of complex technical systems with heterogeneous elements, realizing construction of structure models automatically, and to approbate the intelligent system as an example using a particular complex system.

The tasks of the thesis

In order to achieve the goal of the thesis the following tasks are specified:

- To explore the structural and operational principles of complex and intelligent systems and to identify the properties that must be taken into account when the system modelling is performed;
- To analyse structural modelling current opportunities and to identify weaknesses, which are essential in the development of intelligent computer system;
- To improve the syntax and semantics of the structure models, as well as transformation algorithms between structure models;
- To develop a knowledge acquisition and representation schema that enables complex system structural modelling and can be implemented in the intelligent computer system;
- To develop transformation algorithms that provide automated construction of structure models;
- To develop and implement the architecture of an intelligent computer system, including in it the techniques of structural modelling and analysis;
- To verify the built-in functionality of the developed system and its suitability for structural modelling purposes, realizing within it the real-world system structural modelling.

Research objects

The research object is structural modelling approach that is suitable for complex technical systems with heterogeneous elements modelling.

Research subject

The research subject of the doctoral thesis is architecture of intelligent computer system and its implementation that enables complex system structural modelling and analysis.

Scientific novelty

The scientific novelty is as follows:

- The developed knowledge acquisition and representation schema – frame set, which is implemented in the intelligent system, provides experts' knowledge acquisition and representation about complex systems and allows to store and process the acquired knowledge;
- The developed eight transformation algorithms from the frame set to morphological and functional structure models, that are implemented in the intelligent system for complex system structural modelling (I4S) and enable generation and visualization of structure models;
- The developed architecture of the intelligent computer system for the complex system structural modelling, that is implemented in I4S and provides automatized construction of structure models as well as topological and qualitative analysis of structure.

Theoretical value

The theoretical value is as follows:

- The developed new elements (logical operators) for structure models, their description and visualisation, and verified logical operator application opportunities;
- The developed additional element notation for morphological structure model, which allows to determine whether the represented object is an element or a component;
- The developed notation for a new functional structure model in space of behaviour;
- The improved syntax and semantics of the structure models and the transformation algorithms between structure models;
- The created knowledge acquisition and representation schema and transformation algorithms from the frame set to the structure models;

- The developed architecture of the intelligent computer system for the complex system structural modelling.

Practical significance

The practical significance of the thesis is as follows:

- Knowledge acquisition and representation schema - frame set is implemented in the intelligent system architecture that allows acquire and represent experts` knowledge, and also to store it in the way that knowledge can be shared, reused and applied in the automatized construction of structure models and structural analysis;
- The developed architecture is implemented in the system I4S, thereby for the first time developing an intelligent system that encompasses all aspects of structural modelling approach – both the construction and visualisation of structure models, and structural analysis;
- The developed system's I4S functionality and its suitability for structural modelling goals has been verified by representing knowledge about complex technical system robot AGR8 and performing its structural modelling, as well as structural analysis.

Approbation of the obtained results

4 presentations on the main results of the research have been made:

1) The 10th International Conference on Modeling and Applied Simulation. Rome, Italy, September, 12–14, 2011.
2) International multi-conference on complexity, informatics and cybernetics (IMCIC 2010). Orlando, USA, April, 6–9, 2010.
3) IADIS International Conference on Cognition and Exploratory Learning in Digital Age (CELDA 2008), Freiburg, Germany, October 13–15, 2008.
4) The 5th International Mediterranean Modelling and Latin American Modeling Multiconference, The international Workshop on Modelling & Applied Simulation. Amantea, Italy, September, 17–19, 2008.

In addition, some related results are presented in conferences:

5) The 6th International Conference on Computer Systems and Technologies (CompSysTech 2005). Varna, Bulgaria, June, 16–17, 2005.
6) The 19th European Conference on Modelling and Simulation (ECMS 2005), Riga, Latvia, June, 1–4, 2005.

The main results of the thesis have been presented in 5 scientific papers:

1) Zeltmate I. Logical Operator Usage in Structural Modelling, In: Proceedings of the 10th International Conference on Modeling and Applied Simulation, 2011, Rome, Italy, pp. 338-346.
2) Zeltmate I., Grundspenkis J. An extension of frame-based knowledge representation schema, In: Proceedings of International Multi-conference on Complexity, Informatics and Cybernetics (IMCIC 2010), Vol I, 2010, Orlando, USA, pp. 401-406. (indexed in: IIIS, KGCM 2010, Google scholar).
3) Zeltmate I., Grundspenkis J., Kirikova M., Prototype for the Knowledge Representation Supporting Inter-institutional Knowledge Flow Analysis, Chapter 6, Learning and Instruction in the Digital Age, Springer, 2010, pp. 87-99. (indexed in: SpringerLink, Google scholar).
4) Zeltmate I., Grundspenkis J. Formal Method of Functional Model Building Based on Graph Transformations. In: Proceedings of the 5th International Mediterranean and Latin American Modeling Multiconference, The international Workshop on Modelling & Applied Simulation, 2008, Amantea, Italy, pp. 140-147.
5) Zeltmate I., Grundspenkis J., Kirikova M., The Challenges in Knowledge Representation for Analysis of Inter - Institutional Knowledge Flows. In: Proceedings of the IADIS International Conference on Cognition and Exploratory Learning in Digital Age (CELDA 2008), 2008, Freiburg, Germany, pp. 145-152. (indexed in: IADIS, Google scholar).

In addition, about the results the author has published also the following papers:

6) Valkovska I., Grundspenkis J. Development of Frame Systems Shell for Learning of Knowledge Representation Issues. In: Proceedings of the 6th International Conference on Computer Systems and Technologies (CompSysTech 2005), pp. IV.11.-1 – IV.11.-6. (indexed in: ECET).
7) Valkovska I., Grundspenkis J. Representation of Complex Agents by Frames for Simulation of Internal Relationships in Structural Modelling. In: Proceedings of the 19th European Conference on Modelling and Simulation (ECMS 2005), 2005, pp. 151-157. (indexed in: ECMS).
8) Graudina V., Grundspenkis J., Valkovska I. Usage of Frame System for Modelling of Intelligent Tutoring System Architecture. In: Annual Proceedings of Vidzeme

University College. ICTE in Regional Development. Valmiera, 2005, pp. 105-109 (indexed in: EBSCO HOST).

Results of the thesis have been included in the reports of two scientific projects:

1) „New Information Technologies Based on Ontologies and Transformations" (project manager J.Barzdins (University of Latvia), 2010-2013, National Research programme's „Development of Innovative Multi-functional Materials, Signal Processing and Information Technology for Competitive Science-intensive Products" project).
2) „Development of the prototype for the support of inter-institutional flow of knowledge" (project manager M.Kirikova), 2007-2008, research project financed by Riga Technical University.

Structure of the thesis

The thesis consists of introduction, 4 chapters, conclusion, bibliography and 3 appendixes (in separate volume). The main part of the thesis contains 168 pages and 102 figures. Bibliography contains 153 sources of information.

In the *introduction* the relevance of complex system research and topicality of accomplished research have been described, research goals and tasks have been defined and novelty, theoretical and practical value of the thesis have been described as well.

In *Chapter 1* complex systems has been analysed and main properties identified that are essential in these kind of system modelling. Structural modelling approach opportunities and constraints are described and it has been established that in order to support the objectives of the approach, it is necessary to implement it in the intelligent system. Further the design and functional mechanisms of intelligent systems are analysed.

Chapter 2 is devoted to a detailed description of the structural modelling approach. The notations of structure models have been considered and syntax and semantics of existing and newly created model elements described. In this chapter transformations between models taking into account the usage of logical operators have been demonstrated.

In *Chapter 3* concept frame have been explained, structure and analysis of frame application has been given, in order to create knowledge acquisition and representation schema. Using the results of the analysis the frame set, which is implemented in the intelligent system I4S and supports the automated structure model construction, has been created. Systems I4S design and functional principles, as well as, the transformations from the frame set to the structure models, are described.

The complex technical system – robot AGR8 structure and functional principles are examined in the *Chapter 4*. To verify the functionality of the developed system I4S the structural modelling of robot is performed. The implementation of practical example approves complex technical systems structural modelling and analysis capabilities in the developed system I4S.

In the *conclusion* the main results of the research and conclusions made as well as possible future work have been presented.

The thesis has *3 appendixes*: 1. Frames and their interpretation in different sources of literature; 2. Logical operators and structure models; 3. Description of system`s I4S database and application.

1. COMPLEX SYSTEMS AND STRUCTURAL MODELLING

Conditions that affect people's life and activities are becoming more diverse and extensive. People are developing, managing and maintaining increasingly complex systems, and are confronted with rapidly growing complexity. The first chapter is devoted to the identification of domain concepts, analysis of complex system characteristics, as well as to the research of intelligent system principles, in order to determine the requirements, which are considered developing the intelligent system for complex system structural modelling.

1.1. Domain concepts and their interpretation

System is defined as a set of elements and relationships, which determines the existence of the system [BER 1969, ACK 1971, ROS 1979, CHU 1979, BEE 1995, AMA 2004, SKY 2006, BOP 2008, SOK 2010]. Regardless of the abstraction level in which system is investigated, it can be viewed as consisting of objects [HAL 1968, AMA 2004, WEI 2009] or parts [KRI 1986, BAR 1997, AST 1996]. Part is an element or component that is essential to the viewed object [OXF 2009]. Concept “element” refers to the system primitives, or basic elements; monolithic parts or parts that are not decomposed investigating system [YOU 2007, OXF 2009, AST 1996]. The term "component" is applied to the composite part (subsystem) which can be decomposed [OXF 2009]. Decomposition is a conceptual or physical method, which allows decompose the research object into smaller parts [BRO 1998, HAK 2006] and thus simplifies the system and it is possible to view and understand each selected system`s decomposition level separately.

The system and its parts have a definite structure [YOU 2007], that characterise its composition [BEE 1995, GRU 1999]. Parts of the system may be in different sizes and can be either homogeneous – those who do not have different characteristics and heterogeneous – with different elements and/or structural properties. The structure is the relationship between the parts that together with identity of parts form a whole, taking into account the fact that between parts exists a certain order [MAT 1974, OXF 2009]. Interactions and relationships between parts of the system are as important as the parts themselves [ROS 1979]. Interactions form a certain organization in the system. The organization is defined as a system feature, which is characterized by a structure that is purposefully created to perform certain functionality [MAT 1974, HEY 2001, YOU 2007]. It is noted that the structure of the system remains relatively stable over time [GRU 1997a, GRU 1997b, MOU 2009]; here is meant the structure that complies with the system organization [MAT 1974, GRU 1997a, BAR 1997, SKY 2006, APP 2011]. If the organization of a system stays invariant, while the structure of the system changes (for example, when system evolves and learns), then system remains the same and doesn`t lose its identity [MAT 1974, GRU 1997a, BAR 1997, SKY 2006]. The organization of a system defines it as a unity in any space, while its structure constitutes it as a concrete entity in the space of its components [MAT 1974].

People are faced with complex systems in different ways: designing, developing, analysing, improving, exploiting and managing them. Concept "complex" is multi-dimensional and multi-disciplinary [SIM 1962, HOR 1995, MCC 2000, RIC 2001, WOO 2004, HEY 2008, JOH 2009] and it is defined as: „consisting of interconnected or interwoven parts" and "difficult to understand or analyse" [BAR 1997, HEY 2008, OXF 2009]. Term "complex" refers to the condition of the system, when parts are integrated creating a whole and yet the quantity and/or diversity of parts is too rich to understand the system in simple and conventional ways [MCC 2000]. The objective of complex system research and development is related to existing system understanding and representation that enables to change them and to create new systems that can be used in a variety of domains [BAR 1997, HEY 2008].

There is no single and concise definition of a complex system [SIM 1962, HOR 1995, BAR 1997, VIC 2002, HAK 2006, SKY 2006]; however, there are various explanations:

- A complex system is composed of many and various interconnected parts that interact dynamically in different ways [SIM 1962, MAT 1974, GRU 1972, ROS 1979, ASH 1981, BAR 1997, WHI 1999, EDM 1999, RIC 2000, GLO 2002, HAK 2006, SKY 2006, JOH 2009].

- A complex system is characterised by the structure and relationships that is difficult to analyse and by multi-functional criteria [ROS 1979, BOU 2004].
- A complex system has varied (network and hierarchical) [HOR 1995, BAR 1997] and decomposable structure [HOR 1995].
- Parts of the complex systems are organized at different levels of the hierarchy and there are a variety of relationships between both individual elements and different hierarchical levels [SIM 1962, ROS 1979, BAR 1997, VIC 2002, SKY 2006, YOU 2007, HEY 2008]. At each level of the hierarchy can be distinguished a specific organization and/or structure [HAK 2006, SKY 2006].
- A complex system has one or more system properties, it performs certain functions and despite of the diversity of parts, it demonstrates a common behaviour namely system behaviour, which is qualitatively different from certain functions and behaviour that carry out system parts [SIM 1962, HAL 1968, ACK 1971, GRU 1972, ROS 1979, BAR 1997, JOS 2000, RIC 2000, MCC 2000, GLO 2002, VIC 2002,SKY 2006, YOU 2007, HEY 2008].
- A complex system is described as able to self-organize, adapt, develop and learn [HAL 1968, BAR 1997, MCC 2000, RIC 2000, GLO 2002, WOO 2004, SKY 2006, HEY 2008]. A complex system has a variety of possible states in which it is able to realize its functionality [MCC 2000, HEY 2008].

Combining the explanations of the complex system, in the thesis a following definition is used:

„Complex system is an open system, that is organised in a certain way; that has a structure and that consists at least from two parts between which exist various relationships, besides parts interact mutually, as a result system has system features (like system properties and system behaviour)."

1.2. Complex system modelling

If a system is complex, then the main research instrument is a system model [GRU 1972, BAR 1997, SKY 2006, ЮР 2007, YOU 2007, SOK 2010]. Modelling is the process in which a representation or a model of the system is created. Models are based on observation, evaluation of available information and judgments [HOR 1995, SOK 2010]. Models are abstract [HEY 1990, STA 2006] and constructing them decomposition, abstraction and hierarchical principles are applied [YOU 2007, WEI 2009]. Abstraction is a process in which relevant characteristics of the system are generalized ignoring inessential [AMA 2004, SKY 2006, YOU 2007].

System model describes the system from different viewpoints, allows understand and analyse its structure, functioning and behaviour, as well as to assess and carry out appropriate solutions regarding real-world system and its operations [MIN 1975a, BAR 1997, GRU 1997b, RIC 2000, VIC 2002, SKY 2006, YOU 2007, SOK 2010]. Despite the fact that every complex system is closely connected to a particular domain, in the system research information technology solutions are used [HOR 1995] and the systems analysis, design and modelling is performed using computer [VIC 2002]. To create a useful and appropriate system models, tools are needed, in which modelling methods and techniques are implemented, that enable to cope with the problems and constraints of complexity and acquire and systematize available knowledge [ROS 1979, GRU 1999, RIC 2000, MCC 2000, AMA 2004, SOK 2010]. Useful model is a model that allows realize objectives [EDM 1999, SKY 2006, STA 2006]. Considering the interpretations of the concept "model" [KRI 1986, SIM 1987, EDM 1999, SKY 2006, STA 2006, ASH 2007, BOP 2008, OXF 2009, SOK 2010], further in thesis such definition is used:

"System model is a research object description and/ or representation from a specific perspective, which represents systems morphology, functionality, behaviour or other aspects that are essential for modelling."

The usage of complex technical systems is essential in a variety of information and communication technologies and also in their research [INF 2011, PEI 2011]. With the growth of ICT research modelling capabilities extend, however, the properties of complex systems limit selection of modelling approach and tools. Existing tools and approaches usually are created for a certain domain [GAR 2001]. There is no suitable tool that simultaneously supports: a) deep causal knowledge acquisition and reasoning about complex technical systems; b) unified knowledge representation from morphological and functional aspects; c) maintenance of knowledge base and knowledge sharing among multiple users [UEN 1991, GRU 1997b, GRU 2002, ZEL 2008a, ZEL 2010a, ZEL 2010b]. To perform complex technical system modelling in a computer, the approach that meets requirements regarding complex systems and their modelling must be used. The specifics of complex systems and the amount of available information makes it difficult to create common mathematical description and are key factors choosing the modelling approach. Therefore a structural modelling approach is developed that enables the construction of complex technical system models, qualitative and quantitative system analysis and that can be used also in diagnostics [GRU 1997a, GRU 1997b, GRU 2002].

Structural modelling (SM) is systematic, partly formal approach, which is model and frame based and is created with a purpose to acquire, represent and process knowledge about complex technical systems with varied elements and relationships in conditions of incomplete information, as well as to automate a knowledge base construction [GRU 1993, GRU 1997a, GRU 1997b, GRU 1999, GRU 2002, ZEL 2010a]. SM has been developed in Riga Technical University in the beginning of the 1970s, using the conception of the topological model [OSI 1969], and the author of the approach is J.Grundspenkis [GRU 1972, GRU 1993, GRU 1997a, GRU 1999]. In the structural modelling four different aspects are considered: structure, functions, behaviour and deep causal knowledge [GRU 1999, GRU 2002], and two different paradigms integrated: morphological and functional [GRU 1997b, ZEL 2011]. A morphological structure model (MSM) is created to represent knowledge about system`s structure, but functional structure models (FSM) are constructed to represent functional properties. FSM can be created in a space of functions (SF), behaviour (SB) and parameters (SP) [GRU 1997a, GRU 1999, ZEL 2011]. Since the structure models are visualised in the form of graph also appropriate matrices can be created [SIM 1962, GRU 1993] (for example, adjacency matrix). Structure models are used to support consecutive analysis, design, reasoning and decision making of the research system, to acquire new knowledge about it and to solve diagnostic problems [GRU 1997a, GRU 1999, GRU 2002, GRU 2004, ZEL 2008b, ZEL 2011].

Structural modelling is suitable for complex technical system research, but in order to effectively process and analyse represented knowledge (jointly about many and different elements, relationships and properties) and automatically acquire different calculations, judgements that comply with described system, approach must be implemented in computer system. An intelligent system must be created, that includes properties of knowledge based and expert systems and provides new knowledge acquisition about the research system from the experts` represented knowledge. Intelligent system in which the structural modelling approach is implemented, compared to expert systems for diagnostics, allows obtain deep knowledge about system from domain expert. Acquired knowledge allows see causal relationships in the viewed system from different viewpoints and in different moments of time, moreover it can be used to reason about system structure and to explain system functions and behaviour [GRU 1999].

1.3. Intelligent systems and their properties

The concept “intelligent system” is commonly used in Artificial Intelligence (AI) in relation to systems which use AI techniques and methods. Intelligent systems have become significant in various areas of human activities where, using knowledge about research object, a support for knowledge processing, tutoring, problem solving and decision-making is needed [NEG 2004, YOU 2007, RUS 2010]. System is intelligent only regarding its purpose [ASH 1981, POL 2002]. Intelligent systems are designed to support decision-making, but the final decision is usually taken by the system user. Intelligent systems have become popular and are commonly used in a variety of tasks [DUR 1994, BRO 1998, NEG 2004, BOP 2008]. Intelligent system allows acquire the knowledge from expert about the research object and to organize, use, and maintain it (update according to the real situation) [NEG 2004, YOU 2007, BOP 2008]. To create an intelligent system the characteristics that are related to the design, mechanisms of actions and are significant in the development must be identified.

Architecture of an intelligent system is created using four components that provide its functionality: knowledge base, inference engine, data base and application [BIE 1991, DUR 1994, LIE 1997, PEA 2002, NEG 2004, BOP 2008]. In intelligent systems there is a strong connection between knowledge base and database [UEN 1991]. Knowledge Base (KB) contains the knowledge obtained from expert about the world and/or definite research object. KB maintains knowledge as a set/collection of facts, rules, concepts and relationships between them, which is used to find solutions for certain problems [UEN 1991, DUR 1994, LIE 1997, PEA 2002, NEG 2004, BOP 2008]. The knowledge base is processed using inference engine that allows infer, retrieve the knowledge about research object and its properties, although directly such knowledge in KB doesn’t exist [PEA 2002, BOP 2008]. Inference engine works with the available information stored in the database and knowledge stored in KB, at the moment when user operates with a system [DUR 1994, LIE 1997, PEA 2002, NEG 2004]. In the database are stored collections of a structured and indexed data – sets of facts, evidences, documents, hypotheses, objectives [UEN 1991, NEG 2004]. Knowledge from the database can be obtained indirectly through procedures and using different techniques [PEA 2002, BOP 2008], for example, applying data mining [FAY 1996, POD 2012]. In order to provide the interactions between user (expert) and intelligent system, to acquire, represent, maintain and process knowledge in an explicit and user-friendly way, the application or the interface is used [DUR 1994, LIE 1997, NEG 2004, BOP 2008].

Various AI techniques and methods are used to provide the functionality of the intelligent system [DUR 1994, LIE 1997, BRO 1998, NEG 2004, BOP 2008, RUS 2010, HOP 2012]. If in the intelligent system there are different techniques and methods combined, then it is called a hybrid intelligent system [LIE 1997, NEG 2004, RUD 2008].

As essential intelligent system techniques are mentioned the following one [DUR 1994, BRO 1998, NEG 2004, RUS 2010]:

- natural and artificial language processing;
- knowledge acquisition and representation;
- machine learning, that is used in adaptive systems;
- automated reasoning and inference. Rules and search are used to explain the ways how the conclusions are made. Two reasoning strategies exist: from the goal, from the data.
- search that is performed, to improve existing knowledge. Search is carried out without knowing exactly what will be the result; only the initial criteria are known. Search in a state space is a method that is used to find the target state and the solution path from the start to the target position.

Considering properties that intelligent system must have and its purpose, the concept "intelligent system" in the thesis is defined as follows:

„Intelligent system is a knowledge based computer system that: (1) operates with organized knowledge, (2) use one or more AI techniques and methods, and (3) can be applied for complex system structural modelling."

Summary and conclusions of Chapter 1

- Complex systems have many interconnected characteristics. To carry out the requirements that are imposed by complex system structural modelling an appropriate approach that allows create useful models must be chosen;
- Structural modelling approach is suitable for the complex technical system structural modelling, however, to realize approach capabilities and automated knowledge acquisition and processing an intelligent system must be developed;
- Computer system in which a structural modelling approach is implemented, must be hybrid intelligent system, and it is necessary to use different techniques within, because it gives advantages in both knowledge representation (knowledge can be represented in different forms: in frames, models, as well as in different hierarchies) and processing (knowledge can be stored, transformed and used for modelling and analysis).

2. STRUCTURAL MODELLING APPROACH DESCRIPTION

Structural modelling (SM) supports domain based, partly formal system representation. SM allows create visual, comprehensible structure models that describe both morphological and functional aspects of the research system. SM model development process is supported by formal transformations and well described reasoning mechanisms. Applying formal methods of SM, morphological structure model is transformed in a functional structure model, in a selected space. Transformations allow create appropriate (consistent) models and provide continuous system representation. Structure models are created manually [GRU 1972, GRU 1993, GRU 1997a, GRU 1997b, GRU 2002, ZEL 2008b, ZEL 2011].

In order to use SM for complex technical system modelling in more comprehensive way, within the thesis elements of structure models are improved and new elements created. Element and model visualization is designed, taking into account aspects of structural modelling (structure, functions, behaviour and deep causal knowledge) and modelling purpose. In the second chapter syntax and semantics of models, explaining and visually representing elements, is described and structure model transformations discussed.

2.1. Syntax and semantics of structure models

Structure models are created using the concepts of topological space T(X,Q), where X is a set of elements but Q is a topology that is given by set of arcs [OSI 1969, GRU 1993, GRU 1997a, GRU 1999]. Structure models can be created for each decomposition level of the system. To provide continuous mapping of topological space, it is suggested to construct structure models systematically. The number and types of models are determined by the purpose of the research system and decomposition level [GRU 1972, GRU 1993]. Structure models are visualised as oriented graphs, where nodes represent objects, functions, behaviour states or parameters, but the arcs between nodes depict flows or causal relationships. Each structure model has predefined syntax and semantics [GRU 1997a, ZEL 2011].

The construction of structure models begins with the development of morphological structure model (MSM), representing acquired knowledge about research system structure. MSM depicts the internal structure of the system in a selected level of decomposition, system parts and relationships and structural or causal relationships. MSM supports structural reasoning that is based on the research system direct and indirect relationship determination [GRU 1993, GRU 1997a, GRU 1999]. MSM is defined as a diagraph **G(X,Q),** where each node $x \in X$ corresponds to a real element of the system, that is described using objects. The connections between objects correspond to the flows that are depicted by oriented arcs Q. In structural modelling objects are viewed from a static perspective, because system representation is made for a certain period of time [GRU 1993, GRU 1997a, GRU 1997b, GRU 1999].

In structural modelling objects are basic units that can be depicted in two different ways (Fig. 2.1 (a) and (b)) [GRU 1997a, ZEL 2008b]. To represent both elements and components, author of thesis have created additional notation for the object - with the double line (Fig. 2.1 (c) and (d)). If the object is depicted with one line (Fig. 2.1 (a) and (b)) then it means that the element of the system is represented, but if with double line (Fig. 2.1 (c) and (d)) then system`s component.

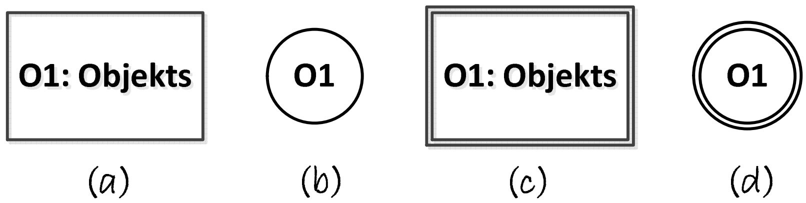

Fig. 2.1. The representation of object

To specify how the objects are connected in MSM two elements are used: contact and flow [GRU 1997a, GRU 1997b]. Contacts correspond to inputs and outputs (or entrances and exits) of the object. Through one object output and another object (or the same object) input exist connection that allows realize some action (activity, process). The connection between contacts in MSM is called flow. For each object in structural modelling two types of contacts exist [GRU 1997a, GRU 1997b, ZEL 2007]. In input contact (Fig. 2.2 (a)) the flow that comes from the viewed or another object is received. From output contact (Fig. 2.2 (b)) flow is passed from viewed object to another object in system.

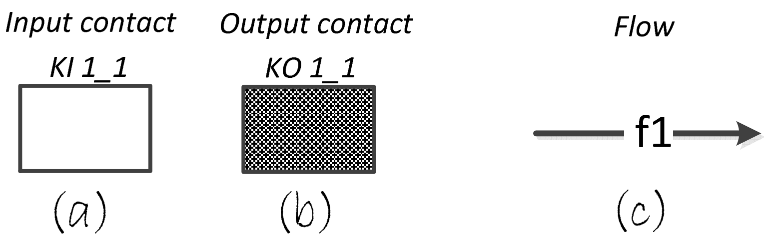

Fig. 2.2. The representation of contacts and flow

Contacts are depicted using identifiers (Fig. 2.2), where: a) KI refers to the input contact, but KO to output contact; b) number "1" indicates the object number which has the contact; c) the symbol "_" separates an object number and a contact number; d) number "1" indicates a contact number. Flow is represented with line and arrow or oriented arc (Fig. 2.2

(c)), on which the identifier of flow is given. Here, as a further identifier consists of a combination of letters and numbers. Considering what flow transfers, in the structural modelling three types of flow are used: energy, matter and information. The type of flow is depicted using colours: red (energy), green (matter) and blue (information) [GRU 1997b].

In order to represent organisation and causal relationships when a system description is created, expert between objects indicates flows, but between flows depicts logical operators [GRU 1997b, GRU 1999, ZEL 2011]. In structural modelling approach logical operators were used also before in the FSM in a space of functions and in event trees [GRU 1999]. However, there were no visualised notations for logical operators and no detailed explanations. Author of the thesis have created a visualisation for logical operators in SM, using them already in the MSM [ZEL 2008b, ZEL 2011].

A square on the flow and symbol ',' (comma) atop of the flow (Fig. 2.3 (a)) are used to display the logical operator AND. The usage of operator AND between flows means that all related flows are necessary to realize the functionality of the object. To depict the logical operator OR (Fig. 2.3 (b)) triangle and symbol ';' (semicolon) are used. Operator OR is applied to show that some of the related flows are needed to realize the functionality, but not necessarily all of them. Related flows are flows that are jointly connected to realize certain functionality in the system. To represent logical operator exclusive OR (Fig. 2.3 (c)), filled triangle and symbol ':' (colon) are used. In the case of exclusive OR only one of related flows is needed to realize the functionality of the object. Brackets (Fig. 2.3 (d)) are used to create more complicated expressions (including several flow combinations), or to show the order of logical operators.

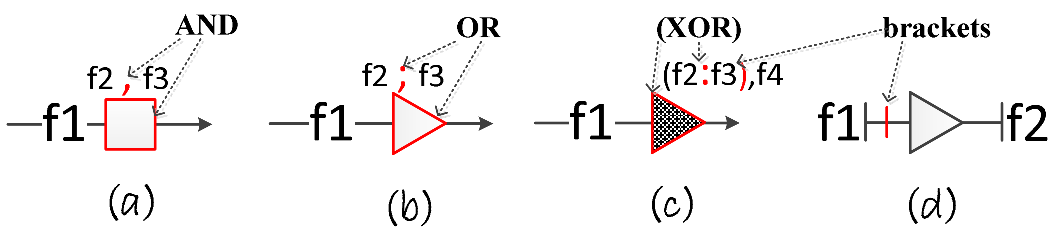

Fig. 2.3. The representation of logical operators

Mainly MSM is represented as a diagram, similar to the block diagram. In this case objects are depicted together with the input and output contacts (Fig. 2.4) or behaviour states. In the second case MSM is represented in simplified way as digraph (Fig. 2.5), showing only objects and flows between them [GRU 1997a, GRU 1999]. The way how the model will be represented is determined by expert, taking into account information that is essential to the modelling purpose [GRU 1997a, GRU 1997b, GRU 1999].

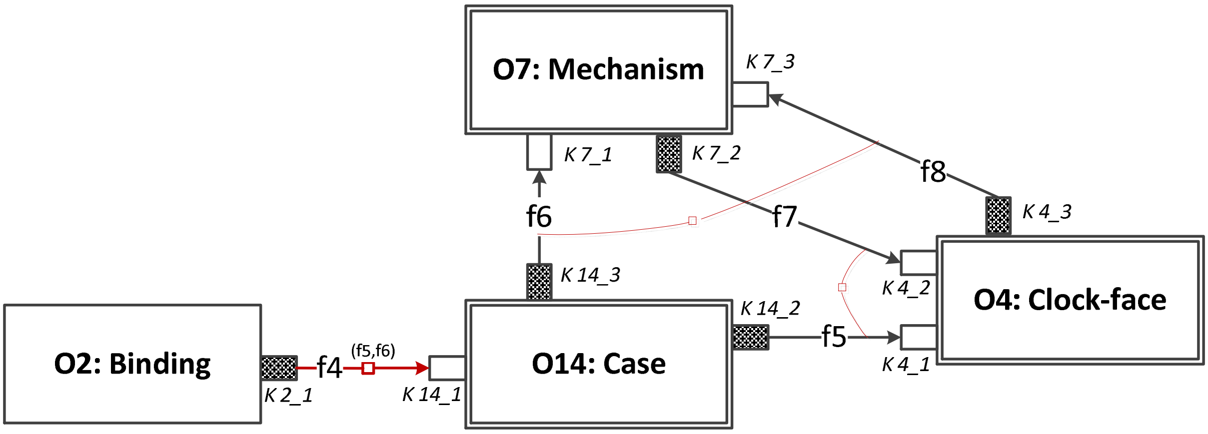

Fig. 2.4. The representation of MSM in a form of diagram

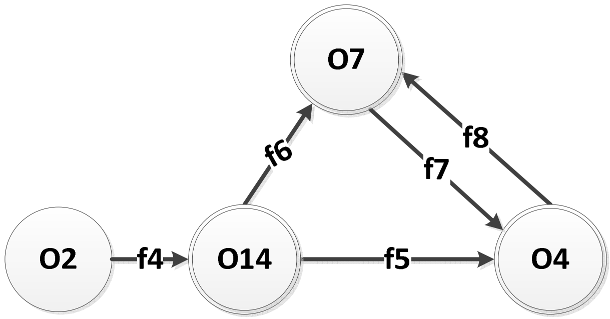

Fig. 2.5. The representation of MSM in a form of graph

To support the reasoning about function that are realized in the system, in the SM approach exist the concept of functional model and transformation algorithms that allow derive functional structure models from MSM [GRU 1997a, GRU 1999]. Functional structure model in a space of functions (FSM SF), similarly as MSM, is represented as diagraph [GRU 1997a]. In the nodes of FSM SF functions are depicted, but arcs represent causal relationships (binary relations) between functions [GRU 1997b, GRU 1999, ZEL 2008b].

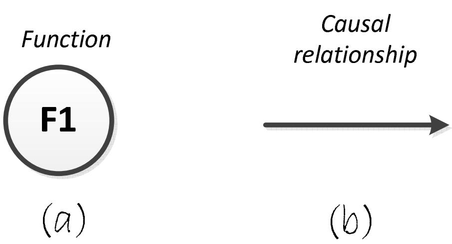

Fig. 2.6. The representation of function and causal relationship

In FSM SF function is drawn using a circle and identifier (Fig. 2.6 (a)). In FSM causal relationships between functions are depicted using arrows (Fig. 2.6 (b)). To show logic between causal relationships (Fig. 2.7) visualised logical operators are represented. Example of FSM SF (Fig. 2.7) corresponds to the MSM showed in the Fig. 2.4.

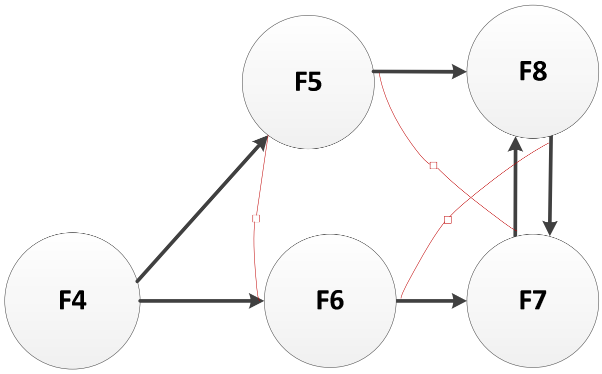

Fig. 2.7. The representation of FMS SF

Although also before in structural modelling approach behaviour states were defined, there existed no separated behaviour model. In the result of research, it was found that two models (with functions and with behaviour states) represent the functional features, but models have different semantics of nodes and therefore the functional structure model in a space of behaviour (FSM SB) was developed [ZEL 2011]. FSM SB or behaviour model represents behaviour states of system objects and relationships between them. Behaviour model doesn't represent the objectives that must be achieved, but describes how the system must operate and functions implemented to realize system goals [GAR 2001, GRU 1997a].

Behaviour is represented using oval, in which two sequential behaviour states that correspond to one flow are depicted. The first behaviour state corresponds to the flow output, while the second to the flow input (Fig. 2.9 (b) and Fig. 2.8 (a)). To investigate single behaviour states and their influence the FSM SB is created representing each behaviour state in separated oval (Fig. 2.8 (a)). Causal relationships between nodes are represented in the same manner as in the FSM SF (Fig. 2.6 (b)). Behaviour states are represented in both FSM SB and MSM, to understand what behaviour is realized, when object carry out definite flow [GRU 1997a, GRU 1997b, GRU 1999]. In the MSM behaviour states are represented similarly as the contacts, showing the identifiers (Fig. 2.8 (b)).

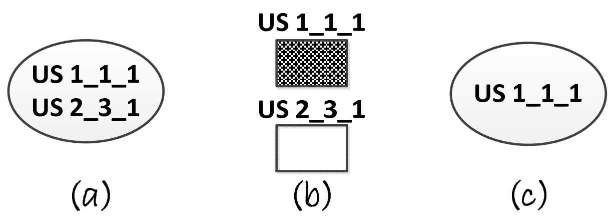

Fig. 2.8. The representation of behaviour states

FSM SB represents behaviour states that correspond to the execution of system object functions in the case of normal functioning as well as under the faults. In a definite decomposition level one or more FSM SB can be constructed. Considering the semantic of nodes (Fig. 2.9), FSM SB is represented in two different ways [GRU 1993, GRU 1997a, GRU 1997b, ZEL 2011].

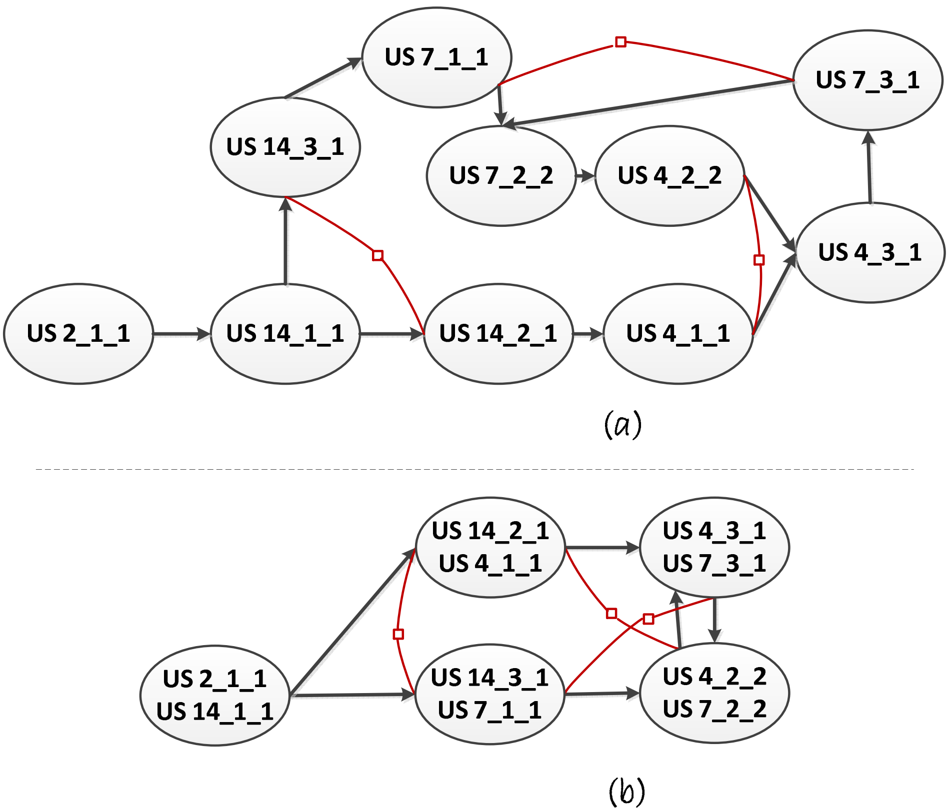

Fig. 2.9. The representation of FMS SB

Behaviour states the same as functions are qualitative characteristics that allow reason about system functionality, but aren't useful for the diagnostics and detailed investigation of the behaviour [GRU 1993, GRU 1997a, GRU 1997b]. To describe a definite behaviour parameters or variables must be used, that describe the efficiency of object function implementation. Functional structure model in a space of parameters (FSM SP) or parameter model allows represent system dynamics and realize diagnostic reasoning. FSM SP is constructed by replacing the behaviour states with the corresponding parameter sets or parameters and using expert knowledge about relationships between parameters in the parameter sets [GRU 1993, GRU 1997a, ZEL 2011]. The parameter set and parameter are represented using oval and identifier (See Fig. 2.10 (a) and (b)).

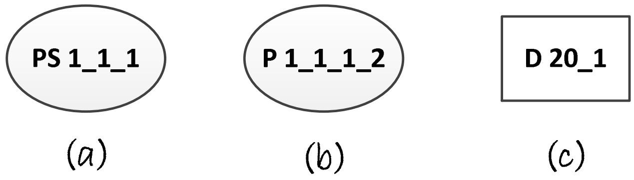

Fig. 2.10. The representation of parameter set, parameter and defect

If there are several parameters in the set then between them relationships and logical operators must be defined. Some logical operators are obtained automatically when the transformation from MSM to FSM SP is performed, but other are depicted using expert's knowledge about relationships between parameters (Fig. 2.11 (b)).

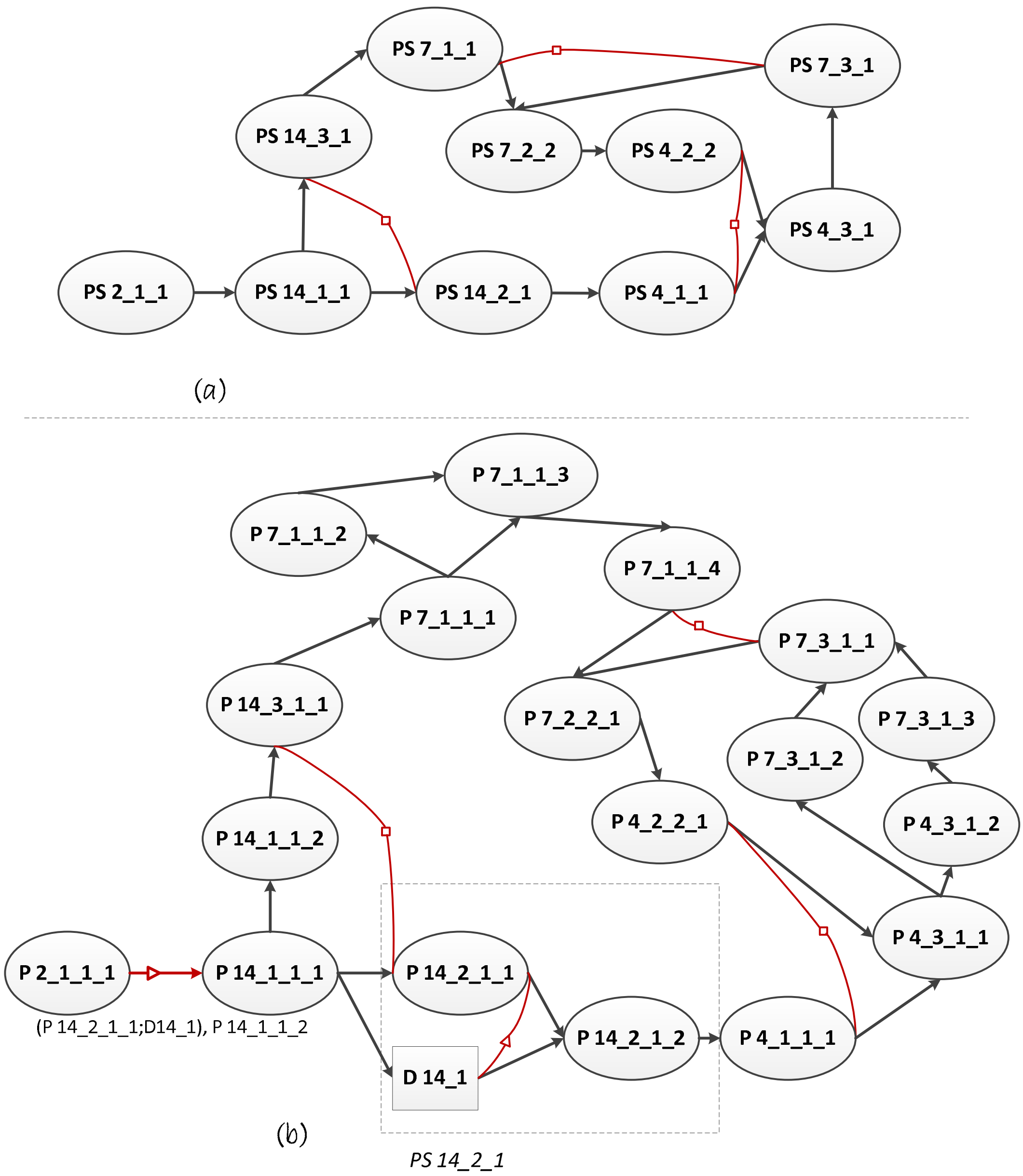

Fig. 2.11. The representation of FSM SP

Relationships between nodes are represented in the same way as in the FSM SB. If system functions incorrectly then extended FSM SP is created [GRU 1997a], in which all possible defects are depicted. Defects are represented using rectangle and an identifier (Fig. 2.10 (c) and Fig. 2.11 (b)) regardless of selected structure model and system decomposition level. Model with separated parameters and defects is obtained performing detailed examination of parameter sets. For example, in the Fig. 2.11 (b) the parameter set PS 14_2_1, corresponding parameters and defect is showed. Parameter model (Fig. 2.11 (a)) complies with the FSM in a space of behaviour that is shown in Fig. 2.9 (a).

2.2. Transformations between structure models

Methods and algorithms that are included in structural modelling create a topology of models, continuous and unified view on the research system. Topology provides consistency between different models and granularity of MSM, when decomposition is continued. Since between structure models exist similarities it is possible to realize transformations [GRU 1997a]. In structural modelling the transformation is the knowledge transfer or transition from one topological space to another, which is realized using algorithms. Model transformations are created, taking into account the formal method of graph theory [TUT 2001, MEN, 2010] for undirected graphs.

Previously in SM approach to obtain FSM topology in a space of functions from MSM was used transformation algorithm, which consists of 3 steps [GRU 1997a]: 1) MSM is considered as undirected graph; 2) Nodes of FSM are acquired (transformation into a line graph); 3) Nodes of FSM are connected. However, changes in MSM notation, in particular, the introduction of logical operators, made it necessary to change transformation algorithm. The author of the thesis have improved transformation algorithm enabling automated logical operator transfer from MSM to FSM. New algorithm also consists of three steps: 1) MSM where logical operators are depicted is considered as an undirected graph; 2) Nodes of FSM are acquired; 3) Nodes of FSM are connected taking into account 3 rules:

1) All nodes of MSM are inspected sequentially, starting from the selected node;
2) If two incident arcs in MSM have opposite directions, then corresponding nodes in the FMS are disconnected;
3) If two incident arcs in MSM have the same direction, then logical operators and conditions are verified. Complying with imposed restrictions in FSM arcs between nodes are created.

Following steps described in the new transformation algorithm, first of all a different number of arcs is obtained (comparing to the old transformation algorithm), second logical operators are represented. Consequently a correct set of arcs is obtained and incompatible connections are excluded from the model.

Considering different logical operators and flow combinations, in the FSM exist several function connection variants that are acquired performing transformations. In the thesis 5 different flow combinations in MSM and structure model transformation cases using logical operators are described [ZEL 2008b, ZEL 2011]:

1) one flow at the object's input side and one at the output side;
2) one flow at the object's input side and many at the output side;
3) many flows at the object's input side and one at the output side;
4) many flows at the object's input side and many at the output side;
5) one or more flows at the object's input side and no one at the output side or no one input flow and one or more output flows.

Taking into account flow combination and logical operators, for structure models also production rules are created that support different reasoning mechanisms (structural, diagnostic, causal) [GRU 1997a, GRU 1997b, ZEL 2008b]. FSM SB topology the same as FSM SF is obtained from morphological structure model using transformation [GRU 1993, GRU 1997a]. However, before in the SM there was no formal transformation algorithm from MSM to the FSM SB, because also behaviour model was not defined and described. In the thesis a new transformation algorithm, which consists of three steps was created: 1) select the type of FSM SB (displaying behaviour or separate behaviour states); 2) obtain behaviour state pairs that are connected with flows, and represent them in nodes; 3) connect nodes with arcs. FSM SP is derived from the behaviour model using transformation [ZEL 2011], and in the nodes parameter sets or parameters can be represented. To acquire FSM SP (in which separated parameters are represented), following steps are performed:

1) Inspect FSM SP where are parameter sets;
2) Using expert`s knowledge each node is decomposed and parameters acquired, as well as defects that exist in the viewed parameter set;
3) Using expert`s knowledge, logical operators are added to the model.

The function structure model in a space of parameters that is acquired in the transformation is used to evaluate rejection of elements and consequences of faults and also to construct events tree that expand the FSM SP usage capabilities [GRU 1993].

Summary and conclusions of Chapter 2

- It is necessary to use logical operators already in the first structure model, to create understanding about system structure and functioning as well as to minimize the workload of the expert when functional structure models are created.
- The analysis of input and output flow combinations and logical order of flows (which input flows influence which output flows) that exist in the system allowed define five possible flow combination cases.
- Model transformation that before existed in the SM, provided continuous system representation. However, to acquire FSM in which logical operators are depicted, additional conditions regarding logical operator usage (appropriate logical operator notations and output flows depicted on the input flows) must be considered.
- Structure models that are obtained using the new transformation algorithm from MSM to the FSM SF, have different syntax as well as different number of arcs between nodes (incompatible connections are excluded from the model).
- Structure models are created manually, drawing them in visual processing tools, however, it is time-consuming process and therefore it is necessary to automate I t.

3. THE USAGE OF THE FRAME SET IN STRUCTURAL MODELLING AND OPERATIONAL PRINCIPLES OF SYSTEM I4S

Before deep knowledge about system morphology, functionality and behaviour in conditions of normal functioning as well as when the system is functioning incorrectly, was obtained from the domain expert, using structure models and methods defined in the structural modelling [GRU 2002]. After acquired knowledge was stored in the frame hierarchy [GRU 1997a, GRU 1997b], but it was too simple (no different slot types defined and no property and alternative frames introduced) and not suitable for intelligent system [ZEL 2007, ZEL 2010a]. Therefore implementing SM approach in the intelligent system (I4S) to support complex system structural modelling, conception of SM, knowledge acquisition and representation principles were changed.

Considering the frame hierarchy that previously was used in structural modelling and the analysis of frame based representation schemas applied in another approaches, author has created frame set [VAL 2005a, ZEL 2007, ZEL 2010a] to enable automated construction of structure models. Newly created knowledge representation schema is used in the intelligent system knowledge base as well in the application, to acquire knowledge from expert about research object and to represent it in one place. To realize automatized model construction for a chosen decomposition level author of the thesis have created transformation algorithms from the frame set to structure models. In the third chapter frame and frame set usage in the SM approach is described and system I4S operation principles and newly created transformations from frame set explained.

3.1. Frame set description and usage

Frame set is created for the structural modelling purposes, to acquire, represent and maintain knowledge about research system as well as about separate objects [ZEL 2007, ZEL 2010a]. Frame set is a specific knowledge representation schema that consists of interconnected frames that have different meaning and each of them has a defined application [VAL 2005a, VAL 2005b, ZEL 2007, ZEL 2010a].

Frames are used to represent small knowledge units (for example about object, function, behaviour) at one place and using single schema [MIN 1975a, KAR 1993, WHE 1993, BRO 1999, BOP 2008]. Frame is a data structure that provides knowledge representation about the stereotypical situation [MIN 1975a, MIN 1975b, CZO 1991, MAR 2006]. Frames are a knowledge representation formalism, that allows acquire knowledge in structured way and organize it in hierarchies [NEG 2004, MAR 2006]. Frames are used to create many intelligent systems [GRU 1999, YOU 2007].

Frame consists of the name that is unique in a frame system and terminals or slots. Frame name describes the object that is represented within frame. Frame slots are used to describe properties of object [MIN 1975a, CZO 1991, KAR 1993]. Frame system is composed of related frame collections/sets, in this way creating network that in a simple and structural way represents chosen research object from different perspectives [MIN 1975b]. This kind of knowledge representation is used to construct system model or several related system models [MIN 1975b, KAR 1993] and it is essential in structural modelling. Each slot consists of slot name and value [MIN 1975b] or list of values [ROB 1977, GRE 1980, SHA 2003] or facets. Facet or facet list replace the slot value and is named also as slot properties [FIK 1985, CZO 1991, KUS 1997, COR 2003, NEG 2004, MAR 2006]. In the frame and slot name and/or value can be more than one word, which describes object. Slot value can be another frame, descriptive variable or the procedure [GRU 1997a, FIK 1985, KAR 1993, MIN 1975a, ROB 1977, VAL 2005c,WHE 1993, SHA 2003, MER 2003, COO 2001, LEE 1999, NEG 2004]. According to the purpose or role of the slot in the frame and the information that is represented in the slot, slots can be divided into different types [FIK 1985, MIN 1975a, GRU 1997a, KAR 1993, WHE 1993, COO 2001, MAR 2006, LEE 1999], which, in turn, can be combined in sets. In the frame based representation approaches are viewed slot differences and various roles, restrictions, but no concrete slot types are defined [CZO 1991, GRE 1980, KUS 1997, OKA 2007]. In slots can be pointers link the represented information with other frames [MIN 1975b]. Pointers the same as other information connected with frames can be represented in frame slots or other frames [MIN 1975a, MIN 1975b, KAR 1993, KAR 1995, GRU 1999, MAR 2006, ZEL 2010a]. In structural modelling slots regarding their role in a frame are divided in different types, for example property slots, contact slots, etc. [ZEL 2007, ZEL 2010a].

Sometimes in frames not only frame name but also the superframe (predecessor) or subframe (descendant) name is included. Different frames in the system can use the same slots. Inclusion of superframe name and sharing capabilities allow organize frames into taxonomies or inheritance hierarchies [ROB 1977, WHE 1993, GRE 1980, SPE 2004,GAN 1993, KAR 1993, GRU 1997a], in which each frame is connected with one (in some systems with more than one) predecessor. Frames enable hierarchical representation and organisation of knowledge. Main properties of frames are specific representation form, inheritance and class-subclass hierarchy [GRU 1997a, ZEL 2010a].

In various frames-based knowledge representation schemas only one type of frames is defined, while in other, two or more frame types (e.g. class and instance frames) are distinguished [KAR 1993]. According to the aspects of structural modelling in the frame set exist one class frame and one or more contact, procedure (rule), property (contextual), alternative and behaviour frames (Fig. 3.1).

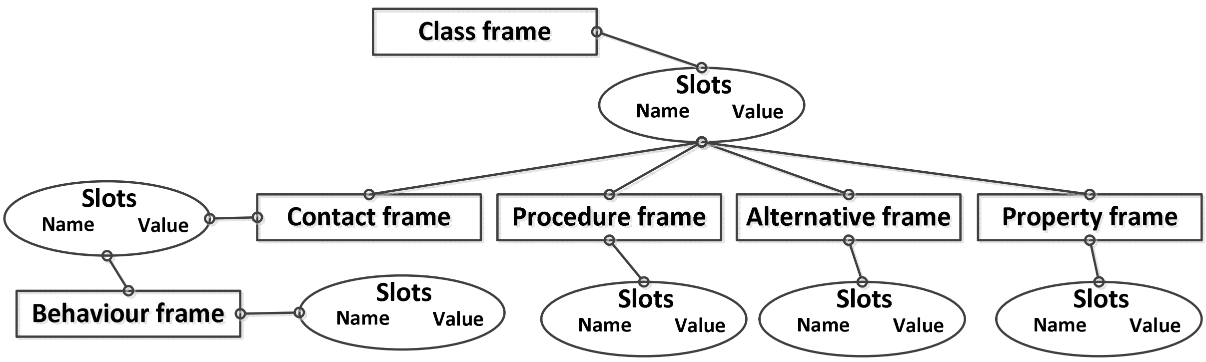

Fig. 3.1. The representation of frame set

In a new frame set the usage and specific characteristics of each frame are determined by the slot to which the frame is connected. In the frame set frames are connected with the pointers in the slots and also organized in the hierarchy that enables the inheritance within the frame set [GRU 1997a, VAL 2005b, ZEL 2010a]. Class frames and related frame sets are organized in taxonomic hierarchy where each class frame has one superframe. If complex systems are described then each decomposition level of system can contain more than one level of the frame hierarchy. Therefore when structure models are constructed essential are relationships that are represented in contact frames. In the frame set overall are described: object name, object properties (names, values), functions, behaviour, rules, contacts and relationships that represent object relationships with other objects and other properties that are relevant to object [GRU 1997a, ZEL 2008b, ZEL 2008b]. Author for each frame have created visualized representation that is implemented in I4S application. The frame set that is used in intelligent system I4S has several advantages:

1) In the knowledge base and in the interface frame set is used as knowledge representation schema [GRU 1997a, VAL 2005b]. Usage of one data structure provides unified and unambiguous representation. Frame set allows systemize the acquired knowledge.
2) In the frame set at the same time it is possible to represent: a) system structure and element distribution in different levels of hierarchy; b) organisation and corresponding system structure.
3) In the frame set is described each system part: system components, system elements, as well as alternatives of system parts;
4) In the frame set are represented interconnections between system parts and rules, that are realized in the case when system part or properties are changed;
5) In the frame set can be represented both the object and class hierarchy. This means that system structure as well as ontologies can be described [GRU 1999, VAL 2005c, ZEL 2010a, ZEL 2010b].

3.2. System I4S and transformations from the frame set

Intelligent system for complex system structural modelling (I4S) is a computer system, in which the structural modelling approach is implemented, to support complex technical system structural modelling with computer. System I4S architecture consists of 3 levels: (1) data and information level that corresponds to the database; (2) logic level that corresponds to the knowledge base and (3) application level that corresponds to the system application. Application is created in the visualised Rad Studio XE2 C++Builder integrated development environment, that enables application development and uses C++ programming language [HIL 2009]. System I4S database is created in open source object-relational database management system PostgreSQL (version 9.1.) [POS 2012]. Knowledge base is developed using C++Builder and PostgreSQL software capabilities. System I4S components are interconnected and include 6 modules and those allow to realize the system I4S functionality: 1) database management module; 2) subsidiary function module; 3) user session module; 4) data deletion module; 5) application management module; 6) model and matric generation module. Transformations from frame set to structure models are created to provide automated structure model construction. For each transformation an appropriate algorithm is created and implemented in the system I4S. Algorithms sequentially acquire the necessary knowledge from definite frames of the frame set and use it to create structure models.

Transformations consist of 4 main parts: selection of system decomposition level, selection of model type, knowledge acquisition from frame set and model element representation and connection. To realize the transformation from frame set to MSM, FSM SF or FSM SB, frame system hierarchy, class and contact frames are used. It shows that structure models are closely connected each to other and that frame set allows represent different aspects (morphological, functional) of the research system at the same place. In the transformation process the information is acquired that after is used to visualise model elements, to connect them and to create proper structure model. Transformation from frame set to MSM consists of 7 steps:

1) Select a certain decomposition level in the frame system hierarchy;
2) Determine which structure model to create and whether to construct it for all system in selected decomposition level or for a single system component;
3) Derive system object names from frame hierarchy and create object list;
4) Verify object relationships (including contacts, flows and logical operators) and create connection list;
5) Choose objects that are not depicted in structure model from the object list and visually represent them, following the notation of MSM;
6) Verify connection list regarding the represented objects and obtain the number of contacts. Visually represent contacts, if they must be represented in the chosen model;
7) Connect objects - representing flows visually (arrow, flow names, and colour according to the flow type).

Similarly to the viewed transformation also rest of transformations from the frame sets to structure models are performed. In the transformation from frame set to functional structure model in a space of parameters (FSM SP) are used: frame hierarchy, class, contact and behaviour frames. In addition to mentioned transformations system I4S creates also transformation from frame set to even trees. FSM SP captures all events and relations between them, in the chosen level of decomposition. Event tree is a graphical representation of a determined causal relationships sequence, which allows identify causes that create changes in a chosen parameter. Changing the system parameters, inferences about parameter influence on system functionality can be obtained. Event tree has an essential role in diagnostics, because it allows reason about causes that change system behaviour. Each event corresponds to a single parameter or defect [GRU 1997b]. Two event causal order and corresponding logic is interpreted as causal relationships. Sequence of causal relationships creates a structure of even tree. Basic elements of an event tree are [GRU 1993, GRU 1997a, GRU 1997b]:

- Events that are represented showing the identifier of parameter or defect. In the event tree 3 types of events are considered: a final event (connected with observed change of parameter value), an intermediate event (each primary even causes one or more intermediate events) and a primary event (cause of final event).
- State transitions are interpreted as causal relationships that are represented as directed arcs.
- Logical operators.

Event tree is created by choosing a parameter in which change of value is observed. To acquire parameter list in specified decomposition level transformation algorithm from frame set to FSM BP is performed. Event tree is constructed using list of parameters and connections, backtrack procedure [GRU 1997b, RUS 2010], and experts chosen parameter. Procedure realize search in the graph (FSM SP), moving backward from the chosen node (final event). Connected nodes are represented in the event tree, considering the existing logical operators. Procedure continues search and add nodes while reach primary events.

Summary and conclusions of Chapter 3

- New created knowledge acquisition and representation schema – the frame set allows represent knowledge about different research system aspects (morphological, functional) in one place and to create various hierarchies.
- It is necessary to consider not only usage of logical operators in transformations but also make addition tests and verify structure model, to exclude simultaneous

predecessor and descendant representation in the model (it is essential precondition to create correct model automatically).

- Created intelligent system I4S allows to realize knowledge acquisition, representation and maintenance.
- System I4S includes 3 main components, in which a frame set is implemented and 6 modules that allow to realize purposes of structural modelling. Using acquired knowledge and created transformations, I4S provides structure model and event tree automated construction.

4. PRACTICAL EXAMPLE IMPLEMENTATION IN THE SYSTEM I4S

In order to verify the developed intelligent system and its functionality, within I4S a representation of the complex technical system – robot AGR8 was created that is described in the fourth chapter. AGR8 is a mobile robotic platform that has been developed at Riga Technical University for mechanics and artificial intelligence research purposes [NIK 2010]. In the system I4S are implemented several solutions that support the automated construction of structure models, new knowledge acquisition about research system and its analysis. To perform structural modelling, system I4S realizes the following tasks:

- supports knowledge acquisition, representation and stores knowledge in such way that knowledge can be shared, reused and applied to reach goals of SM;
- system I4S uses acquired knowledge and transformation algorithms to create structure models and event trees automatically in different decomposition levels;
- using the represented MSM or FSM SF, system I4S creates matrices and performs system topological and qualitative system structure analysis, that is essential in system research.

4.1. Knowledge acquisition and representation in the system I4S

Working with the system I4S, expert`s main task is to create a formal representation of the research system, including aspects that are relevant to structural modelling: what system is viewed, what objects and relationships exist in the system, what are the properties and behaviour of the system and objects. System I4S can acquire and represent expert`s knowledge about research system in various ways:

- describing system`s objects, relationships between objects, properties (e.g. colour, weight) and alternatives;

- describing relationships in more detailed way – representing flow name and type, functions name, behaviour, possible flow combinations, as well as flow properties (for example, type of matter: oil);
- specifying parameters and relationships between them for each behaviour state;
- creating and representing system`s object, function and property hierarchies;
- transforming the knowledge acquired from expert in structure models.

System description starts adding the first frame, in which system name is represented, that in the thesis is *robots AGR8.* When the first frame is created then system I4S automatically creates another frame, called: *O0: Ārējā vide* (Fig. 4.1. **1.**). This is done to allow expert describe research system relationships with external environment as well as to show flows that influence system functions and behaviour or that are realized by system to influence external environment. When the system name is specified, further system objects are represented, adding new frames in the frame hierarchy. Author in the system I4S has represented knowledge about robot AGR8 structure. In the frame hierarchy robot decomposition can be viewed (Fig. 4.1), which confirms I4S capabilities to represent knowledge about various complex system parts:

- **components**, for example *O43: Kontrolieris 1* (Fig. 4.1. **2.**) is a system`s component, that includes elements: *O89: Mikroprocesors*, *O90: Impulsu ģenerators* and *O91: Barošanas spriegumu balansētājs*;
- **elements**, for example, *O101: Riepa* is system`s element (Fig. 4.1. **3.**);
- **heterogeneous parts**, for example, *O48: Otrais ritenis* (Fig. 4.1. **4.**) is a system`s component, that includes 2 different elements: *O103: Riepa* un *O104: Disks*;
- **homogeneous parts**, for example, *O13:Motora kontrolieru grupa* Fig. 4.1. **5.**) is system`s component, that includes 4 components - controllers which structure and operating principles are identical.

System I4S allows create connections only between objects that are represented in a frame hierarchy, therefore all system parts must be described. Author has represented system objects and relationships between objects in the contact slots, as well as has specified flow and function names, adding values in the contact frame flow slots. The flow value corresponds to the flow type defined in SM that can be energy, matter or information. Function name is given in a free form, such as "To capture data about state". Creating a new contact slot, system I4S automatically creates two behaviour states that correspond to the input and output contacts, as well as parameter set to each behaviour state. Creating representation, parameters and defects included in the parameter set are described (adding parameter slots in behaviour frame). Parameter and defect identifiers system I4S creates automatically, but values must be defined by an expert. Once parameters and/or defects are added, the connections between them in the connection slots must be described.

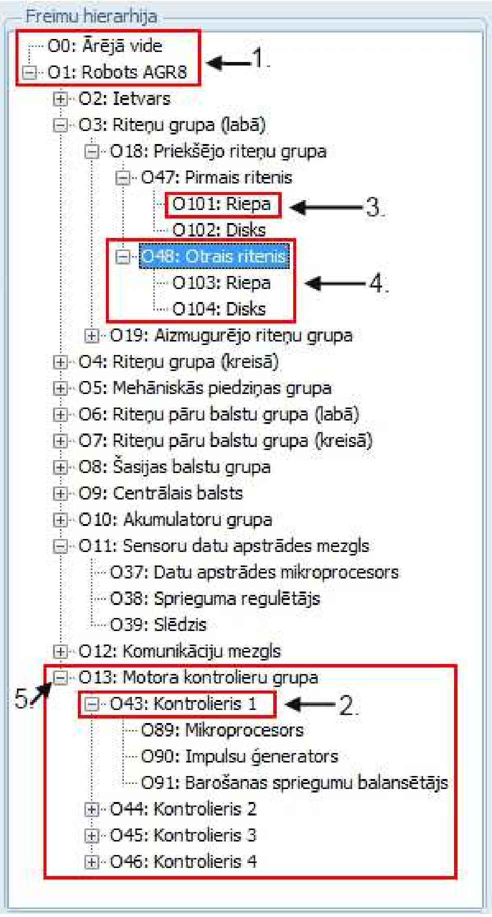

Fig. 4.1. Frame hierarchy for the system robot AGR8

System I4S allows manipulate with represented knowledge about objects, relationships, properties and behaviour. Expert can add not only object description, but also to change and delete it, and also to reorganize system objects. Reorganisation capability is developed, to implement self-organisation process that is essential in complex systems. Reorganization here means that a chosen system object (also with all descendants) can be relocated in other place within the hierarchy, changing objects predecessor. It is relevant not only to change system representation in the case when system changes, but also if an expert has created inaccurate system representation. Using the frame hierarchy in the system I4S can be represented various hierarchies: system`s parts, functions and properties. System creates object and function hierarchies also in corresponding models. When in the system I4S the description of research system is created using frame set and are represented all systems parts, relationships, behaviour and parameters as well as logical operators, then the construction of different structure models in different decomposition levels is performed.

4.2. Structural modelling and analysis of robot AGR8 with the I4S

Investigating complex technical systems in conditions of incomplete information, their models must meet following criteria [GRU 1993, GRU 1997a]:

- It must be possible to create model, using only available knowledge;
- Model must describe all system, regardless of element heterogeneity;
- Model must be easy adjustable, when the system is changed;
- Model must ”work” in conditions of incomplete information and must give new knowledge about the research system.

Realizing the structural modelling of robot AGR8 following confirmation is obtained: structural modelling approach implemented in I4S allows structure model construction, considering before mentioned criteria. Choosing a definite frame and pressing right key of mouse, expert gives a command to system I4S, to generate structure models. System I4S opens a new form in which it is possible to choose, what kind of structure models to visualize (Fig. 4.2 shows example of visualised structure model):

1. MSM – objects are represented considering either it is component or element. Expert may choose to show flow names or not. MSM in system I4S are marked as:
    a. *MSM (only objects)* is morphological structure model, in which only objects without contacts and flows are visualised;
    b. *MSM (with contacts)* – objects are represented with contacts and between objects are depicted flows;
    c. *MSM (with behaviour states)* – in the model objects are represented with behaviour states and between objects are depicted flows;
2. FSM SF in the system I4S is marked as *FSM (in a space of functions)*. In a model are represented functions and causal relationships between them. To support expert reasoning about the system, system I4S creates also production rules table that corresponds to the system's functions and relationships in the chosen decomposition level.

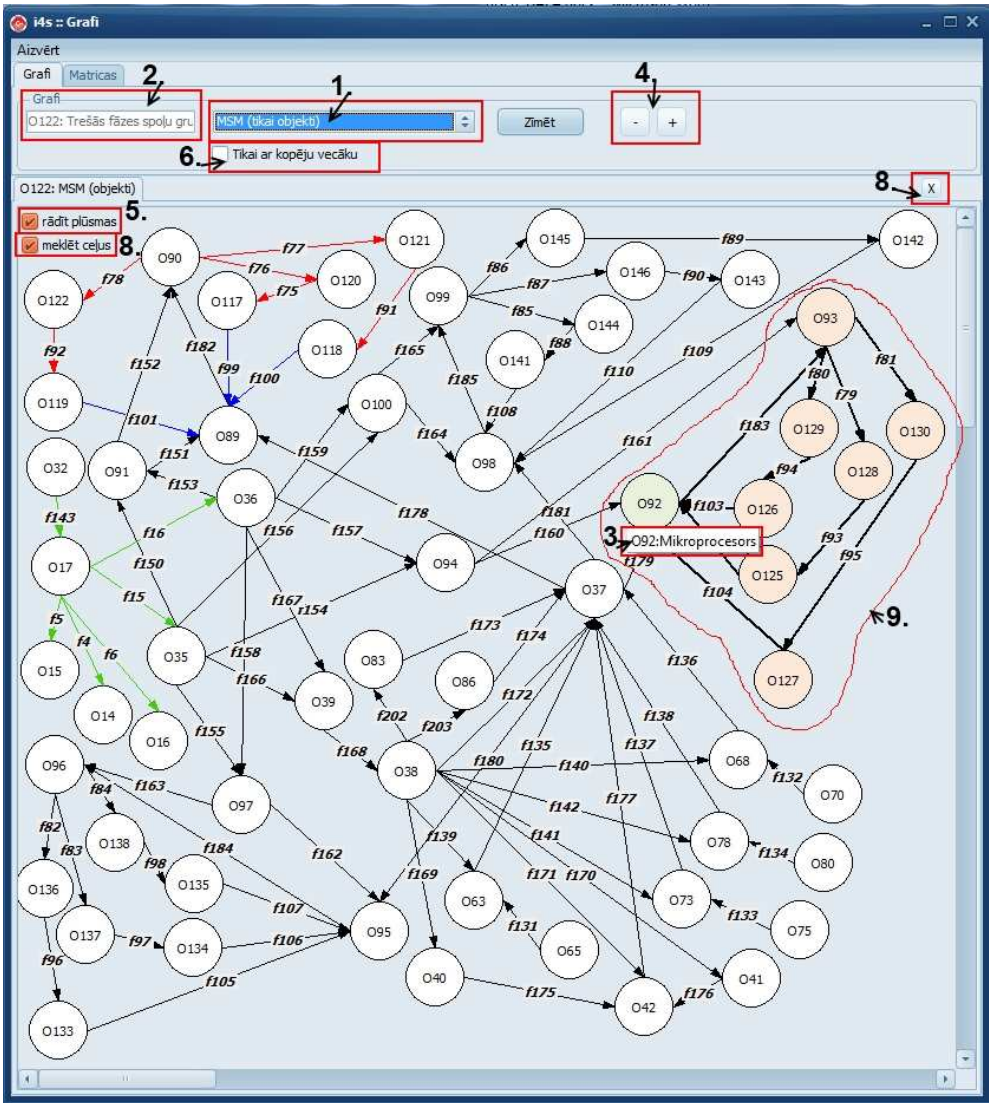

Fig. 4.2. The representation of MSM (only objects)

3. FSM SB in the system I4S is marked as:
    a. *FSM (in a space of behaviour - behaviour).* In the structural model behaviour is represented (two behaviour states in one node) and causal relationships;
    b. *FSM (in a space of behaviour – behaviour states)* – in each node a single behaviour state is represented and between nodes are depicted causal relationships;
4. FSM SP in the system I4S is marked as:
    a. *FSM (in a space of parameters – parameter sets)* – in the model parameter sets and causal relationships are represented;
    b. *FSM (in a space of parameters – parameters)* – parameters, defects and causal relationships between them are represented;

Choosing the model type and pressing button “Draw”, system I4S visualise structure model. Structure model represents all system or chosen component of the system, regardless of system part physical diversity, different behaviour and properties. It is easy to change models. The expert performs change in frame set and system I4S constructs a new model. Developing the system I4S, within it is included also graph analysis that is described in structural modelling approach [GRU 1993]. Therefore for constructed MSM or FSM SF system I4S perform topological and qualitative structure analysis. System I4S automatically can create following matrices: (1) adjacency matrix; (2) reachability matrix; (3) incidence matrix (4) distance matrix. In system I4S expert can view also multiplication of adjacency matrices in a chosen power (from 1 to n, where n is number of nodes in model). Multiplication is relevant to find the number of paths and cycles between objects represented in the structure model in a definite length and also distances between nodes.

Structure topological analysis is a form of analysis in which interconnections between created structure elements are investigated [НИК 1985, GRU 1993]. In system I4S is implemented capability to perform direct link analysis and topological sorting for viewed system structure that is represented in MSM or FSM SF. To realize direct link analysis, adjacency matrix is used to perform classification and to divide nodes in four groups [KNO 2005]. System I4S allow to realize research system structure qualitative analysis, that is analysis in which are determined qualitative indices of structure – element ranks. Rank can be determined by several criteria [GRU 1993]:

- By local degree. Rank is marked as R(LP);
- By number of paths and cycles with definite length (in the system I4S expert can indicate length from 1 to n, where n is number of nodes), that comes from viewed node. Rank is marked as R(CE);
- By number of reachable nodes. Rank is marked as R(S).

System I4S allows also to search paths in created MSM and FSM SF, between any two nodes and to create event trees that can be used to reason about consequences of defects. Expert chose parameter in which changes are observed and press button “Draw” and system I4S automatically creates event tree in which chosen parameter is in the top of event tree.

Summary and conclusions of Chapter 4

- The research system *robot AGR8* is described representing knowledge about: objects from which it consists; relationships between these objects; flows; functions and behaviour that are realized in the system; parameters and possible defects.

- System I4S using expert's knowledge realizes complex technical system structural modelling as well as performs structure topological and qualitative analysis (for MSM and FSM SF).
- Explaining capabilities of structural modelling and analysis that can be performed in system I4S and realizing examples regarding system robot AGR8 it is established that in the system I4S it is possible to:
    - perform knowledge acquisition, representation, correction, and maintenance regarding chosen research system;
    - represent different hierarchies (object, function, property), that allow understand system structure;
    - construct 8 different structure models and event trees in different levels of decomposition for all system as well for experts chosen component.
- Performing automated structure model construction in a system I4S, comparing it with model manual drawing, expert don't need to spend so much time, to create needed structure models (pressing the button system I4S creates the model).

MAIN RESULTS AND CONCLUSIONS

The goal of the doctoral thesis is to develop the knowledge acquisition and representation schema, implement it the intelligent computer system that provides complex system structural modelling and to verify it constructing structure models for a complex technical system. To determine the requirements regarding the system, in the thesis the following tasks have been solved:

- Analysis of complex systems performed and relevant properties determined that must be considered creating the model of complex system:
    - Many and different (homogeneous, heterogeneous, simple, composed) parts that interact in different ways;
    - varied (network and hierarchical) and decomposable structure;
    - each part in system has properties and behaviour and system itself has system properties and system behaviour;
    - system interacts with external environment, self-organize and develops in time.
- In the research it is found that specifics of complex technical systems and available information are the main factors when modelling approach must be chosen and to these mentioned criteria correspond structural modelling approach.

- Analysed structural modelling approach and obtained its capabilities and shortcomings that must be disposed to realize structural modelling in computer.
- Explored intelligent system design and mechanisms of actions and intelligent system definition given that is used in thesis.
- Analysed frame usage in different approaches and main characteristics given, as well as shortcomings of the knowledge representation schema that were used before in structural modelling have been viewed. Analysis enabled to obtain requirements for a new knowledge acquisition and representation schema that must be implemented in the intelligent system to fulfil structural modelling purposes.

In order to eliminate shortcomings identified in structural modelling approach and create the intelligent system in the thesis new theoretical results are obtained:

- Created new elements for structure models (logical operators) and explained their usage capabilities.
- Improved structure model syntax and semantics and transformation algorithms between structure models.
- Created knowledge acquisition and representation schema – the frame set and transformation algorithms from frame set to structure models.
- Developed architecture of intelligent system for complex system structural modelling.

Acquired practical results are used and to develop intelligent system I4S realizing following tasks:

- The frame set is implemented in the intelligent system architecture. Schema allows acquire knowledge from expert and to store it in the way that it can be shared and reused, as well as applied for automatized structure model construction and analysis.
- Developed intelligent system architecture is realized in the form of software.
- Verified functionality of developed intelligent system I4S and its compliance to the structural modelling purposes, representing in it knowledge about complex technical system *robot AGR8* and performing structure model generation and structure analysis.

Directions of research in near future are as follows:

- Additional graphical model and algorithm implementation in the intelligent system I4S that support more detailed research system analysis as well as would enable system design.
- Development of mechanisms that allow interpret and use production rules obtained in the system I4S.

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