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EVALUATION OF KEY FACTORS OF ERGONOMIC DESIGN OF CONTROL ROOMS IN COMPLEX SYSTEMS IN SERBIA

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Abstract Complex technical systems require special process monitoring and control. The control room is a location that is designed to allow the operator to monitor the process and coordinate activities. The ergonomic design of control rooms allows operators better insight into supervised process within a customized and pleasant working environment. This paper presents example of application of the analytical-synthetic model of ergonomic research in complex systems in Serbia.

Keywords: Ergonomic design; key factors; control room; complex system.

1. INTRODUCTION

The central term in systems theory is the term “system”. Mutual relations between the elements of a system lead to the fact that the system as a whole acquires properties that are not the properties of its individual elements. Numerous authors agree that the system is a set of elements connected by functional connections that are based on certain principles and laws [1]. Systems should be understood as entities that are maintained in a changing environment by stabilizing the difference between what constitutes the interior of a system and its exterior [2]. A special type of systems is a complex system characterized by a number of elements and connections between them. It can be said that a complex system is a system consisting of a number of powerful interactive entities, whose understanding requires the development and use of new accurate tools, specific reproductions, descriptions of imbalances and simulations, realistic modelling and application of existing knowledge to new research areas [1, 3].

Definitions and interpretations of complexity differ significantly upon the goal of the research or the method of application [4, 5]. In [6], the author determines complexity using specific criteria, emphasizing that in complex systems there is no single control, but numerous communication units. The most pronounced feature of complex systems is irreducibility, where the system as a whole is more than the sum of its parts and shows unexpected patterns of behaviour [1]. In [4], the author points out that a complex system is characterized by a large or medium number of elements, but also high variability of elements and their relationships, i.e. high behaviour variability. In [7], the author describes complexity using the following characteristics: diversity, connectivity, and dynamics. Diversity refers to the type and number of elements, connectivity describes the type and number of variable relationships, while dynamics implies uncertainty and unpredictability [8, 9, 10]. The main properties of complex systems are emergence and nonlinearity. Emergency is typified by the fact that some system properties do not have a meaningful interpretation at subsystem and element levels, while nonlinearity is a property of a system described by the fact that inputs have disproportional impact on outputs.

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Technical systems are becoming more complex. They contain a large number of interconnected components, and defined by a specific structure and way of functioning. In addition, significant features of these systems are management and cooperation. The main subsystems are most often defined as man, technology and environment. These subsystems contain a number of functions that are implemented by a large number of related elements. The success of these systems is reflected in the efficient hierarchical organization of monitoring, decision-making and control, monitoring a large number of related variables and overcoming the simple feedback principle in solving control tasks [11, 12, 13]. The system functioning is based on the subordination principle, while cooperation is realized by effective information flows, coordination of events and cooperative connections, as well as various “side-effects” in the cause-effect chain of events [14, 15].

The control centre of a complex technical system is a location developed to permit an operator to control a process [13, 16]. The process complexity causes that observed technical process is controlled by monitoring equipment, and an operator may find himself or herself in a situation of deciding on conflicting goals when coordinating activities [11]. The increased complexity of the system causes increased complexity of tasks and a larger number of unwanted events that need to be monitored, which increases the complexity of the operator’s work activities [13]. Automation causes the dynamic properties and structure not to be fully displayed to the operator, but only those properties that are necessary for his or her successful response when adverse events occur. The control room operator must monitor dynamic process changes using measurement and control systems, and make decisions based on presented data [17, 18, 19]. It is important to study the performance of operators in control rooms of complex technical systems [20, 21], i.e. their functional convenience and efficiency [22]. To be able to obtain appropriate assessment, the properties of the work environment are considered [12, 23, 24], as well as information flow [25, 26, 27], information presentation [28], operator fatigue and workload [29, 30]. Technical complexity is only one side of the coin. Social complexity is also very important if several operators participate in the control. This is called the complexity of crew coordination [25], or the complexity of various interactive processes required to control a complex technical system [31, 32].

The systems approach is suitable for the purpose of complex system research. System complexity requires the development of new workforce skills with an emphasis on systems capability [33]. Therefore, the development of an applicable system methodology is needed, as a combination of systems approach and cooperation. Specific systems require special approaches for the development and modernization of control rooms, as well as an analysis of operators’ decision-making process [34, 35]. Due to a large number of influencing factors, it is necessary to identify the key ones. This can be successfully accomplished by applying the methods of multi-criteria or multi-attribute analysis and expert evaluation. In Serbia, research using these methods was conducted when considering three complex technical systems [12, 13, 23, 24], with the aim of improving and adapting existing methods of managing according to new identified situations and risks, i.e. reconstruction of existing elements and introduction of new elements of control centres. The procedure itself required a detailed analysis of existing solutions and identification of new solutions using systems approach and multi-criteria analysis. By applying the fuzzy logic and including a group of experts in the decision-making process, uncertainty was significantly reduced, with simultaneous quality improvement of obtained results.

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2. METHODOLOGY

In this paper, an analytical-synthetic approach is applied, as a methodological framework for research of key factors in the ergonomic design of control rooms of complex systems in Serbia. It incorporates two models: model of system analysis and model of system synthesis. The first model is used to identify functions in the "man-technique-environment" system. The second model, according to analysis results, gives the proposal of improving the design of the control centre elements, working environment, and operators' working skills. The initial variant of proposed model was applied for the purpose of the research of management and control in three complex systems in Serbia - coal mines, electric power and railway companies [12, 13, 23, 24, 27].

2.1. Analytical-synthetic model of ergonomic research in railway control rooms

The structure of the analytical-synthetic research model of control rooms for railway traffic management is shown in Figure 1. This model consists of five specific research levels.

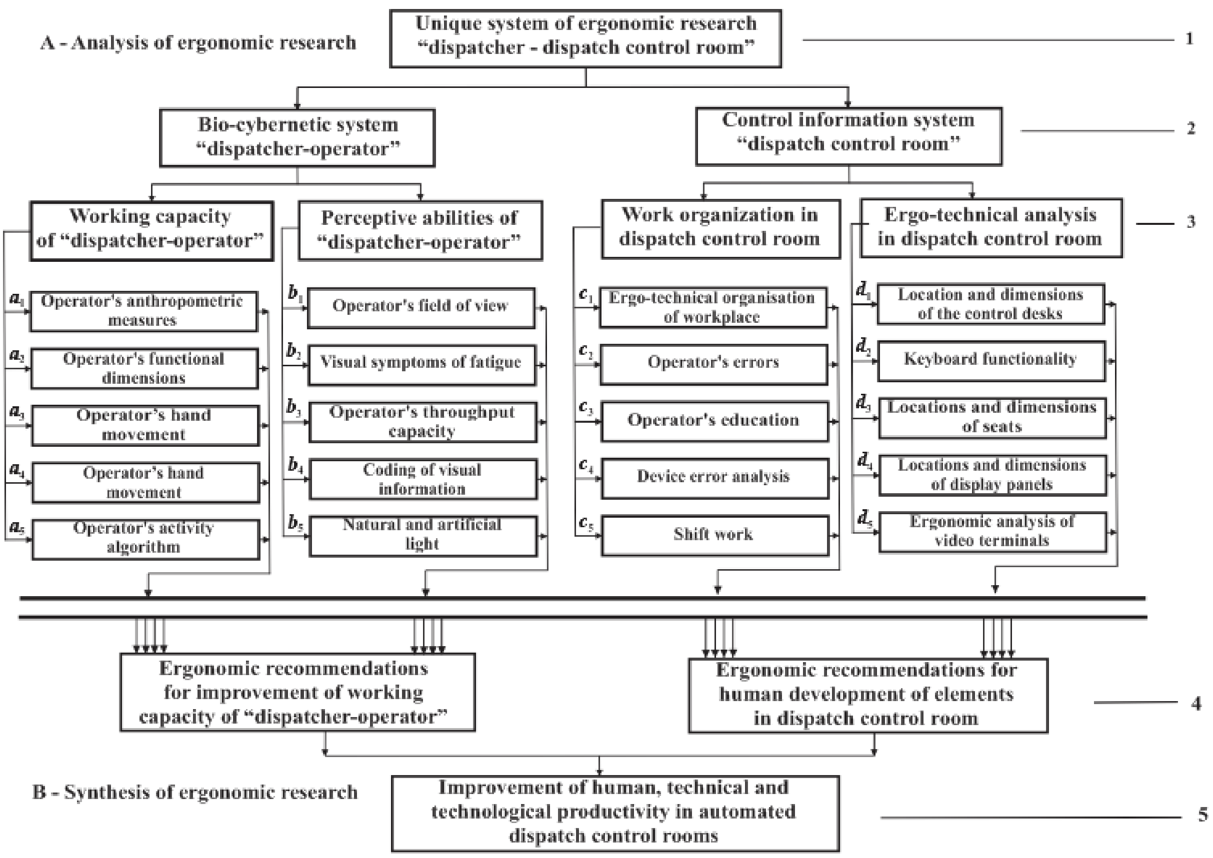

Figure 1. Analytical-synthetic model of ergonomic research in railway control rooms.

The first level involves setting the hypothesis and research goal in relation to obtained research task. At the second level, the formulation of research methods and techniques is performed. The third level

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is especially important because it allows the following: determining the operator's body anthropometric measures; determining the attitudes and movements of operator's body; mathematical modelling of operator's activity; determining operator's field of view; determining subjective feeling of operators' visual fatigue; determining operator's throughput capacity; analysis of time plan of work in the control room; analysis of control panel; analysis of operator's seat; as well as design analysis and ergotechnical analysis of control room elements.

At the following levels, the synthesis of previously obtained data and decision-making is performed. The fourth level enables a unique estimation of the functional suitability and effectiveness of the workplace. The last, fifth level, enables the prediction of possibility of applying solutions for improving working ability of operators and more humane and rational design of control room elements.

2.2. Analytical-synthetic model of ergonomic research in electric power control rooms

The structure of the analytical-synthetic research model of control centres in the power industry is shown in Figure 2. This model is presented by five levels of research.

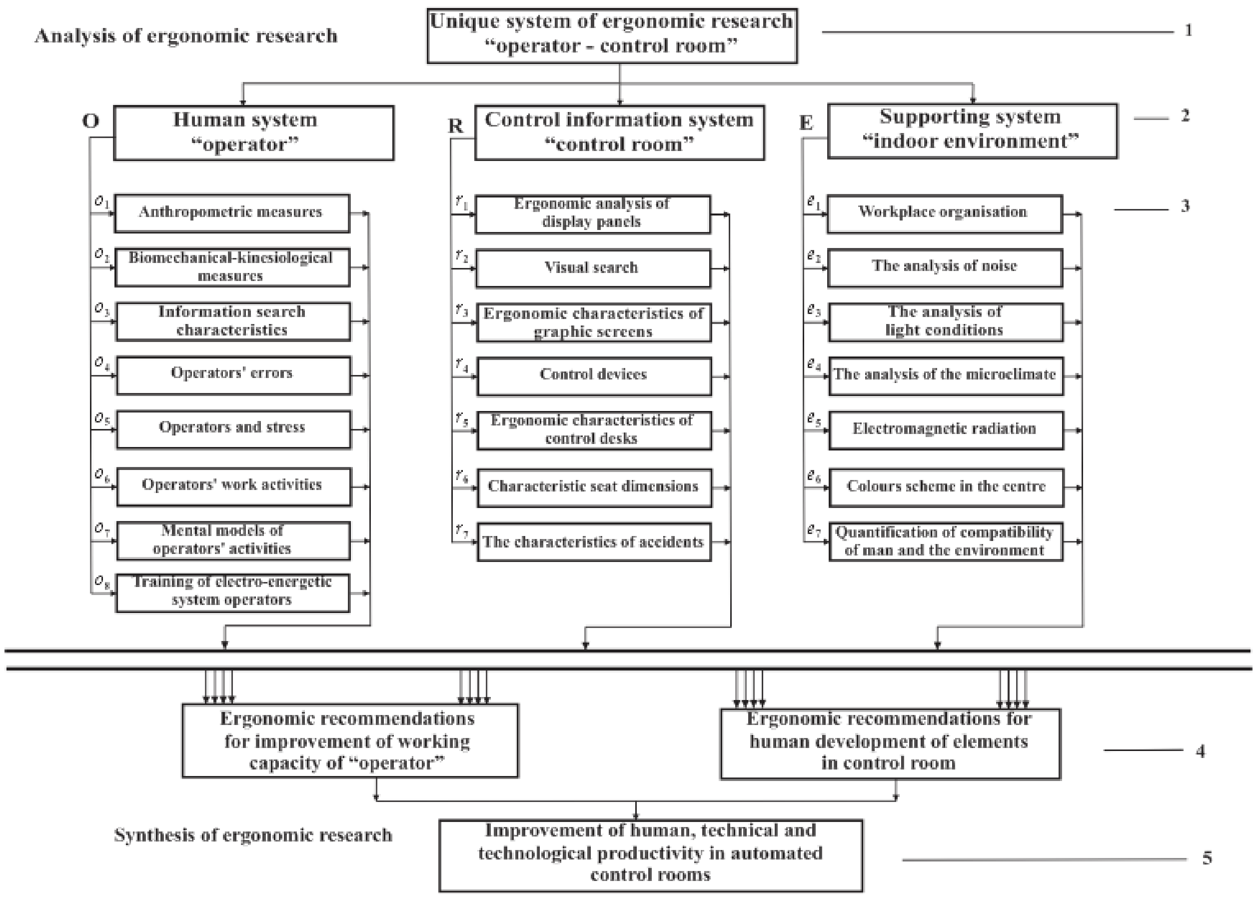

Figure 2. Analytic and synthetic model of research in electric power control rooms.

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The first level of ergonomic research is the definition of hypotheses and goals related to unique system of ergonomic research “operator-control room”. At the second level, research techniques and methods are formulated in the context of three subsystems (human subsystem “operator”, control information system “control room”, and supporting system “indoor environment”). The third level allows a detailed analysis of all identified subsystems. The following is considered for the human subsystem: anthropometric measures; biomechanical-kinesiological measures; information retrieval characteristics; operators’ errors; operators’ stress; operators’ work activities; mental models of operators’ activities; training of electro-energetic system operators. The control information system is analysed using: ergonomic analysis of the display panels; visual search; ergonomic characteristics of graphic screens; control devices; ergonomic characteristics of control panels; characteristic seat dimensions; and accident characteristics. The supporting system “indoor environment” is described by: workplace organization; noise analysis; lighting analysis; microclimate analysis; electromagnetic radiation; colour schemes in the centre; quantification of compatibility of man and the environmental.

Based on the obtained data, at the fourth level, ergonomic recommendations are given for operators’ working capacity improvement and more humane development of the elements in the control room. The synthesis of ergonomic research ends with the fifth level, which defines proposals for improving technological and human productivity in automated control rooms in electric power systems.

2.3. Analytical-synthetic model of ergonomic research in coal mine control rooms

The structure of the analytical-synthetic model of research of control centres in coal mines with underground exploitation is shown in Figure 3. It contains five levels of research.

The first level of research is setting the hypothesis and goal of the research. At the next level, the selection of methods and techniques for research of biocybernetic system, management information system and data monitoring system is performed. The third level defines the research process in more detail, as follows: determination of anthropometric measurements of the operator's body (a_1); research of operator activity (a_2); research of the effect of the volume of presented information on psychophysiological behaviour of an operator (a_3); exploring the “operator-means of information presentation” dialogue (a_4); ergotechnical research of control devices in the pit (b_1); ergotechnical research of control panels (b_2); ergotechnical research of video terminals (b_3); research on management through means of presenting information (b_4); research on the impact of underground coal exploitation on the environment (c_1); research of environmental parameters important to control centre (c_2); research on the application of information technologies in the control of the mining environment (c_3); and research on the concept of a coal mine environmental information system (c_4).

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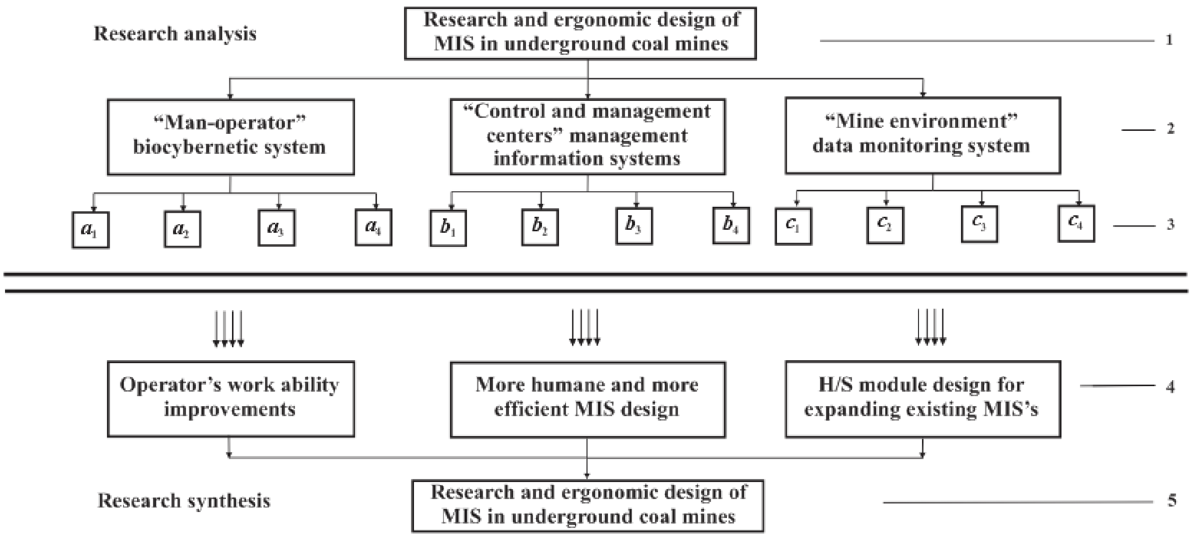

Figure 3. Analytical-synthetic model of ergonomic research in underground coal mine control rooms.

The fourth level provides assessment and determination of limiting factors of the system "operator - management information system - environmental control". The last level is the assessment of the possibility of applying solutions to improve the working capacity of operators, more humane and rational design of the elements of control centres and working conditions improvement.

2.4. Integral analytical-synthetic research model

Based on the experience achieved during the application of the analytical-synthetic model in railway, mining and electric power systems in Serbia [12, 13, 23, 24, 27], an integral research model is proposed, as presented in Figure 4.

The initial research model is expanded with research plan and programme activities and research assessment, which are defined in the process of network planning [13]. The abstractness of the model enables its application in various complex systems. Research plan and programme development activity defines research hypothesis and goals, and presents research model details. It selects corresponding experimental research frameworks and corresponding research methods and techniques, as well as expert team.

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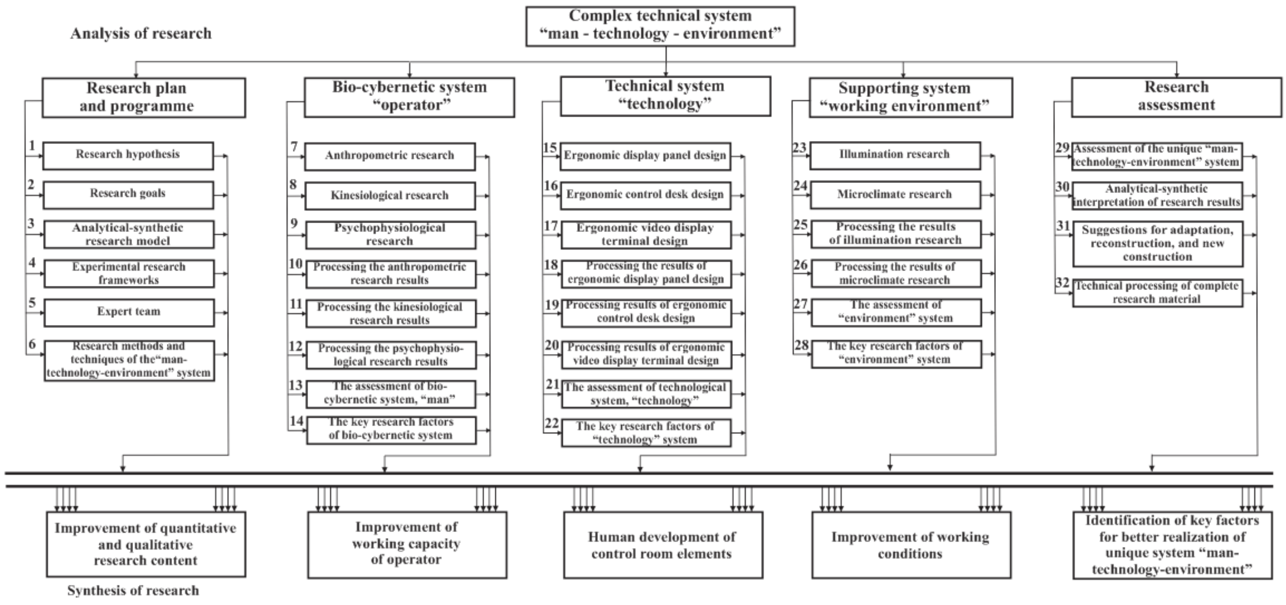

Figure 4. Integral analytical-synthetic model of research of complex technical system "man-technology-environment".

Research assessment consists of the analysis of the unique research system and interpretation of research outcomes. The results of the analysis consist of proposals for adaptation, reconstruction and new construction of control room elements. All previously mentioned activities require appropriate technical processing of the entire research material.

3. RESULTS

Detailed ergonomic analysis of three complex systems in Serbia involved the identification of key factors. These factors were identified by group expert evaluation, with a detailed analysis of the current state of analysed systems [12, 13, 23, 24].

During the analysis of key factors of ergonomic assessment of the control rooms in the electric power industry [23], the following weights were determined: w_R=0.40 for the control information system (control room), w_O=0.35 for the human system (operator), and w_E=0.25 for the supporting system (indoor environment). The relative weights in relation to each criterion and final weights are shown in Figure 5.

In the analysed system, taking into consideration the control information system (control room), ergonomic characteristics of the control boards (r_5) and ergonomic analysis of display panels (r_1) were pointed out as the most significant. Among others, operators' stress was identified as very important, as well as light conditions in observed control room.

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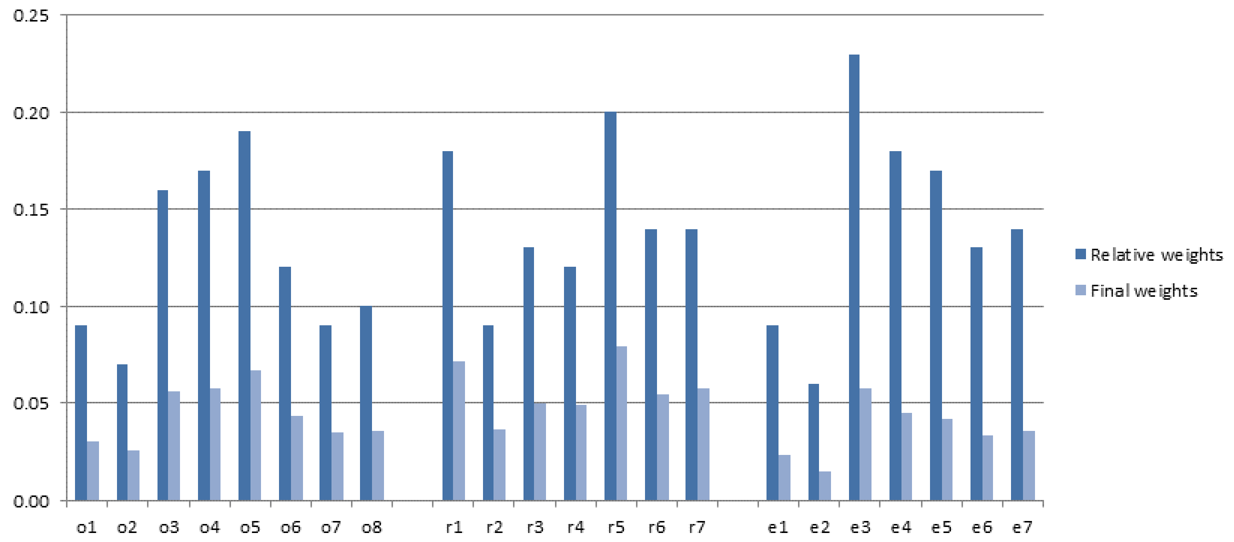

Figure 5. Relative weights in relation to the criteria and final weights in electric power control room.

The analysis of key factors in railway control rooms gave the results shown in Figure 6 [24]. The results of expert evaluation, using the fuzzy logic and group decision-making, are the weights for the organization of work in the control room (w_A=0.36), operators' perceptual abilities (w_B=0.18), work organization (w_C=0.14), and ergo-technical analysis (w_D=0.32). The relative weights in relation to each criterion and the final weights are shown in Figure 6.

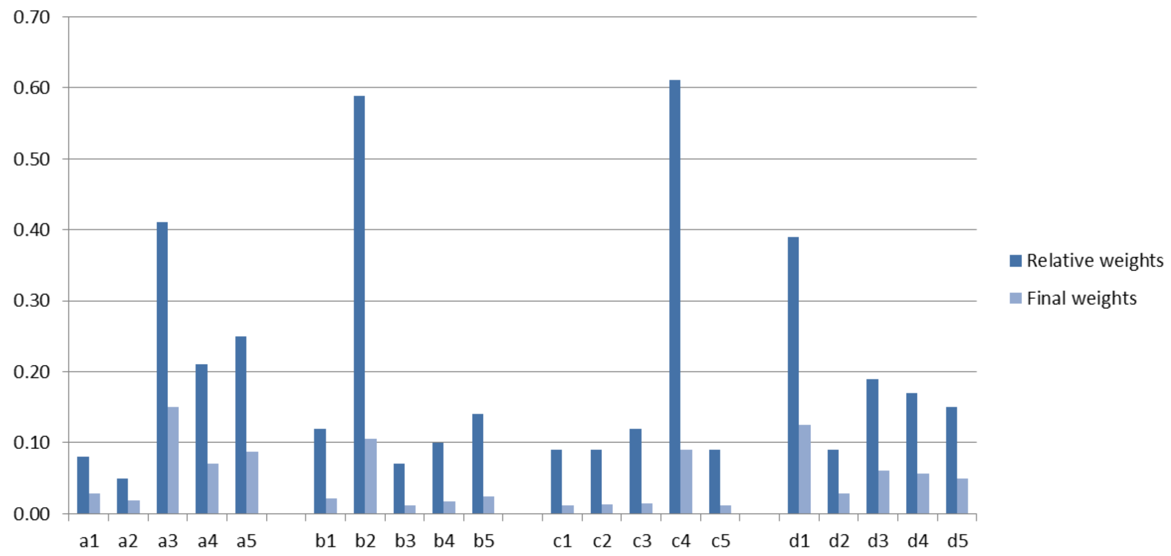

Figure 6. Relative weights in relation to the criteria and final weights in analysed railway control room.

In analysed railway control rooms, as the most important indicators the following were identified: hand movements (a_3), location and dimensions of control desks (d_1), and visual symptoms of fatigue (b_2). The analysis of the operator activity algorithm (a_5) was also identified as very important.

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During the analysis of coal mine control rooms [12], the following factors of operator quality are identified as the most important: work organisation (w_{f2}=0.130), ergotechnical characteristics of control panel (w_{f3}=0.342), manner of information presentation (w_{f4}=0.342), expansion of the system with occupational and environmental parameters (w_{f7}=0.130), and operators' education (w_{f8}=0.130).

The results of the ranking of key indicators in the research of the underground coal mine control rooms are presented in Figure 7. Based on the group AHP method, according to final weights, the following key indicators are identified [12]: (1) VDT functionality, (2) control panel shape and dimensions, (3) keyboard functionality, (4) alarm response time, and (5) expansion of MIS with occupational and environmental parameters.

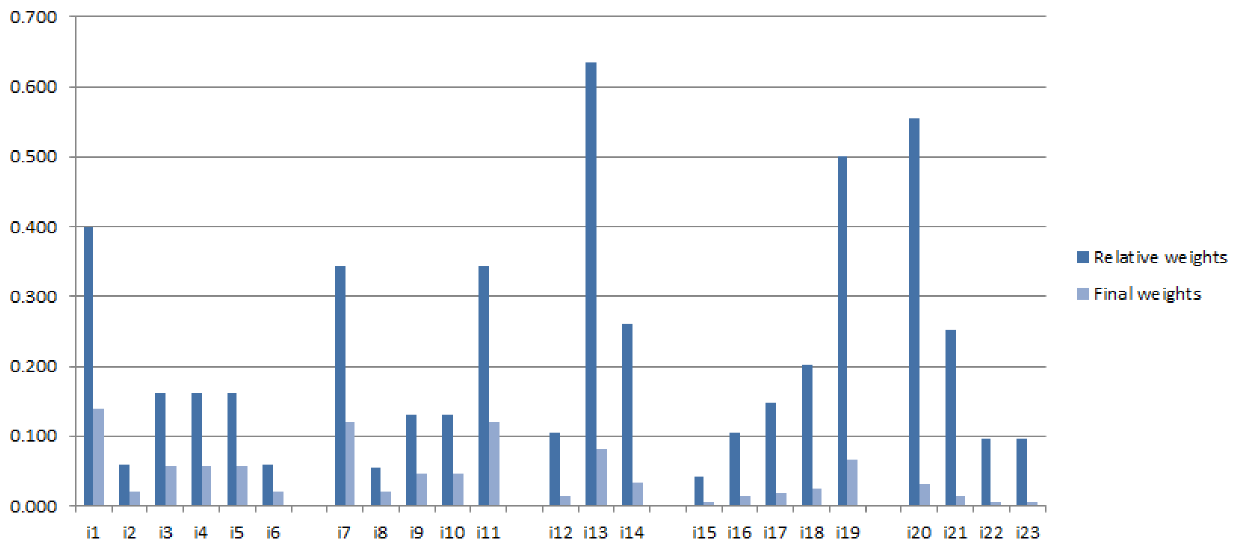

Figure 7. Relative weights in relation to factors and final weights of indicators in analysed underground coal mine control room.

During the research of complex technical systems, the extended model is applied [13]. The results of ranking of factors based on the integral analytical-synthetic model are shown in Figure 8.

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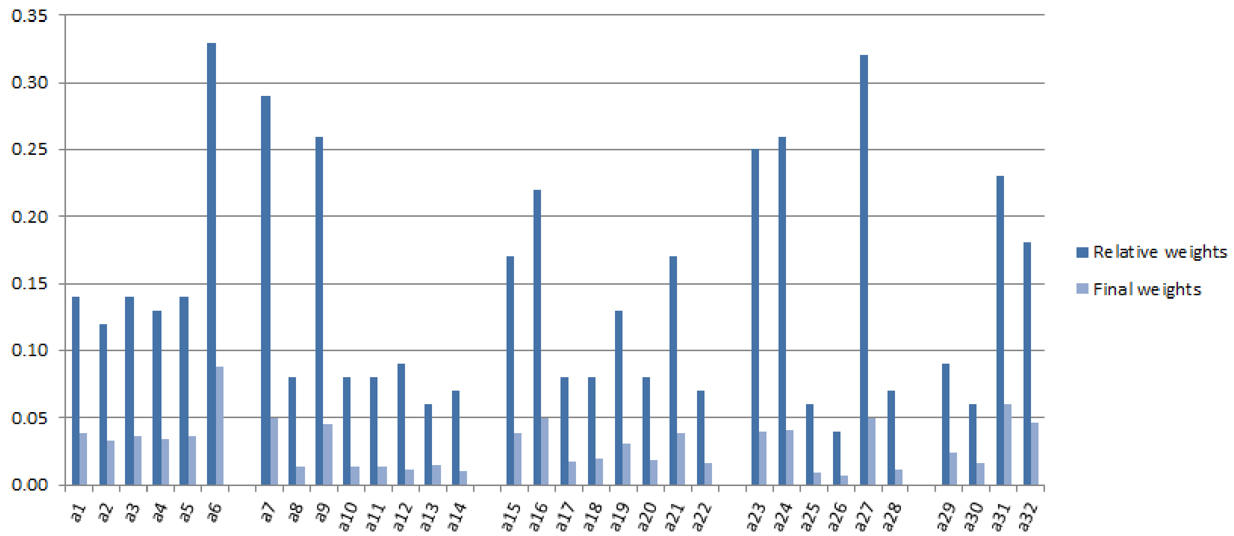

Figure 8. Relative weights in relation to criteria and final weights in the integral analytical-synthetic model of complex technical systems.

During the analysis of representative systems and factor determination, the experts determined the weights describing significance of the research plan and program (w_R=0.27), bio-cybernetic system “operator” (w_B=0.18), technical system “technology” (w_T=0.23), supporting system “working environment” (w_S=0.16) and research evaluation (w_A=0.17), especially emphasizing the importance of the research program and plan and characteristics of the technical system.

4. DISCUSSION

Analytical-synthetic model of ergonomic research was applied in Serbia during the consideration of three complex systems. Due to their specifics, these systems are of special importance for the functioning of the society, and dangers that may occur require special measures to monitor and control these processes. Operators are very important elements of these control systems, so their well-being caused by appropriate working conditions, as well as adequate information from supervised processes are the key to success of these systems and prevention of adverse events. The complexity of these systems requires a detailed analysis of all influential elements and identification of key factors and indicators that lead to better working conditions and operators’ efficiency.

Ergonomic analysis of electric power included three factors and twenty-two indicators. The relative weights of indicators in relation to factors were very close, and weights of the factors (w_R=0.40, w_O=0.35, i w_E=0.25) conditioned that several key indicators could be distinguished, which can be clearly seen in Figure 5. Information presentation in this system is very important, which was shown by expert evaluations of ergonomic characteristics of control boards (w_{r5}=0.0792) and display panels (w_{r5}=0.0718). Furthermore, light conditions in the control room help operators to better understand the current state in the monitored system (w_{e3}=0.0576). The organization of work requires a significant workload of operators, so stress is identified as crucial for the efficiency of an operator (w_{o5}=0.0669). The redesign of the control board will solve the operator's inadequate hand and body

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movements, while different organization of displayed information will improve visibility and facilitate correct and timely decision-making, which is especially important in emergency situations. Small differences in values of final weights of some indicators indicate the importance of constant monitoring of the situation and proposing the improvement of control room elements. Therefore, the results of the analysis of this control room cannot be considered as a final solution, and must be adjusted to the latest ergonomic and occupational safety recommendations and standards.

The results of analysis of the control room in the railway industry emphasized the organization of work and ergotechnical analysis of the elements of the control room. The experts assessed other two factors (perceptual abilities of the operator and the organization of work) as such that the weight values were approximately twice less than the other previously mentioned factors. All four factors are described by groups of five key indicators. In each of these groups, a single indicator stands out. In the context of work organization, hand movements dominate in the control room (w_{a3}=0.150). Also, the indicator describing the algorithm of operator activity (w_{a5}=0.088) can also be considered as significant one. The most important among the indicators that describe perceptual abilities of the operator is visual symptoms of fatigue (w_{b2}=0.105). During the analysis of this system, control boards location and dimensions were identified as very important (w_{d1}=0.124). Inadequate dimensions of the control board result in an inadequate arrangement of control elements. This leads to dysfunctional movements of an operator, which often cause workplace injuries. Also, discomfort and fatigue of the operator can be caused due to inadequate quality of information display. The most common problems with display are information overload, frequent changes in the displayed content and insufficient readability, as well as inadequate quality of information presentation. These are the most important causes of subjective feeling of visual fatigue and operators' workload. The solution to the problem was found by experts in the design of a new control board, which enables elimination of dysfunctional movements of the body and arms. Also, use of graphical screens to display part of necessary data allows a significant reduction in the operator's information load.

During the analysis of the underground coal mine control room, five factors and twenty-three indicators were used. The experts identified as the dominant factors the manner of information presentation and ergotechnical properties of the control panel. In all groups of indicators that describe the factors, there are one to two dominant indicators, which made it easier for experts to propose measures to improve the existing system. Among the indicators that describe the way information is presented, the most significant is VDT functionality (w_{i1}=0.140). The use of three monitors to display information complicates the work activities of operators, bearing in mind that they display data in real time. All ergonomic recommendations were not met. The angular dimension of the visual characters is α=16.32’’ versus recommended values of α=(35-40)’’. The distance between monitors and operator's eye are d=105cm in relation to recommended values of d=49cm for computer monitor and d=86cm for the touch screen. This requires different location of monitors and modification of the control panel. The area of the operator’s control panel is occupied by four keyboards for the alarm and voice communication subsystem. The keyboards measure 400×270mm. The weights of the indicators describing the control panel shape and dimensions (w_{i7}=0.120) and keyboard functionality (w_{i11}=0.120) are equal. In addition to existing information, the experts recommended the upgrade of existing system to be able to present new parameters, primarily environmental data (w_{i19}=0.065). Special training is needed to prepare operators to work in such an environment and to respond precisely and timely to the occurrence of adverse events, as described by experts with the alarm response time indicator (w_{i13}=0.082). This is helped by an adequate arrangement of control elements

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(buttons, switches and signals), divided into logical groups (four of them). They meet all necessary ergonomic recommendations. Also, the priority-of-use principle is met and marking is done so that the fastest possible response is enabled.

By applying ergonomic research models, according to the outcomes of the research of previous systems, a new integral methodological approach for the analysis of complex technical systems is proposed. This model uses thirty-two indicators that describe five factors. The objective of the model is to analyse the research of complex technical systems, where the key subjects of the research are operator, technology and work environment. The model describes five research areas, from the research plan and program definition to research evaluation. Although the names of some research activities differ slightly in formulation from previously presented models, they have essentially the same roles. By applying the model in various complex systems, shortcomings and key indicators have been identified to enable the improvement of working conditions and system efficiency. The model is defined to enable the selection of methods for application during the analysis of control rooms of complex systems (anthropometric, biomechanical, ergonomic, mathematical methods and other experimental and analytical methods) and application of interdisciplinary knowledge during the analysis of these systems. During the initial state of the control room development in observed complex technical systems, not enough attention was paid to ergonomic and functional requirements, i.e. the consistency of information-management units and operators. The integral model defined in this way can be further extended to enable its application to other control centres.

5. CONCLUSION

Complex systems require special monitoring and control. The key control element in these systems is an operator. Ergonomic aspects of control room design are the key factors that affect the efficiency of operators' activities. The design of control rooms must be adapted to characteristics of system being monitored and operator's needs. In order for the operator to react in a timely and correct manner in case of an adverse event, the data collected from monitored process have to be presented in an unambiguous manner. The analytical-synthetic models of various complex systems, presented in this paper, allow to adequately analysing ergonomic aspects of control rooms. According to results of presented analyses, using multi-criteria methods and group expert decision-making, key factors and indicators can be identified. Additionally, the experts can identify potential problems, suggest improvements of existing elements or introduce new control room elements.

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