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TRANSFORMATION OF ENGINEERING THINKING OF COMPLEX SYSTEMS DESIGNER

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INTRODUCTION

For many years, the hypothesis in the security field has been the superiority of technology over the human factor. The increase in the number and level of threats has led to new solutions focused on technological means. However, research related to the human factor has been limited. For example, organizations often ignore the human factor in security planning. In recent years, statistics on accidents in the transport sector and practical results in the field of security indicate that with addressing the human factor, technological solutions are able to ensure the viability (safety, stability, reliability and efficiency) of complex systems and structures. That is, the critical problem in the field of security, as before, remains the problem of the human factor[1 2 3].

The plane where dangers arise. Nobel laureate psychologist Daniel Kahneman described the catastrophic consequences of the human factor problem[4]. There are theories, concepts, approaches, and methods for solving security problems that are reduced to attempts to manage the human factor[5 6 7]. In our opinion, problems in the security industry are realized as a

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[1] Dul J, Bruder R, Buckle P, Carayon P, Falzon P, Marras WS, Wilson JR, van der Doelen B. A strategy for human factors/ergonomics: developing the discipline and profession. *Ergonomics*. 2012. V. 55(4). P. 377-95. doi: 10.1080/00140139.2012.661087.

[2] Reiman A., Kaivo-oja J., Parviainen E., Takala Esa-Pekka, Lauraeus Th. Human factors and ergonomics in manufacturing in the industry 4.0 context – A scoping review. *Technology in Society*. 2021. V. 65, article id: 101572. DOI: 10.1016/j.techsoc.2021.101572

[3] Mygal G., Protasenko O. Human Factors: The Problem of Man-machine Interaction in the Digitalization Conditions. *Scientific Journal of Polonia University*. 2021. V. 48(5). P. 198-210. https://doi.org/10.23856/4825

[4] Kahneman D.; Sibony O.; Sunstein C.R. Noise: A Flaw in Human Judgment. *William Collins*. 2021. ISBN 978-0008308995.

[5] Mygal V. P., Mygal G. V. and Mygal S. P. Transdisciplinary convergent approach – human factor. *Radioelectronic and Computer Systems, Modelling and digitalization.* 2021. V. 4 (100). P. 7–21. DOI: https://doi.org/10.32620/reks.2021.4.01

result of the intersection of the plane of risks affecting humans and human capabilities to exist and operate under the influence of these risks (Fig. 1):

1) *Growing risks*. Today, in Ukraine, Europe, and around the world, there is an increase in the number and level of threats – social unrest, environmental degradation, full-scale invasion and war in Ukraine, risks of transition to war in Europe, and world war.

2) *Digitalization*. The digitalization of all processes, games and communication to complex dynamic systems and complexes, the automation of processes and systems have led to a significant transformation of the thinking of young people, changes in the characteristics of information perception and the emergence of fragmented thinking. This has created a new person, to whom the application of old familiar teaching methods does not give the necessary results in their changed activities[8].

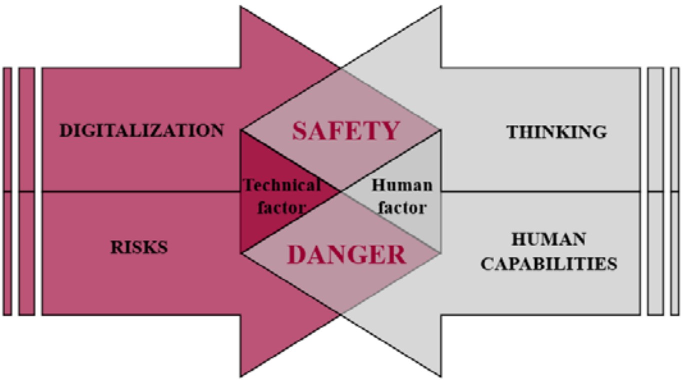

Fig. 1. Planes that form hazards.

3) *Human factor*. The current approach to security is "security problems are usually problems of specialists". However, security is a complex problem in which every person plays a vital role at every stage, and problems are

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[6] Parasuraman R., Mehta R. Neuroergonomics: a review of applications to physical and cognitive work. *Frontiers in Human Neuroscience*. 2013. V.7(889). P. 1–10. https://doi.org/10.3389/fnhum.2013.00889

[7] Fedota J.R., Parasuraman R. Neuroergonomics and human error. *Theoretical Issues in Ergonomics Science*. 2010. V.11(5). P. 402–421. DOI: 10.1080/14639220902853104

[8] Mygal V., Mygal G., Mygal S. Cognitive Space for Online and Offline Learning: A Convergent Approach. *The Educational Review, USA*. 2022. V.6(4). P. 109–123. DOI: http://dx.doi.org/10.26855/er.2022.04.001

created by the influence of the human factor on the security of complex systems.

4) *Thinking*. Today, there is an almost complete absence of security thinking among modern people (citizens, specialists, design engineers, managers, etc.). This trend is multifactorial, it is generated by anomalous trust in the automated digital world, a low level of security culture in society, mentality and other factors.

What's happening today? That is, there is a problem in clearly understanding what education is necessary for a person who must solve the problem of safety/sustainability/viability of the most complex systems built on a combination of human-machine interaction, artificial intelligence, and robots. The consequence is that in the educational space of Ukraine, there are practically no disciplines that can provide applicants with knowledge and skills to reduce the risks of the human factor on the safety of simple and complex socio-technical systems. As a result, there is a lack of awareness of a modern design specialist about the existence of a person in simple and complex socio-technical systems (technological, production, sociological, environmental) and, ultimately, low viability of a person as a system, collectives, organizations, and country.

What should happen? Today, designers' creativity is being transformed by the system of new technologies, revolutionary technological changes, and a radical revision of civilizational strategies. The emergence of Industry 4.0. and Industry 5.0, digital ecosystems and digital workplaces, robots, cobots, and artificial intelligence have exacerbated the problem of adequate training of specialists to create viable systems and the human habitat of the future. It is necessary to form and develop a certain type of engineering thinking, which is the most important component of modern human activity – engineering, management, social[9].

Ukraine's integration into the EU in the field of sustainable development involves the implementation of national and international programs aimed at public and personal awareness of security principles and concepts in all spheres of life: education, transport, medical services, production, management, design, everyday life, etc. The transition from traditional approaches based on risk response to a predictive proactive approach based on the design of complex systems, taking into account the influence and role of humans in these systems, following the European example, is one such program. This requires rethinking and changes in the further development of Ukraine, especially in the context of global problems and crises of the

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[9] Mygal G., Protasenko O. Designing human-machine systems: transformation of a designer's thinking. *Bulletin of the National Technical University "KhPI"*. Series: New Solutions in Modern Technologies. 2023. V. 4(18). P. 27–35. https://doi.org/10.20998/2413-4295.2023.04.04

country's post-war reconstruction. It is also important to take into account the changes occurring in the psychophysiological and cognitive capabilities of modern man in the context of the current level of digitalization and the development of information and communication technologies.

Educating young people and retraining adults on European security principles, the foundations of sustainability, and human-centricity are the keys to preserving and developing a viable society[10]. Our challenge is to ensure the viability of the individual through the design of viable systems and increase the viability of society. Solving the security problems of society requires changes in worldview, thinking, values, norms, and culture.

1. The problem of the human factor in complex systems. The human factor at the center: safety, sustainability, and adaptation to the future

Hybridity of modern complex systems. Modern systems are complex technological and social structures that ensure specific processes and operations' efficiency, reliability, and safety. They play an essential role in ensuring the mobility of society and the development of the economy. In them, the human factor plays a critical role[11]. Vehicles, information systems, security systems, maintenance systems, management and logistics systems, energy and medical systems, infrastructure and its components are complex human-machine systems. They exist thanks to human potential (intelligence, cognitive capabilities, psychophysiological properties), technological potential (transport, machinery, equipment, infrastructure), and their interaction (control, service, logistics technologies). The development of autonomous systems, hybrid technologies, intelligent systems, information and communication technologies, security systems, and systems for warning of dangerous situations requires special hybrid thinking and hybrid approaches.

However, all efforts to increase the reliability and safety of any systems (technical, energy, economic, social) encounter such complex issues as human error, deliberately wrong decisions, inconsistencies in human physical capabilities, cognitive distortions, inherited properties, and formed qualities. That is, the human factor is an obstacle to the creation of stable and safe systems. The human factor explains 70–80% of accidents and disasters

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[10] Cortese, A. D. The Critical Role of Higher Education in Creating a Sustainable Future. Planning for Higher Education. 2003. V. 31(3). P. 15–22. https://www.redcampussustentable.cl/wp-content/uploads/2022/07/6-Cortese CriticalRoleOfHE.pdf

[11] Mygal G. Problems of the human factor in transport systems. *Transport technology*. 2024. V. 5. Number 1. P. 31–43. https://doi.org/10.23939/tt2024.01.031

in aviation and water transport, more than 90% of cases in motor transport, and about 50% of cases in rail transport[12].

For many years, ergonomics has noted an increase in the frequency of human errors due to the lag of human capabilities from the level of technical equipment. The complexity of systems leads to a rise in the "price" of human error. The complexity and multi-vector nature of the human factor problem increases with the increase in the complexity of systems. Automation and digitalization were supposed to reduce the likelihood of human errors but led to their appearance at a new level, cognitive. In autonomous systems, the problem of the human factor is still relevant[13]. This is the problem of human trust in technology, the problem of the illusion of security, the ethical and legal aspects of automation and the use of artificial intelligence, and the increase in cognitive load. Automation leads to decreased human attention, the removal of responsibility, and the transfer of control.

Ensuring the reliability and efficiency of complex systems requires a special approach that considers technical innovations and organizational and structural changes through the prism of a person and his mental, physical, and social essence. A hybrid approach is needed to solve hybrid problems in complex hybrid systems.

Therefore, systemic efforts at the level of education, technology, infrastructure, management, and human behavior can significantly improve the reliability of complex systems. Understanding safety culture, ergonomic design, timely detection of ergonomic deficiencies in systems and ergonomic auditing, human factors principles –all this becomes especially important for the safety of complex systems.

Evolution of interest in the concept of human factors. The concept of the "human factor" in various industries has a long history of development, which emphasizes the importance of man’s role in the processes of design, operation, and interaction with technical systems. The first wave of interest in considering the human factor arose in the late 60s of the twentieth century in connection with the study of human-machine systems and the awareness of the problems of human-machine interaction. At the same time, the human operator is perceived as both a subject of control and an object of power. British ergonomics specialist Brian Shakel offers the following periodization of the development of ergonomics (Fig. 2).

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[12] Mygal G. The problem of human factors in unmanned systems. *Scientific Journal of Polonia University*. 2022. V. 52(3). P. 237–245. https://doi.org/10.23856/5229

[13] Mygal G., Mygal V. Interdisciplinary approach to the human factor problem. Municipal economy of cities. Series: Engineering science and architecture. 2020. Vol. 3, # 156. P. 149–157. DOI 10.33042/2522-1809-2020-3-156-149–157

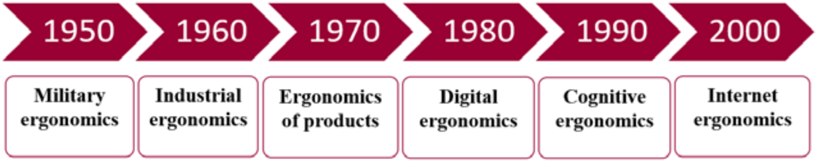

Fig. 2. Periodization of the development of ergonomics, according to Brian Shakel

Ideas about the influence of humans on technical industrial systems began to take shape at the beginning of the 20th century. The first theorists of quality and scientific management, such as F. Taylor and E. Deming, emphasized the importance of human resources, their skills, and work organization for productivity. During World War II, aviation accidents revealed the need to train pilots and design cockpits, instruments, and interfaces for safety and flight efficiency. In the 1950s-1980s, industry research focused on optimizing work and reducing human errors, influencing the design of workplaces and equipment. In the 1990s, after the Chornobyl disaster, the vital contribution of the human factor to the safety of critical systems became clear. This led to changes in approaches to ensuring safety and training personnel. Today, the concept of the human factor is integrated into the design of technical systems and constantly expands with the development of autonomous technologies, digital interfaces, and artificial intelligence.

European experience. Transferring European expertise is one of the tasks that are of priority in educating young people. In Ukraine, a concept of sustainable development until 2030 has been developed by the Resolution adopted by the UN General Assembly in 2015. Teaching European studies and using European principles for learning students should be among the first things on Ukraine’s path to the EU.

Despite the European and global trend towards interest and teaching of disciplines aimed at studying the human factor, the existing educational and scientific approaches taking into account European experience and innovative methods and solutions for increasing the viability of society are not fully taken into account in modern courses and scientific developments of departments of Ukrainian universities. This leads to an increase in demand and personal interest of specialists in such issues.

The demand for interdisciplinary knowledge and skills is growing, as modern technologies and systems require specialists of a new formation with broader competencies. This is reflected in the creation of new technologies that integrate the achievements of various sciences, ensuring high efficiency. However, training in fields such as mechanical engineering, production, and transport often needs to take these needs into account. Interdisciplinary knowledge is required to create complex reliable systems. One of the essential professional skills that an engineer needs to master during his studies in higher education institutions is the ability to identify risks, know how to prevent risks, and minimize negative consequences associated with the human factor. Modern educational programs for training engineers include disciplines aimed at studying safety issues. However, within the framework of these disciplines, students often do not acquire the skills to research and analyze the reasons that affect the level of safety. This negatively affects the quality of their training. Unfortunately, in educational institutions of Ukraine, disciplines aimed at creating a system of knowledge about the influence of the human factor on the safety of complex systems and taking it into account when designing are insufficiently represented.

Human factor engineering. However, today the problem of ensuring the safety of complex systems can be effectively solved already at the stage of their design since taking into account the human factor significantly increases the reliability and efficiency of ergatic systems. It is this direction of cognitive perception of technologies that underlies the academic discipline "Human Factors Engineering" which is taught in most technical universities in Europe and the USA[14]. There are subtle differences between human factors engineering, engineering psychology, and ergonomics. Ergonomics is usually viewed as a design discipline focused on standards and norms. Human factors engineering, on the other hand, builds on engineering knowledge and introduces students to the fundamental principles of behavioral science, physics, and engineering concepts. This knowledge is used to create reliable human-machine systems, which is the main field of human factors engineering. It should also be noted that human factors engineering is not the only discipline taught in educational institutions worldwide to equip students with the necessary safety skills (Figure 3). Bachelor's, master's, and doctoral programs in human factors engineering have also been established and are in demand[15]. When training specialists of this profile, the primary attention is focused on research and analysis of problems of psychological characteristics of a person, his psychophysiological limitations, the level of awareness and motivation of employees, their desire to use their resources and knowledge as efficiently as

[14] Lee J. D., Wickens C. D., Liu Y., & Boyle L. N. Designing for People: An Introduction to Human Factors Engineering (3rd ed.). CreateSpace. 2017. https://www.researchgate.net/publication/319402797

[15] De Felice F., Petrillo A. Human Factors and Reliability Engineering for Safety and Security in Critical Infrastructures. Springer International Publishing. 2018. 263 p.

possible. There are commercial offers of certified educational courses, for example, from Nexus at Michigan Engineering[16].

Human factors engineering is a branch of knowledge that combines the systemic principles of the functioning of organic systems and the principles of human existence in the ergatic system, its capabilities, and its limitations. It plays a vital role for engineers, developers, designers, and managers, who must take into account the peculiarities of human-machine interaction, activity style, and environmental impact when designing. The main goal of this discipline is to ensure the efficiency of human work in the "man – technology – environment" system at all stages of the life cycle from design to operation. The experience of other countries shows that implementing this discipline contributes to increasing the level of industrial safety and turning safety standards into an effective operating tool.

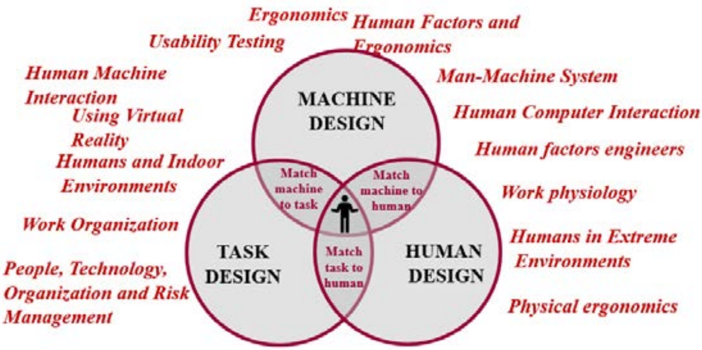

Fig. 3. The diversity of educational offerings in the world regarding the human factor

The main emphasis of the discipline "Human Factors Engineering" is on taking into account the psychophysiological characteristics of a person when developing ergative systems. These systems involve people, tools, and technologies, as well as the working environment to ensure the safety and efficiency of activities. In essence, it is the application of knowledge about the limitations of human nature to design equipment, systems, and work methods in order to increase the safety, reliability, and efficiency of complex systems. This discipline is necessary for any modern engineer who is engaged in the design and commissioning of technical systems. It helps to consider the peculiarities of human-machine interaction, the style of activity, and the influence of environmental stress factors. A key element is the

[16] URL: https://nexus.engin.umich.edu/pro-ed/human-factors-engineering/

consideration of psychophysiological, mental, biomechanical, anthropometric, and other human characteristics when designing systems and technologies. For this, human factors engineering uses the following components: cognitive ergonomics, neuroergonomics, cognitive psychology, human bioengineering, and other sciences. This unique combination of engineering sciences, information technology, psychology, medical diagnostics, neuro– and cognitive sciences allows us to ensure the safety, reliability, and sustainability of complex human-machine systems, human-dependent technologies, and processes.

The ideology of the interdisciplinary course on the human factor. We propose to fill this niche with a multidisciplinary course aimed at increasing the viability of organizations, systems and society by transforming the thinking of a modern specialist and citizen in Ukraine on security issues and the role of the human factor in it. The existence of a course that disseminates European experience in the educational process and world scientific ideas is extremely important as one of the steps of internationalization of the educational process.

In our opinion, an interdisciplinary course aimed at increasing the viability of organizations, systems, and society should contain a triad of goals. At the first stage – acquaintance with the field of human factor engineering and the concepts of safety and the human factor, which underlie the reliability of simple and complex dynamic human-machine systems. The second phase introduces the basic principles of human factors, basic behavioral sciences, physical sciences, and engineering concepts used in the field to create reliable human-machine systems. The third phase focuses on advanced topics in human factors design to create reliable human-machine systems.

The introduction of an academic discipline dedicated to human factors engineering into the training program of students is critically important for improving their qualifications. This will contribute to the effective training of specialists who design and operate technologies and systems. Human factors engineering is an interdisciplinary view of human capabilities in an ergative system at all stages of its life cycle. For specialists involved in the design and decision-making in dynamic systems, studying the principles of viability of complex systems is necessary for creating safe conditions in the workplace and using a systems approach to ensure safety.

Mastering in practice the principles and concepts of ensuring the viability of complex systems for specialists involved in the design, operation, and decision-making in complex dynamic systems is a necessary condition for creating safe conditions for activity in the workplace, and understanding their close dependence on the characteristics and capabilities of a person, as the main link in complex ergatic systems, allows us to speak about the application of a systemic approach in solving safety issues.

In any field of activity, the safety and effectiveness of systems depend on their consistency with the psychophysiological and cognitive capabilities of a person (driver, pilot, dispatcher, designer, manager) who makes key decisions. This emphasizes the importance of taking into account the human factor for the reliability and stability of systems that are designed and operated by a person.

Such an interdisciplinary course should be based on a triad of interrelated concepts – human-centricity, safety, and viability. This allows achieving the main long-term goal – to increase the education of the broad masses of the country's population in matters of safety and the human factor and to ensure a triad of goals:

1) "preservation of man and society" – increasing the level of safety culture in society, based on knowledge of the principles of safety and the human factor and the preservation of human potential and society for the restoration of post-war Ukraine;

2) "transformation of the thinking of a modern engineer" – the development of hybrid thinking and worldview based on eco-ergonomic and strategic design thinking;

3) "organizational growth" – design thinking is integral to achieving organizational growth. Creating organizational change in society is not a linear process. Implementing innovative ideas requires transformational leadership and a human-centered approach to design.

Thanks to this practical interdisciplinary course, students will be able to gain important design experience and learn to solve a wide range of engineering and ergonomic problems related to the human factor. The implementation of the course will lead to higher quality of designed systems and human activity in these systems, as well as higher quality of products and services. For companies and enterprises, this is a way to improve processes, better meet customer demand, and achieve big goals. Regardless of the field of knowledge, the knowledge and skills after completing this course will lead to measurable positive results.

2. Transforming the designer's mindset to create viable systems

2.1. Design thinking is the path to creating viable systems

Engineering thinking and the human factor. Modern systems are complex technological and social structures that must be efficient, safe, and economical. Ensuring their safety requires a transdisciplinary approach, as modern systems and technologies require interdisciplinary solutions and innovations to improve safety, efficiency, and sustainability. This applies to various fields such as medicine, transport, human factors, infrastructure, management and maintenance. The design and management of such systems require a broad worldview and convergence of knowledge, covering safety issues (e.g. road safety, vehicle safety, environmental safety), transport infrastructure issues (integration of different modes of transport, logistics), environmental issues, information flow management issues (data management, digital technologies, digital transformation), economic and social issues. This leads to a rapid change in the requirements for people working in such complex systems.

Modern technologies and systems require specialists of a new formation, possessing interdisciplinary knowledge, located at the intersection of different sciences. A contemporary specialist must compete not only with other people, but also with artificial intelligence and robots. To do this, it is necessary to develop hybrid thinking based on an ergonomic approach, environmental awareness, and engineering knowledge. Such an approach is critically important for specialists who design human-machine systems[17].

The key elements of hybrid engineering thinking are the ability to see and resolve contradictions (logical, technical, physical) and a broad scientific worldview, which is possible only through interdisciplinary knowledge.

This can only be achieved through a transdisciplinary approach to combining engineering sciences, information technologies, psychology, bioengineering, neuro– and cognitive sciences, which allows for creating conditions for ensuring the safety, reliability and sustainability of complex human-machine systems that are designed and operated[18] [19] [20].

In the era of digital transformation, engineering thinking is becoming multidisciplinary and integrated. Engineers are actively using machine learning, artificial intelligence, and data analytics to optimize design, resource management, and decision-making. In addition, sustainability, safety, and social aspects in design are coming to the fore. This means that modern engineers must consider not only technical and economic parameters but also the impact of their decisions on the environment and society as a whole. Thus, engineering thinking is becoming increasingly complex,

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[17] Mygal V. P., Mygal G. V. and Mygal S.P. AI: Unique Opportunities and Global Challenges – A Hybrid Approach to Modeling Reality and Its Perception. Jul 4. 2024. *Qeios* ID: https://doi.org/10.32388/GIJ3RI.4

[18] Bernstein J. H. Transdisciplinarity: A Review of Its Origins, Development, and Current Issues. *Journal of Research Practice.* 2015. V.11(1), R1. https://www.researchgate.net/publication/282285072

[19] Transdisciplinarity: stimulating synergies, integrating knowledge. International Symposium on Transdisciplinarity, UNESCO, Division of Philosophy and Ethics. Val-d'Oise, France. 1998. P. 37–38. https://unesdoc.unesco.org/ark:/48223/pf0000114694

[20] Mygal V., Mygal G., Mygal S. Transdisciplinary convergent approach – human factor. *Radioelectronic and computer systems.* 2021. #4(100). P. 7–21. DOI: 10.32620/reks.2021.4.01

requiring a wide range of knowledge and skills from different fields of science and technology.

Evolution of ergonomic views on safety and the human factor. Japanese scientists, in collaboration with American scientists, in the 1950s proved the need to create and develop a certain "quality" mindset in all participants in the production process to ensure quality and technological breakthrough (William Edward Deming, Joseph M. Juran, Philip Crosby, Armand W. Feigenbaum, Kaoru Ishikawa, Genichi Taguchi, Shigeo Shingo, Frederick W. Taylor, Joseph M. Juran).

In the period from 1990 to 2000, the analysis of the Chernobyl disaster and its connection with the safety culture showed the importance of developing a "safety" mindset. It turned out that the human factor plays a critical role in the safety and development of catastrophic events, such as the Chernobyl disaster and other accidents.

Organizational ergonomics and human factor engineering have become necessary directions for mastering the human factor and increasing the safety of complex systems in critical areas of life. Their development was aimed at reducing risks and preventing similar disasters in the future.

The problem of safety culture has been studied by many scientists and specialists in the fields of safety, labor protection, psychology, sociology, and other related fields. British psychologist James Reason made a significant contribution to the study of the human safety factor, and also developed a model of the "accident ladder". American psychologists Edward Deci and Richard Ryan studied motivation and its connection with safe behavior in the workplace. Sidney Dekker is a human factors and safety researcher and author of works on human error and safety culture in air and other modes of transportation. Erik Hollnagel is a safety and risk management researcher and author of the theory of "next-generation safety management". Research in this field is conducted in different countries of the world and includes both academic research and practical aspects related to the development of safety policies and safety programs in the workplace.

During the same period, such directions as ergoecology and green ergonomics appeared in ergonomics. Their fundamental principles are the study and analysis of the interaction of the human-machine system with the environment. The emergence of ergonomics of information technologies was aimed at developing the principles of creating ergonomic digital products. Today, the digitalization of work operations affects the issue of occupational safety. Digital technologies have changed the approach to work and the requirements for its protection and led to the emergence of a new labor concept, "Work 4.0". The creation of the concept "Work 4.0" became the impetus for the transition of ergonomics to a new stage of development.

The key trend of this stage is a comprehensive study of the problems of human-machine interaction in the digital environment. The evolution of the understanding of the human factor emphasizes the constant desire to improve human interaction with technical systems, prevent errors, increase safety and ensure optimal working conditions (Fig. 4). But we see that the constant growth of requirements for technology, people, processes, and systems has not been able to solve safety problems, and some technological innovations have led to the development of new aspects of the problems (for example, the problem of automation has led to the emergence of new human operator errors).

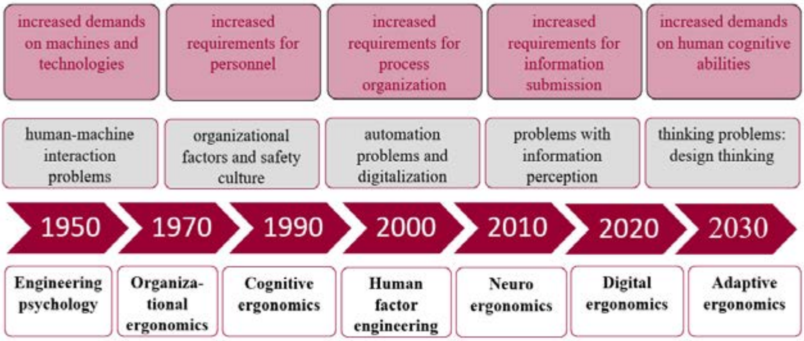

Fig. 4. Evolution of views and priorities regarding the human factor problem

Design thinking. Today, design thinking is increasingly being discussed, which is based on the cognitive abilities, experience, predictive and practical knowledge and skills of the designer[21]. It should be noted that design thinking is a methodology for solving complex problems of various nature – engineering, business and other tasks, and is based on a balance of creativity and analysis.

Design thinking is necessary for an important goal – coordinating human needs, resources, and technical and technological capabilities. Design thinking is based on the ability to be intuitive, to identify patterns, to create

[21] Mygal S., Mygal V., & Mygal G. Strategy for the development of design education in post-war Ukraine: transdisciplinary approach. *Bulletin of Lviv Polytechnic National University*. Series of Architecture. 2023. V. 2(10). P. 119–129. https://doi.org/10.23939/sa2023.02.119

ideas based on emotion and functionality[22] [23] [24] [25] [26]. It is simultaneously science and creativity, emotional and rational, physical and mental.

Design thinking[27] – it is a particular way of solving a problem and looking at it. Design thinking is the key to solving complex problems, to creative and innovative activities in science – when looking for similarities between different things; in art – when looking for differences between things that are similar; in design – when creating a possible whole from impossible parts. In essence, it is an approach to problem-solving that has crystallized in the field of design and combines a holistic, user-centered approach with rational and analytical research – all with the aim of creating innovative solutions.

Eco-ergonomic thinking. In our works[28] (Mygal V. et al., The Educational Review, 2022; Mygal G., Protasenko O. Designing human-machine systems…, 2023; Mygal V. et al., Qeios, 2024) it is shown that special attention should be paid to the development of specific eco-ergonomic thinking, which is a necessary element of a safety culture. A necessary feature of eco-ergonomic thinking is the recognition of the exceptional priority of environmental problems and human-machine interaction about others among all problems of human activity. Combined with a human-centric approach and ecological thinking, ergonomic thinking creates a space for forming a safety culture. The human-centric approach, on which ergonomics, engineering psychology, usability, UA/UX design, and a dozen disciplines and educational programs at world engineering universities are based, is the basis for risk-oriented thinking. The concept of a human-centric approach is based on a person, a worker, a manager, a consumer, and their interests and capabilities. This allows us to understand the processes

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[26] Camacho M. David Kelley: From Design to Design Thinking at Stanford and IDEO. She Ji: *The Journal of Design, Economics, and Innovation.* 2016. V. 2(1). P. 88–101. https://doi.org/10.1016/j.sheji.2016.01.009

[27] Altraide D. New thinking: from Einstein to artificial intelligence, the science and technology that transformed our world. Coral Gables: mango publishing. 2019.

[28] Mygal G., Protasenko O., Kobrina N., Mykhailova E. Ergonomic thinking in the design of human-machine systems. *Scientific bulletin of National Technical University "KhPI*". 2023. № 1 (15). P. 42-52. doi:10.20998/2413-4295.2023.01.06

of human-machine interaction; to be able to predict risks in these systems and plan the development of systems with these risks in mind.

Strategic thinking and vision. The development of design thinking towards risk identification, prediction and forecasting of consequences is a key aspect of Strategic thinking and vision[29]. Forward thinking and strategic foresight are the basis for solving future problems, designing future systems and organizing human activity within them. This approach involves developing and searching for all possible scenarios of events and preparing for them, regardless of their probability. This approach allows you to create systems and environments that are competitive, reliable, and safe, ensuring their viability and sustainability. This thinking forms the basis for ensuring safety and reliability in future technological and social systems, allowing them to function effectively even in unpredictable conditions.

Hybrid thinking and hybrid worldview. The 21st century has brought hybrid thinking, hybrid warfare, and hybrid learning – the next step in the philosophy of perceiving the world around us and designing systems within it[30]. This is due to the increasing complexity of systems and problems.

Hybrid thinking is a concept that involves combining different types of thinking and approaches to solving problems to achieve more effective results. It includes a combination of elements of analytical, creative, systemic, critical, and intuitive thinking. Examples of hybrid thinking are: analytical-creative thinking (the ability to analyze information analytically and simultaneously apply creative methods to find innovative solutions); critical-system thinking (the ability to evaluate a situation critically and simultaneously consider it from a systemic point of view, taking into account relationships and consequences); transdisciplinary thinking; integration of rationality and emotionality (combining logical, rational thinking with emotional intelligence to make more balanced and informed decisions). This concept emphasizes the importance of flexibility in thinking and the ability to adapt to various scenarios and conditions. Fig. 5 shows the onion model of the hierarchy of thinking types.

Therefore, to ensure the security of modern systems, convergence of knowledge and the use of interdisciplinary approaches and strategies are required. For life in new conditions, it is necessary to develop new design thinking and new tools in order to learn to think, live, and act in accordance with the conditions of the time. After all, the beginning of the 21st century was marked by a change in paradigmatic attitudes in education, which are characterized by a reorientation from technology to man, his ways of

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thinking, and methods of cognition. The whole system of views on the development of complex human-machine systems and the role of man in them is important.

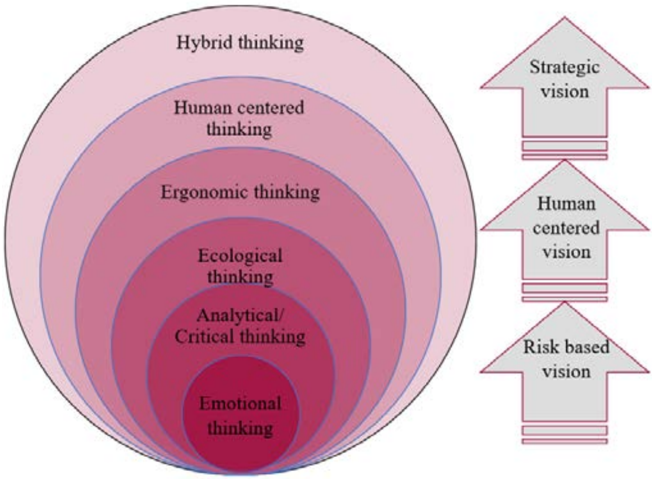

Fig. 5. Onion model of the hierarchy of thinking types[31]

2.2. Development of a new type of thinking – metaergonomic thinking

The synergistic effect is achieved by combining types of thinking into a single system. Effective and competitive design is impossible today without a complex-systemic[32]. Thus, when designing complex systems (control systems, machinery, equipment, furniture, etc.), the developer must first of all see the person and his existence in this system. In the era of rapid development of technologies and opportunities, metaergonomic thinking gives designers an advantage and competitiveness. The modified model of metaergonomic thinking shows the intersection of the human and technical planes and the birth of emergent qualities – viability, feasibility and desirability (Fig. 6). The central idea is to maintain a balance between ecological principles (existence in the ecosystem), ergonomic principles (human activity in the ecosystem) and human factor principles (human errors and decision-making).

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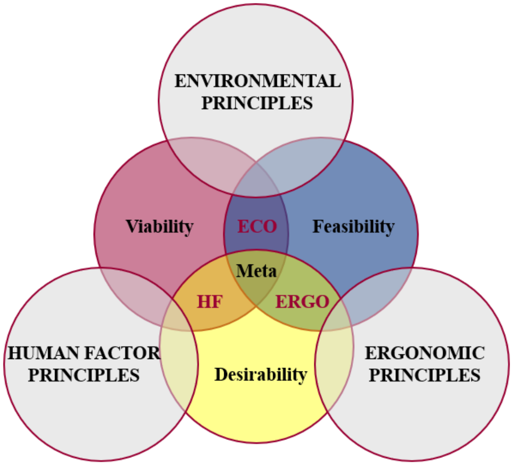

Fig. 6. Structure of relationships in the metaergonomic thinking system for creating viable systems

What is important is not only the adaptation of the system to the capabilities and limitations of a person but also a whole system of views on the development of complex human-machine systems and the role of a person in them; understanding the complex processes of not only human-machine interaction but also human-robot interaction; the ability not only to predict risks in these systems but also to purposefully go one step ahead and predict possible challenges and plan the development of complex systems taking these challenges into account. A person must be selected, trained, provided with information, provided with e-support, controlled, and removed where it is justified and possible. The system itself must be designed to be viable and resistant to the functional state, actions, and intentions of a person. That is, the viability of complex systems is ensured by the designer.

3. Transforming Education: Basic Concepts Necessary for Growing Engineering Maturity and Creating Viable Systems

Two approaches to creating fault-tolerant systems. There are a number of approaches, methods, and strategies to reduce the risks of human error and ensure the viability of complex systems. For a long time, the basic approach was based on the individuality of a person, which was focused on the mistakes of individual people: that is, it was believed that all problems are due to "bad" people (illiteracy, negligence, inexperience, etc.). However, decades of analysis of aviation and man-made accident statistics have shown the effectiveness of a predictive approach and strategic thinking when designing complex systems. The strategy for preventing operator errors is based on eliminating errors in the system at the design stage, and the predictive approach allows you to predict their occurrence. Thus, the focus has shifted from the person-executor to the person-designer. That is, the creation of fault-tolerant systems is the result of applying a systems approach, which provides increased resistance to human errors. This is an attempt to predict the worst-case scenarios and to foresee the possibilities of avoiding their development.

The concept of fallibility. The basic concept in human factor engineering is "human error", which today is perceived not as a cause, but as a consequence of non-systemic learning and process organization. According to the theory of "Practical bias" by Scott A. Snook, the real viability of complex systems differs significantly from the expected one since it is based on assumptions that are difficult to predict precisely because of the influence of the human factor (Fig. 7). Such a shift in real properties is inevitable in the system. Taking into account the influence of the human factor can reduce this "practical bias" and bring the result closer to the predicted one. A person adds an element of unpredictability to the system due to his mistakes, ignorance, and lack of safety culture. Human error at any stage of the life cycle of a system or technology is one of the key reasons for the emergence of risky situations. Designing a viable system involves identifying possible hidden failures and creating conditions where human error is impossible or does not have serious consequences.

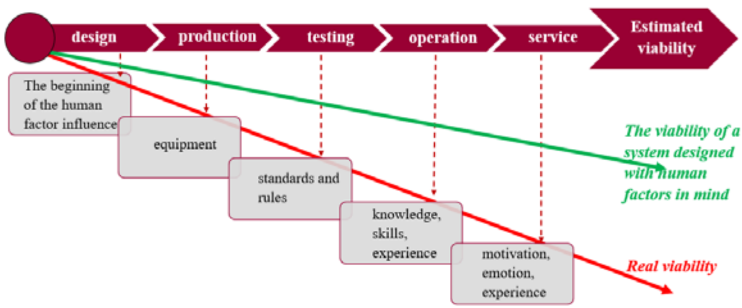

Fig. 7. Practical offset of expected system viability parameters.

It is very important to realize that mistakes are inevitable, but not all mistakes are bad. Harvard Business School professor Amy Edmondson, in her book "Right Kind of Wrong", chosen as the book of 2023 by the Financial Times and called "The Handbook of Right Mistakes", showed that there are two categories of mistakes. The first category of mistakes is mistakes that can be prevented. You have to work hard to do this. It is a bad strategy if mistakes occur in "known territory" because, thanks to knowledge and actions, this can be avoided. The second category of mistakes is "smart" mistakes, which are undesirable, unanticipated results of risky actions. Risks are always taken in new "territory", where there are no instructions and rules yet. So you need to train yourself to take risks because the task of an intelligent mistake is to gain new knowledge, regardless of whether this lesson will be good or bad.

The concept of human factor management. Thus, the concept of error management is based on the classification of errors. Fig. 8 shows a model of the error ecosystem, which reflects two main directions – predicted and unpredicted errors.

Accordingly, the concept of human factor management can be described in three stages: 1) removable dangerous factors are eliminated; 2) normalized dangerous factors are regulated; 3) means of protection are developed against the action of constant (systematic) factors. Systematic factors have the most significant impact on the safety of systems. Analysis of the statistical distribution of random (10%) and systematic (90%) risk factors shows that the vast majority of systematic errors are the result of human activity.

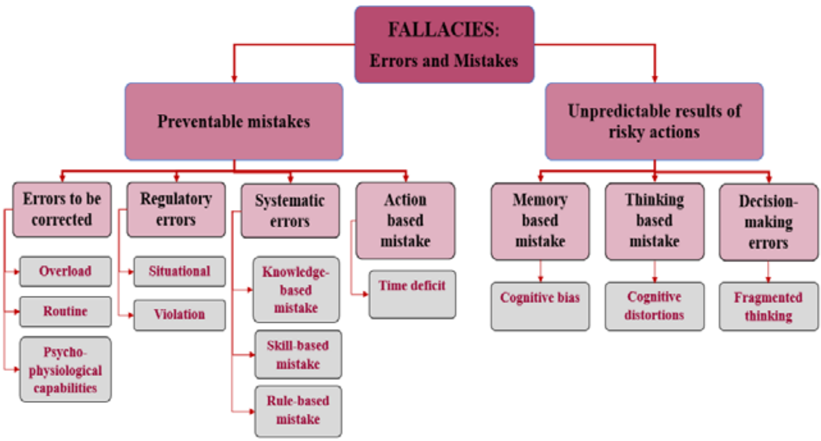

Fig. 8. The ecosystem of human errors.

Note that it is the organizational factor that has a decisive influence on the functioning of complex systems in extreme conditions. It is under the influence of stress factors that all typical problems of the human factor begin to manifest themselves – random errors of memory or actions, errors of ignorance and incompetence; and the consequences of human fatigue/ stress/illness. And even organizational errors are created by people. A certain closed circle of problems associated with the phenomenon of the human factor is obvious.

Safety culture concept. The main idea of this concept is that safety should be everyone's responsibility and a core value, not just an obligation or burdensome expense. Safety culture is a set of norms, beliefs, values, attitudes and assumptions in the field of safety, which are reflected in the daily activities of the organization and the behavior of all its departments and personnel. The main thing is the attitude to safety as a priority, as well as public awareness of the responsibility of each member of the organization for ensuring safety in the working environment. Safety culture structurally has two interrelated components: 1) the construction of conditions, goals, and policies of the organization, which is the responsibility of management; 2) understanding and awareness by personnel of all levels of their responsibility for safety. This connection can only be ensured by the transdisciplinary knowledge of specialists at all levels – a combination of engineering sciences, information technologies, psychology, bioengineering, neuro– and cognitive sciences. This allows for the creation of conditions that ensure the safety, reliability, and stability of complex human-machine systems that are designed and operated.

Programming a model of safe human behavior. The formation of a safety culture is based on programming a model of safe human behavior, which can be illustrated by a modified Heinrich pyramid (Fig. 9). According to the pyramid presented in the figure, the basis for creating safe working conditions is the mastery by employees of the concept of the "human factor" and its importance for ensuring safety.

The concept of management in the form of an iceberg model is gaining a new interpretation. We do not see the thousands of decisions and actions that lead to critical errors or accidents, but we must ensure that they are implemented in such a way that the risk of a mistake or accident does not become catastrophic for the system, preserving its viability. This means that a significant part of management decisions and actions remains "underwater," invisible. It is these invisible decisions that are key to preventing catastrophic consequences and ensuring stable system operation. Preventing accidents and errors involves a systematic approach to every aspect of activity, where even the smallest actions can have a great impact on the safety and efficiency of the system.

Edwards Deming quality cycle. This can be achieved by using the Deming quality cycle, which is an algorithm of actions for managing a process/system and achieving its goals (Fig. 10).

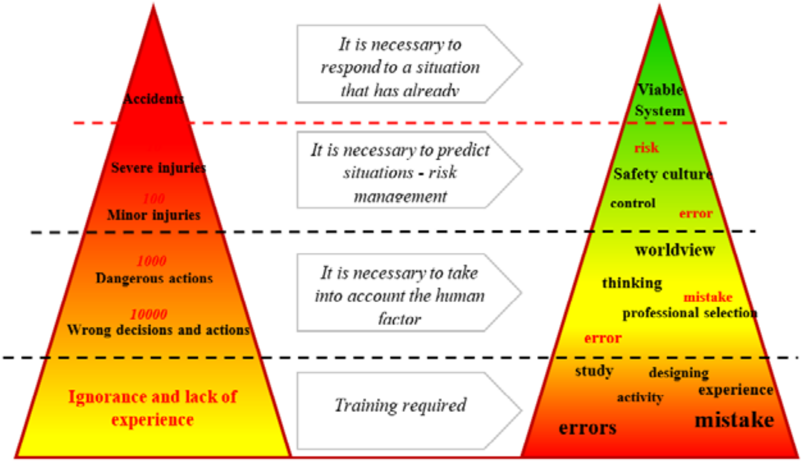

Fig. 9. Modified Heinrich`s pyramid as a model of problem development into a hazardous event (a) and reflection of the concept of human factor management in the form of an iceberg model (b)

Fig. 10. Deming's quality cycle

Security strategies in complex technical systems. The human factor greatly influences the success and failure of measures to ensure the security and stability of systems and technologies, enterprises and services, and information systems. The proven possibility of unpredictability of human actions can destroy the most intelligent system. If the security of the system is overlooked by the developer at the design stage, the system becomes vulnerable. Failure to take into account the laws of interaction of the components of a complex system is a direct path to creating conditions that provoke human error and then an accident. Security strategies in complex technical systems are developed to prevent, identify, and manage risks associated with their operation and functioning.

Risk management strategies can be systematized as follows:

1) response strategy – responding to problems and risks that have already been realized;

2) error mitigation strategy – applied directly by reducing or eliminating factors contributing to the occurrence of an error: active monitoring and feedback; alerts and alarms; training and simulations; error management training;

3) error prevention strategy – norming and standardization, human factors in engineering and design; ensuring competence; training and coaching; procedural control; risk identification and assessment activities;

4) interception strategy assumes that an error can be made, therefore its goal is to "intercept" the error before the consequences arise;

5) tolerance strategy – assumes that an error will be made. Accordingly, the system is fully prepared for it, but the consequences will not be destructive, and the system remains stable.

Fig. 11 shows a matrix of the relationship between risk management strategies and approaches to security management of complex systems.

Security Management Approaches	***Risk Management Strategies***				
	response	mitigation	prevention	interception	tolerance
retrospective	elimination of consequences				
retroactive		standardization and regulation			
proactive			eliminating risks during production		
predictive				eliminating design risks	
strategic					willingness to take risks

Fig. 11. Matrix of the relationship between risk management strategies and approaches to security management of complex systems

Today, the tolerance strategy is implemented through smart concepts such as "smart road", "smart car" and "smart transport". These concepts focus on energy efficiency, environmental friendliness, ergonomics, comfort and efficiency using modern IT technologies. The idea of "smart transport" includes: energy efficiency, environmental friendliness, ergonomics, comfort and efficiency. "Smart roads" take into account the human factor and physical limitations of a person, compensating for them through design solutions and technological innovations. In this context, speed sensors, acoustic sensors, IP video surveillance cameras, smart traffic lights, condition/weather monitoring systems and digital signage are used. The goal is to create a road infrastructure that forgives human errors. A safe "smart" car is based on compensating for human shortcomings using the latest technologies. The Vision Zero concept illustrates a strategic approach aimed at achieving zero road fatalities.

Adaptive ergonomics is a modern concept of ergonomic design that implements a tolerance strategy. Adaptive ergonomics has its roots in bionics and is closely related to hybrid thinking. In our works we have shown that the main idea is to make technologies and systems adaptive to human individuality. This means creating hybrid systems and technologies that are able to compensate for human imperfection and in which human error is not a critical factor affecting safety and sustainability.

For example, adaptive ergonomics can be implemented through the following measures: a) when designing the system itself: ensuring modularity and customizability; ensuring technological flexibility; creating an adaptive interface to the preferences and skill level of users; b) when designing the human operator’s workplace: creating an adaptive workplace that can be easily adjusted in ergonomic parameters to the individual requirements of the person; developing systems taking into account the individuality of the human operator, taking into account their different physical, mental and cognitive abilities.

The concept of human factor management in complex systems. Analysis of modern theoretical positions and practical results of research on the problem of the human factor in complex systems allowed us to formulate the main provisions of the concept of human factor management in such systems:

a) human errors are inevitable;

b) professional selection makes it possible to reduce/mitigate errors but not to avoid them;

c) a person is only the perpetrator of an error, but not its source. A person has the right to make a mistake, but the system must be designed in such a way as to prevent him from using this right;

d) there are no wrong people-executors, but there are incorrectly designed systems. Today it is impossible to allow the design and management of complex systems, ignoring basic knowledge about a person;

e) a correctly designed system is flexible, adaptive, stable and viable. It allows for the possibility of human error and has everything necessary so that human errors and their consequences are not critical.

An integral model of the designer's engineering maturity. It is obvious that the designer of human-machine systems, in addition to mastering the necessary professional knowledge, must learn to overcome the inertia of thinking, identify and resolve technical contradictions, generate non-standard technical ideas, master the skills of multi-variant problem solving and their objective evaluation. It is important to understand and master the logic of human-machine interaction; design through the prism of human factors analysis (industrial, bioengineering, systems engineering, software engineering, etc.). In systems of increased danger and risk, it is important to: understand the interaction between technical and social systems; develop complex human-machine systems; manage safety in systems with a high degree of risk. Fig. 12 shows an integral model of the sequential growth of the "engineering maturity" of the designer of complex dynamic systems and their effectiveness, which is reflected in color from red with low efficiency to green with high efficiency.

Thus, the transformation of the thinking of a modern specialist the growth of his engineering maturity to create effective viable systems requires the formation of transdisciplinary hybrid thinking based on the following principles:

1. Transdisciplinary education to understand the connection between different components of the system.

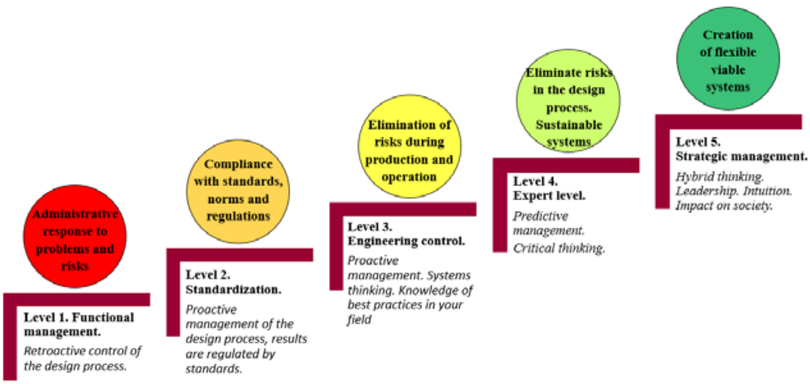

Fig. 12. Five-level integral model of the growth of "engineering maturity" of a designer of complex dynamic systems

2. Gaining experience because working on real projects develops skills in solving real problems.

3. Developing flexible thinking to be able to adapt to changes and consider problems from different perspectives.

4. Developing systems thinking to understand structure and connections.

5. Developing technical and engineering intuition.

6. Stimulating creative thinking to generate new approaches and ideas.

7. Developing technical management skills, because a modern specialist must not only be able to solve technical problems, but also effectively command and manage development processes.

8. Developing ethical thinking to take into account social and cultural aspects.

9. Stimulating continuous education, because technologies and systems are changing.

10. Developing leadership and motivation.

Transforming the thinking of a modern specialist to create effective viable systems requires hybrid solutions – a combination of technical and non-technical skills, as well as an understanding of the systemic aspects of problems and their solutions.

CONCLUSIONS

The development of digital technologies, the use of artificial intelligence and automation have provided unprecedented opportunities to ensure the safety of technologies. The evolution of transdisciplinary ideas shows that the only way to safety is to abandon the concept of separate sciences and develop transdisciplinary research to promote innovation. The activities of a modern engineer should be aimed at creating a safe, effective, and sustainable environment, which lies at the intersection of human factors engineering and dynamic systems engineering. Despite the fact that engineering education is focused on modern technologies, insufficient attention to human factors issues still leads to problems in ensuring safety in complex systems. System designers are not sufficiently aware of the cognitive aspects of human-technology and equipment interaction, which prevents them from properly designing viable systems. This leads to human errors and accidents that could be avoided with a better understanding of human factors. It is important to consider these factors at all stages of technology development and implementation in order to create systems that are not only effective, but also safe.

Analysis of the evolution of approaches to designing complex systems and ensuring their viability proves the need for developers of future systems to transform thinking on a transdisciplinary basis. Design thinking opens up new non-standard solutions to complex problems of human and societal existence and is a key tool for innovation and competition, growth and development. Special attention should be paid to the development of the ergonomic component of thinking in everyone whose activities are related to the life cycle of a complex system because this is a whole system of views on the development of complex human-machine systems and the role of humans in them. This is an understanding of complex processes of human-machine interaction; the ability to predict risks in these systems and develop systems with preliminary consideration of these risks. For a modern specialist, ergonomic thinking, along with ecological and critical thinking, is a sign of education and is the foundation of a highly qualified specialist.

Given the current challenges and needs, the introduction of a discipline dedicated to human factors engineering into the curricula of engineering training in Ukraine is extremely relevant. This discipline should become a mandatory worldview component that will ensure higher qualifications of future specialists in their diverse activities, which include the design and operation of technologies. Such an approach will create the necessary foundation for improving the quality of training of engineering specialists, will help them to better understand the human factor, which is critical for the development of safe, effective and viable systems. The integration of this knowledge will contribute to the formation of engineers capable of responding to modern challenges and ensuring sustainable development of technologies.

SUMMARY

Modern technologies and complex socio-technical systems require specialists of a new formation who have a wide range of interdisciplinary knowledge. The work analyzed the evolution of ergonomic thinking on safety and the human factor. Today, more and more attention is paid to the formation of specific design thinking in the learning process, which is based on the cognitive, predictive and practical knowledge and experience of the designer. This is a whole system of views on the development of complex human-machine systems and the role of man in them; this is an understanding of the complex processes of not only human-machine interaction, but also human-robot interaction; the ability not only to predict risks in these systems, but also to purposefully go one step ahead, to develop complex systems taking into account these challenges. This is reflected in the proposed onion model of the hierarchy of thinking types and, accordingly, in the development of a new type of thinking – metaergonomic thinking.

The activity of a modern engineer should form a safe, effective, and viable environment. The solution to the problem of ensuring the viability of systems lies in the plane of the intersection of human factor engineering and dynamic systems engineering. This requires the formation of a new hybrid, meta-ergonomic thinking and new tools to learn to think, live and act in accordance with the conditions of the time. The paper presents ways of transforming modern education, basic concepts necessary for the growth of

engineering maturity and the creation of viable systems. The transformation of the thinking of a modern engineer to create viable systems requires the formation of transdisciplinary hybrid design thinking and, accordingly, hybrid solutions, a combination of technical and non-technical skills, as well as an understanding of the systemic aspects of problems and their solutions. The programming of a model of safe human behavior is illustrated using a modified Heinrich pyramid. Security strategies in complex technical systems are analyzed, and a matrix of the relationship between risk management strategies and approaches to security management of complex systems is proposed. Design thinking opens up new non-standard solutions to complex problems of human and societal existence and is a key tool for innovation and competition, growth and development. The concept of human factor management in complex systems and an integrated model of the designer's engineering maturity are proposed.

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