CHAPTER 22

THE HUMAN FACTOR IN ENSURING THE VIABILITY AND SUSTAINABILITY OF COMPLEX TECHNICAL SYSTEMS

Mygal G. V.
DOI https://doi.org/10.30525/978-9934-26-653-9-22

INTRODUCTION

In contemporary engineering practice, the concept of sustainability of complex technical systems is traditionally associated primarily with technical characteristics: energy efficiency, resource use, environmental indicators, the level of automation, and technological sophistication. Within the framework of this study, sustainability is considered not as a static characteristic of a technical solution, but as a property of the real use of a system, which is formed through the interaction of technical architecture, design assumptions, and human behaviour during operation. Many systems lose their declared characteristics not due to physical failures or design flaws, but as a result of the specifics of real use. “Green” and formally safe solutions often do not function as intended at the design stage and, over time, may demonstrate reduced effectiveness, the emergence of unsafe operational practices, and gradual degradation of safety. This indicates the need for a broader view of the sustainability of complex technical systems. From this perspective, sustainability appears not only as a set of technical parameters, but as a property of interaction between the technical system, people, and the conditions of its use. In this context, the human is no longer viewed exclusively as a source of errors that should be maximally constrained or replaced by automation, but rather as an active element of the system that determines its actual behaviour in operation.

Complex technical systems, therefore, most often “fail” not at the point where technological capabilities are exhausted, but where real operation begins and the limitations of human capabilities come into play. An energy-efficient system may prove to be unstable in use, intelligent solutions may require excessive cognitive workload, and safety degradation occurs gradually through the adaptations of users and operators to real working conditions. In this context, a human-centred design approach is considered as a tool for ensuring the long-term effectiveness, safety, and sustainability of complex technical systems, rather than as an auxiliary or secondary element of the engineering process.

Thus, a scientific and practical problem arises related to the mismatch between the declared sustainability characteristics of complex technical systems and their actual behaviour at the operational stage. In contemporary engineering and scientific research, the human factor is predominantly considered in a fragmented manner – as an isolated risk element, a source of errors, or a set of limitations that must be compensated for through technical solutions, automation, or regulations. Such an approach inherits a linear design logic, within which it is assumed that a correctly designed system will function according to its intended purpose regardless of the context of its use.

This work shows that bridging this gap is possible only under the condition of engineering operationalisation of the human factor – not as a set of individual human attributes, but as parameters of "human–system" interaction that can be incorporated into assessment models and design decision-making. Real-world operation demonstrates that system behaviour is shaped not only by technical parameters, but also by the ways in which people interact with the system, their adaptations, compromises, informal practices, and cognitive limitations. It is precisely these processes that often determine the long-term viability of a system or, conversely, the gradual degradation of its safety and effectiveness.

In this sense, the human factor acts not as an external source of disturbances, but as an internal mechanism of the evolution of a complex technical system during operation. Ignoring this mechanism leads to a gap between design assumptions about sustainability and the actual behaviour of systems under real conditions of use. The aim of this work is to substantiate the role of the human factor as a key engineering element in ensuring the safety, sustainability, and viability of complex technical systems, as well as to formulate a human-centred approach to the analysis and design of these systems, within which sustainability is considered not as a set of technical characteristics, but as a property of interaction between the technical system, the human, and the operating conditions.

1. Man as a resource for safety, not a source of errors.

1.1. Traditional engineering concept of a person in a system

Within the classical engineering safety paradigm, the human as part of a technical system was for a long time considered primarily as a risk factor. Such an approach emerged in the context of the development of industrial systems, which were characterised by rigidly defined operating modes, relatively stable operating conditions, and a clear separation between the technical system and the operator. Within this logic, safety was associated primarily with the reliability of technical components, compliance with regulatory requirements, and the minimisation of the influence of the human factor.

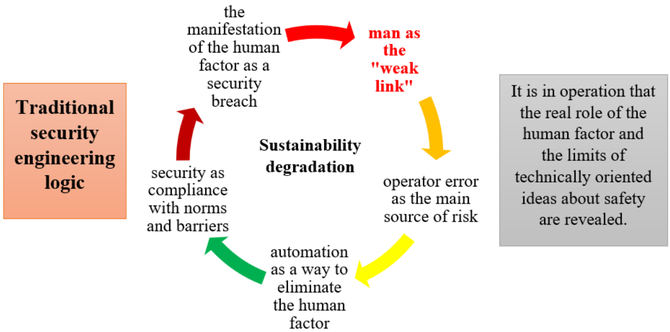

Fig. 1. Idealization of the classical engineering safety paradigm – illustration of the degradation of sustainability due to improper work with the human factor

The central element of this model is the view of the human as the "weak link" of the system. Operator or user errors are interpreted as the primary source of danger, while human behaviour is regarded as unstable, unpredictable, and prone to deviations from prescribed procedures. Accordingly, the task of engineering design is to reduce the dependence of system functioning on human actions or to minimise the space for erroneous decisions. Within this approach, automation is considered the key instrument for improving safety. It is assumed that transferring control functions to technical means makes it possible to eliminate subjective factors, reduce the likelihood of errors, and ensure more stable system operation. The human is thereby gradually shifted to the periphery of the control process, performing the role of an observer or a backup element that intervenes only in the event of failure of automated components. Safety within this paradigm is interpreted as the system's compliance with established norms, standards, and protective barriers. The primary attention is given to the design of technical and organisational protective measures, the development of instructions, regulations, and procedures, as well as to monitoring their compliance. It is assumed that, under conditions of correct design and proper execution of prescribed actions, the system will function safely.

It is important to emphasise that this model is not the result of an underestimation of the human as a professional. On the contrary, it historically emerged as a pragmatic response to the limited capabilities of early technical systems and the need to ensure controllability and predictability of processes. However, with the increasing complexity of technical systems, the level of their integration, and the variability of operating conditions, the limitations of this paradigm become increasingly evident. Within the traditional engineering perspective, safety is achieved by minimising human involvement in system operation. It is precisely this assumption – regarding the desirability of eliminating or maximally limiting the human factor – that serves as the starting point for a further rethinking of the role of the human in ensuring the safety of complex technical systems.

1.2. Limitations of the "human as a source of errors" approach in complex technical systems

Despite its historical expediency, the approach in which the human is viewed primarily as a source of errors demonstrates significant limitations under the conditions of functioning of modern complex technical systems. With the increasing levels of complexity, integration, and dynamism of such systems, it becomes evident that their behaviour cannot be fully described by means of formalised procedures and regulations. One of the key problems is that design assumptions regarding operating conditions rarely fully correspond to reality. Complex technical systems operate in changing environments, under conditions of incomplete information, limited time for decision-making, and conflicting goals. Under such conditions, operators and users are forced to constantly adapt, deviate from formally prescribed procedures, and seek compromises between efficiency, safety, and productivity.

Another significant limitation is the effect of latent safety degradation. An exclusive focus on regulatory compliance and formal protective mechanisms creates an illusion of control, while in reality the conditions of system operation or functioning gradually change. Operators develop informal ways of interacting with technology that allow them to achieve assigned goals, but at the same time may accumulate systemic risks. These processes usually remain unnoticed until the occurrence of an incident.

Within the traditional paradigm, such adaptations are often interpreted as violations or errors. However, it is noteworthy that in practice it is precisely these adaptations that allow systems to remain operational under conditions that were not fully anticipated during design. Thus, a significant proportion of what is later classified as "human error" is in fact the result of rational decisions made within the constraints imposed by the system itself. It is fundamentally important that increasing levels of automation do not eliminate the human factor. Rather, the role of the human is transformed: the human is not removed from the system, but shifts from direct control to functions of monitoring, information interpretation, and intervention in non-standard situations. Under such conditions, the demands on the operator's cognitive resources increase, while the opportunities for maintaining situation awareness often decrease. Paradoxically, attempts to "remove" the human from the control process may lead to a reduction in the overall level of safety.

Thus, an approach that considers the human exclusively as a source of errors not only fails to account for the real role of the human in complex technical systems, but also limits the possibilities for analysing the causes of hazardous situations. This creates prerequisites for the repetition of the same problems within new technological frameworks.

1.3. Transition to modern safety thinking: man as an adaptive element of the system

In response to the limitations of the traditional paradigm, an approach has emerged in engineering science that rethinks the very nature of safety in complex technical systems. Within this approach, safety is considered not as a static state or the result of compliance with standards, but as a dynamic property of the system, formed in the course of its everyday operation.

A key feature of contemporary safety thinking is the shift in focus from the analysis of failures and accidents to the analysis of normal system functioning. Contemporary safety thinking views the human not as a threat, but as a necessary element of the safe operation of the system. For most of the time, complex technical systems operate without incidents, and it is precisely in this mode that interaction practices, adaptation mechanisms, and implicit rules are formed, which determine the actual level of safety. In this perspective, accident events are considered not as exceptional phenomena, but as extreme manifestations of the same processes that are present in everyday operation. The table 1 illustrates the complementary nature of the proposed approach rather than a conceptual replacement of existing frameworks.

Table 1

Positioning of the proposed approach relative to established safety frameworks

Aspect	**Established safety and resilience frameworks**	**Proposed approach**
Primary focus	Understanding accidents, failures, and normal work	Supporting engineering design decisions
Level of analysis	System behaviour, organisational processes, safety culture	System architecture, design assumptions, human–system interaction
Treatment of the human factor	Source of adaptation, resilience, and variability	Engineering parameter of human–system interaction
Temporal orientation	Predominantly analytical (after incidents or during operation)	Proactive (early design and lifecycle decisions)

Continuation of table 1

Role of design	Contextual factor influencing behaviour	Primary engineering instrument shaping behaviour
Intended use	Safety analysis, accident investigation, conceptual understanding	Design evaluation, comparison of concepts, early risk embedding
Contribution to sustainability	Implicit, through resilience and normal work	Explicit, through viability and real-use sustainability

The proposed approach builds on the core ideas of existing safety and resilience theories, providing engineering operationalization focused on decision-making processes for system design and development. Although concepts such as Safety-I and Safety-II, resilience engineering, and systems-theoretic approaches to safety have fundamentally changed the understanding of accidents, failures, and normal operation, they are primarily focused on the analysis, interpretation, and ex post facto explanation of system behavior. However, these approaches need to be complemented by shifting the focus to the early stages of system design, where assumptions about human behavior, system use, and adaptation are embedded in technical solutions. In this sense, the proposed contribution is not to rethink safety theory, but to transform established safety and resilience principles into practical engineering criteria that can be incorporated into system architecture, function allocation, interface design, and validation in conditions close to real-world operation.

1.4. Man as a source of flexibility and resilience

Within this approach, the human appears not as a weak link, but as a source of flexibility and adaptability of the system[1]. Operators and users continuously compensate for the imperfections of technical solutions, the incompleteness of information, and the variability of operating conditions. It is precisely through these adaptations that the system is able to maintain an acceptable level of functioning and safety under conditions of uncertainty. Contemporary safety thinking also transforms the interpretation of the concept of error. An error is viewed not as the root cause of an incident, but as a symptom of deeper systemic problems related to design decisions, organisational constraints, and operating conditions. This shifts the focus from the search for those at fault to the analysis of how the system shapes human behaviour and which actions it makes likely or inevitable. Error ceases to be a property of the human. It becomes a property of the system, the result of inadequate design and a low level of safety culture. Within such a paradigm, safety emerges not when human involvement is

[1] Mygal S.P., Mygal V.P., Mygal G.V. A hybrid approach to learning based on emotional experience and the development of innovative metathinking in post-war Ukraine. *Art & Design*. 2024. No. 3(27). P. 86–97. doi: 10.30857/2617-0272.2024.3

minimised, but when the system creates conditions for adequate, timely, and well-grounded operator actions. The human becomes a full-fledged element of the control loop, and their capacity for adaptation is regarded as one of the key resources for ensuring the safety of complex technical systems. It is precisely this philosophical and engineering shift that provides the foundation for the further analysis of system viability and the role of human-centred design, which will be addressed in the subsequent sections[2].

The described transition reflects a shift in focus from the search for deviations and errors to the analysis of mechanisms that allow a system to remain safe under conditions of uncertainty. Indeed, an exclusive concentration on accident events creates a distorted understanding of the actual behaviour of complex technical systems. Normal operation is not a static or ideal state. It is constantly accompanied by variability of conditions, incomplete information, local deviations, and the need for timely decision-making. Operators and users adapt their behaviour to these conditions on a daily basis, balancing the requirements of efficiency, productivity, and safety. It is precisely these adaptations that allow systems to remain operational and achieve their intended goals in situations that were not fully formalised at the design stage[3][4].

In this context, safety is a consequence of how people interpret system signals, make decisions under constraints, and interact with technical elements. If these processes remain outside analytical attention, a system may retain formal safety while gradually accumulating latent risks. What in everyday operation contributed to the achievement of results may, under additional constraints or a coincidence of unfavourable factors, lead to a hazardous development of events. Therefore, the analysis of accidents alone does not provide a complete understanding of the causes of risk emergence[5]. From this perspective, the fundamental difference between accident analysis and the analysis of normal operation lies in the following: accident analysis focuses on exceptional events, whereas the analysis of normal operation focuses on typical operating conditions; accidents provide information about the limits of the system, whereas normal operation reveals the mechanisms of its everyday stability; accident analysis explains what happened, whereas the analysis of normal operation explains why the system usually works; safety within accident-centred logic appears as

---

[2] Mygal G. Problems of the human factor in transport systems. *Transport Technology*. 2024. V. 5(1). P. 31–43. doi: 10.23939/tt2024.01.031

[3] Hollnagel E, Woods D.D, Leveson N. Resilience engineering: concepts and precepts. Aldershot: Ashgate; 2006. doi: 10.1201/9781315605685.

[4] Hollnagel E. Safety-I and Safety-II: the past and future of safety management. Farnham: Ashgate; 2014. doi: 10.4324/9781315257396.

[5] Dekker S. Drift into failure: from hunting broken components to understanding complex systems. Farnham: Ashgate; 2011.итdoi: 10.4324/9781315257419.

the result of protection against failures, whereas within the logic of normal operation it emerges as the result of coordinated interaction between the human and the system.

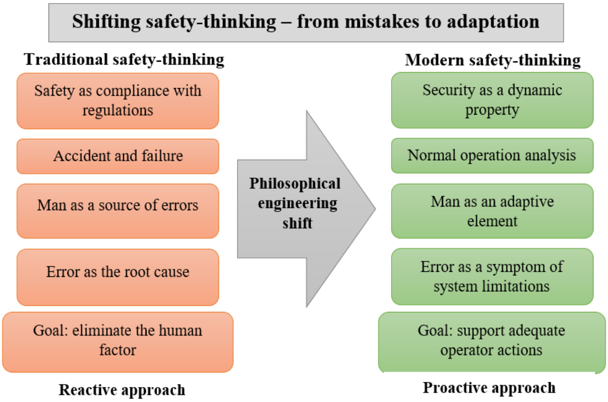

Fig. 2. Transition from traditional to modern safety thinking in the interpretation of the role of humans in complex systems

1.5. The human operator and user as an active element of a complex technical system

In complex technical systems, a significant portion of regulatory functions cannot be fully automated or formalised. In such cases, it is precisely the human who performs the role of an adaptive element that interprets information, assesses context, compensates for the limitations of technical solutions, and makes decisions under conditions of uncertainty. These functions constitute an integral part of the control loop, even if they are not formally described in the system's algorithms[6]. The operator and the user provide the link between the system's design model and the real conditions of its functioning. Viewing the human as an active element of the system changes the approach to safety analysis. Operator actions cease to be perceived as isolated events occurring "outside the system" and begin to be considered as a regular response to the structure of interfaces, the logic of automation, organisational constraints, and the available information. Human behaviour, in this perspective, serves as an indicator of how the system actually functions, rather than as a deviation from its "correct" mode.

[6] Norman DA. The design of everyday things. Revised and expanded edition. New York: Basic Books; 2013.

An important characteristic of the human as an element of a complex technical system is the capacity for learning and adaptation. In the course of operation, operators and users accumulate experience, form mental models of the system, and develop interaction strategies that they consider effective. These adaptations may either increase system resilience or create new risks, depending on the extent to which design decisions support – or, conversely, hinder – adequate human actions. Ignoring this role or attempts to reduce human involvement to a minimum do not eliminate the human factor, but rather make its influence less visible and less manageable.

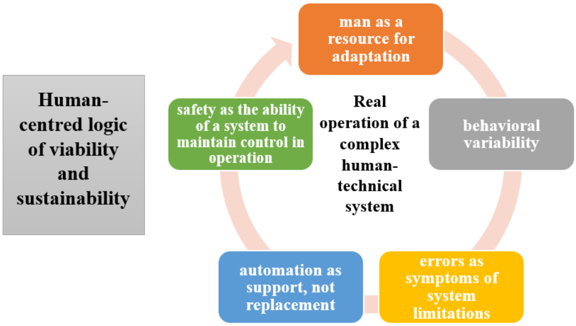

Fig. 3. Human-centered logic of interpreting the role of the human factor in ensuring the safety, viability and sustainability of complex technical systems

1.6. Design as the formation of a space of possible actions

Within traditional engineering logic, the design of technical systems is often regarded as a stage aimed primarily at improving usability or reducing the likelihood of errors. The main attention is given to the creation of protective barriers, constraints, and warnings intended to prevent incorrect actions by the operator or user. The potential of design as an active instrument for shaping safe behaviour often remains outside the focus of engineering analysis. At the same time, in complex technical systems, design determines not only the external appearance of interfaces, but also the fundamental logic of human–system interaction. Design does not neutrally reflect the structure of the system, but actively shapes the way it is used. Design is not limited to the function of protecting against errors, but forms the space of possible human actions within the system.

Safety arises not as a result of removing the human from the control process, but as a consequence of the system allowing and supporting adequate actions under conditions of variability, uncertainty, and constraints. If design decisions do not take into account real operating conditions, human cognitive capabilities, and the need for adaptation, operators and users are forced to compensate for these limitations through their own actions. This leads to the accumulation of latent risks and the degradation of safety. Within this logic, error is viewed not as an individual user's fault, but as an indicator of a mismatch between the system's design model and its operational practice. Human-centred design makes it possible to reduce this gap by integrating safe actions into the very structure of the work process. Thus, design shapes the space of possible human actions, determining not only what is formally permitted, but also which actions are likely, natural, or practically inevitable under real operating conditions[7][8][9]. Through the structure of interfaces, the logic of procedures, the availability of information, and the distribution of responsibility, design determines which interaction scenarios are supported by the system and which are marginalised or made more difficult[10].

Human behaviour is a systematic consequence of design decisions. Safe actions cannot be ensured exclusively through prohibitions, instructions, or control. Within this logic, safety emerges not when human involvement is minimised, but when the system structurally supports timely, adequate, and well-grounded actions under conditions of variability and uncertainty. In this perspective, system safety and viability are determined not only by its technical characteristics, but by how design structures real modes of use.

Conclusions to chapter 1. In summary, it can be argued that design is one of the key engineering instruments for transforming the human factor from a potential source of risk into a resource for safety. Design decisions not only constrain undesirable actions, but also determine which actions become natural, likely, and supported under real conditions of use. Safety emerges when a system is designed with consideration of the real role of the human, supports adequate human actions, and enables effective adaptation to changing operating conditions.

---

[7] Mygal S., Mygal V., Mygal G. Strategy for the development of design education in post-war Ukraine: transdisciplinary approach. *SA*. 2023. V. 5(2). P. 119–129. doi: 10.23939/sa

[8] Mygal G., Protasenko O., Kobrina N. The eco-ergonomics issues of the digital workplace. In: Nechyporuk M., Pavlikov V., Krytskyi D. (eds). *Integrated Computer Technologies in Mechanical Engineering – 2023*. Lecture Notes in Networks and Systems, vol. 1008. Springer, Cham, 2024. doi: 10.1007/978-3-031-61415-6_4

[9] Protasenko O., Mygal G. Eco-ergonomic thinking under human–machine system design. In: Mleczko K., Płaza G. (eds). *Industry Ergonomics: Insights into Industrial Ergonomics*. Gliwice: Silesian University of Technology Publishing House, 2024. P. 37–53.

[10] Endsley MR. Toward a theory of situation awareness in dynamic systems. *Human Factors*. 1995. V.37(1). P.32–64.doi: 10.1518/001872095779049543.

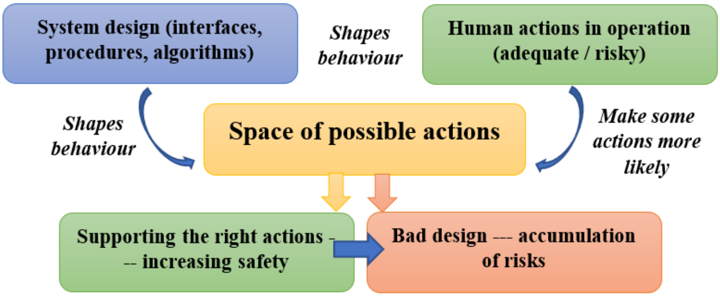

Fig. 4. The role of design in shaping the space of possible human actions and supporting safe behaviour in the operation of complex technical systems

Contribution of Chapter 1: a methodological shift in the interpretation of the human factor in complex technical systems is formulated – from viewing the human as an external source of errors to interpreting the human as an adaptive element of the system and a safety resource; a shift in focus is proposed from accident analysis to the analysis of everyday operation as a source of understanding the mechanisms of system resilience and safety degradation; the role of design as an engineering instrument for shaping the space of possible human actions is substantiated.

2. Viability of complex technical systems.

2.1. The concept of viability in the context of complex technical systems

In contemporary engineering science, increasing attention is being given to the concept of the viability of complex technical systems. Its emergence is associated with the recognition that traditional characteristics – reliability, safety, and robustness –although they remain necessary, are insufficient for describing system behaviour in the long-term perspective and under conditions of change. Viability, in contrast, focuses on the ability of a complex technical system to maintain functioning and achieve its goals over time under conditions of change, uncertainty, and incomplete predictability. It encompasses not only the system's response to individual failures or disturbances, but also the mechanisms of its gradual adaptation to changes in the environment, organisational conditions, and usage practices. An important feature of viability is its dynamic nature. After implementation, complex technical systems inevitably undergo changes: operating conditions are transformed, performance requirements evolve, levels of automation change, as well as the role of the human and the associated workload. A system that is reliable and safe at the initial stage may gradually lose these properties if it is not capable of adapting to such changes. In this sense, viability reflects not only the system's ability to "survive" individual disruptions, but also its capacity to evolve together with the environment of use. Another fundamental characteristic of viability is that it cannot be ensured exclusively by technical means. Adaptation of a system to real conditions is to a large extent realised through human actions, organisational processes, and design decisions that define the possibilities for such adaptation. As a result, a system may formally comply with design parameters and regulatory requirements, yet remain non-viable if its structure does not support effective human–technology interaction under changing conditions.

2.2. The life cycle of complex technical systems as a source of sustainability

The viability of complex technical systems is formed at all stages of the system life cycle – from conceptual design to everyday operation and subsequent modernisation. At each of these stages, decisions are made that determine the system's ability to adapt to change and to maintain effectiveness over time. At the design stage, a key role is played by assumptions regarding the conditions of system use, the role of the human, the nature of workloads, and possible operational scenarios. It is at this stage that the system's design model is formed and the potential for viability degradation is embedded. Formally correct technical solutions may, in such cases, prove poorly suited to real operating conditions. The implementation stage is usually accompanied by additional compromises related to organisational, economic, and time constraints. Initial user and operator experience is formed, which subsequently determines the character of interaction with the system. All of this affects the further viability of the system.

The degradation of viability becomes most apparent at the operation stage. In the course of everyday operation, the system encounters changing conditions that were not fully accounted for during design: increasing workloads, transformations of organisational structures, and the emergence of new requirements and constraints. Operators and users are forced to adapt to these conditions, forming work practices that ensure the achievement of goals, but do not always align with the original design logic.

An important characteristic of viability degradation is its gradual and low-visibility nature. A system may demonstrate satisfactory levels of effectiveness and safety for a long time, while simultaneously accumulating internal tensions and latent risks. Problems become evident only when the system's adaptive capacities are exhausted. Thus, the points of viability degradation of complex technical systems are located not only in the domain of technical failures, but also in design assumptions, organisational decisions, and everyday operational practices. In other words, viability is the result of the coherence between the system's design model, real conditions of use, and the human capacity to adapt to change.

2.3. The role of the human factor in shaping the viability of systems

It can be observed that, in complex technical systems, viability is not exclusively the result of design decisions or technical characteristics. It is formed in the course of real operation through the actions of people who interact with the system on a daily basis. It is precisely the human factor that determines whether the system will be able to adapt to changing conditions, compensate for the limitations of the design model, and maintain an acceptable level of functioning over time[11]. In such systems, the human performs the role of a carrier of adaptation. In response to non-standard operating modes, conflicting requirements, and limitations of resources and time, people modify their modes of interaction with the system, develop local solutions, and establish informal practices that allow the system to continue functioning. In many cases, it is precisely these adaptations that constitute the key factor in maintaining system viability. At the same time, the human factor may become a source of slow degradation of viability if the system forces people to operate at the limits of their capabilities or to constantly compensate for shortcomings of design decisions.

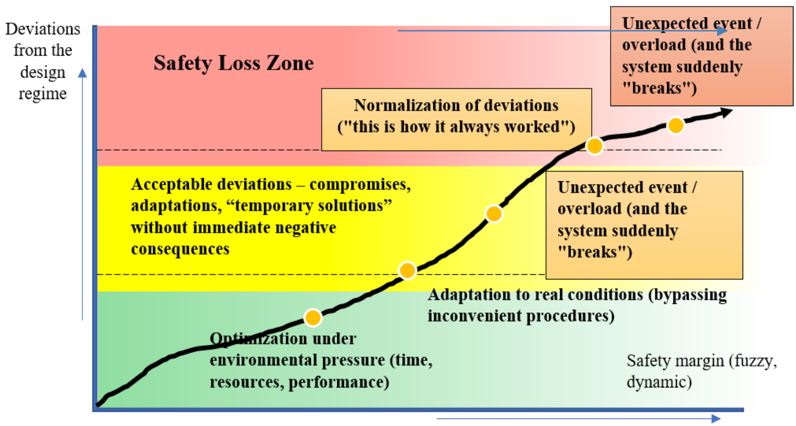

Fig. 5. Scott–Snook Law – Drift into failure: gradual degradation of safety during the operation of complex technical systems

[11] Snook S. A. Friendly Fire: The Accidental Shootdown of U.S. Black Hawks over Northern Iraq. Princeton University Press, Princeton, NJ, 2000. ISBN: 978-0691016202

In such cases, viability is maintained only at the cost of an increasing human workload, which is unsustainable in the long-term perspective. In this context, a key idea is captured by the law of gradual degradation, *"Drift into failure"* (the Scott–Snook law): catastrophes do not arise due to sudden rule violations; they emerge through the gradual normalisation of deviations. Thus, on the one hand, humans provide flexibility, variability, and learning capabilities that cannot be achieved by a rigidly formalised system. On the other hand, these same adaptive mechanisms may mask structural problems of the system, postponing their manifestation and complicating timely detection. A system may appear functional and effective until the limits of human adaptation are reached. Design decisions, the level of automation, interface design, and organisational rules determine which adaptations are possible, acceptable, or inevitable. In this sense, human behaviour is not random, but a predictable reaction to the structure of the system.

2.4. Why formally secure systems turn out to be unviable

In the practice of designing and implementing complex technical systems, a situation is quite common in which a system formally complies with existing norms, standards, and safety requirements, yet demonstrates low viability during operation. Such systems may pass certification, be successfully put into operation, and function for some time without serious incidents, while simultaneously gradually losing the ability to operate effectively and safely under real conditions[12]. One of the key reasons for this paradox is the gap between the normative model of the system and its actual behaviour in operation. A system may be "safe on paper" but insufficiently adapted to practical conditions of use. Another contributing factor is the orientation of design towards compliance with formal requirements rather than the analysis of real use. In such cases, engineering solutions are optimised for passing inspections and meeting regulations, while usability, clarity, and support for adequate human actions are treated as secondary aspects.

Formally safe systems are often characterised by excessive complexity or a high cognitive workload imposed on the human. In an effort to cover all possible risks, the system becomes burdened with additional procedures, levels of control, and signals, which complicate information perception and decision-making. Under such conditions, people begin to ignore part of the signals, simplify procedures, or rely on informal rules that allow more efficient work, but at the same time reduce the actual level of system safety and viability. If a system does not provide opportunities for adaptation and revision of design

[12] Leveson N. Engineering a safer world: systems thinking applied to safety. Cambridge, MA: MIT Press; 2011. doi: 10.7551/mitpress/8178.001.0001.

decisions, it becomes increasingly less viable, even while remaining formally safe. Thus, the non-viability of formally safe systems is the result not of isolated design errors, but of a systemic orientation towards regulatory compliance rather than the support of real work. Without consideration of the human factor, usage dynamics, and adaptive capacities, safety turns into a declarative property that does not guarantee the long-term effectiveness of the system (Fig. 6).

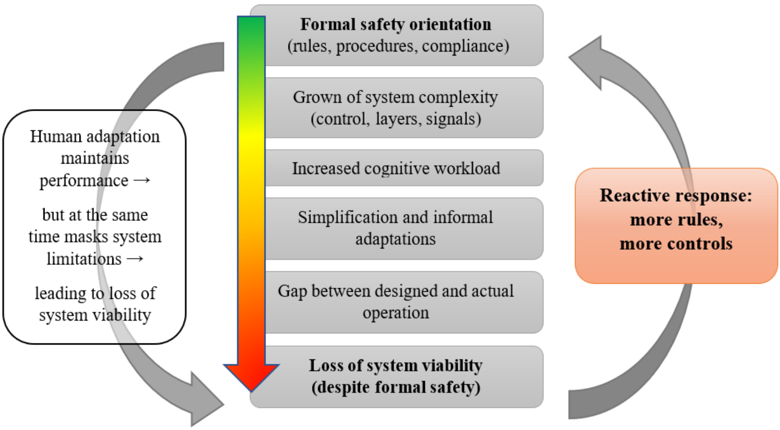

Fig. 6. Mechanism of loss of viability of formally safe systems

2.5. Adaptation, compromises and slow degradation of complex technical systems

The functioning of complex technical systems under real conditions is inevitably accompanied by processes of human adaptation. In the short term, these adaptations allow effectiveness to be maintained and intended goals to be achieved; however, in the long term they may lead to a slow degradation of system viability. Operators strive to optimise work processes, reduce excessive workload, shorten task execution time, or compensate for deficiencies in interfaces and procedures. Such solutions are often perceived as successful, since they allow the system to continue functioning without disruptions or accidents. For this reason, these practices are quickly stabilised and transmitted as the “normal way of working”.

At the same time, each such adaptation represents a compromise between different requirements – safety, productivity, convenience, and limited resources. Slow degradation of viability often remains unnoticed, as it is not accompanied by obvious failures or accidents. On the contrary, a system may demonstrate stable operation over a long period while becoming increasingly dependent on informal practices, the experience of individual specialists, and tacit knowledge. Under such conditions, system viability is maintained not because of design decisions, but in spite of them, which makes the system vulnerable to changes in personnel, operating conditions, or workload. A particular danger lies in the fact that successful adaptations mask structural problems of the system. People compensate for shortcomings of design decisions, and when the possibilities for adaptation are exhausted, the system encounters a sharp decline in effectiveness or safety. In such cases, incidents appear sudden, although in reality they are the result of long-term gradual processes. Thus, adaptation and compromise are an integral part of the viability of complex technical systems, while at the same time they may be a source of its slow degradation. Accordingly, a transition is required from a reactive approach to managing safety and effectiveness towards the design of systems capable of supporting adaptation without loss of viability.

2.6. Viability as an engineering criterion for evaluating solutions

Considering the viability of complex technical systems as a dynamic property formed throughout the entire system life cycle necessitates the inclusion of this concept in engineering criteria for the evaluation of technical solutions. In classical engineering analysis, primary attention is given to the compliance of technical solutions with regulatory requirements, reliability indicators, and efficiency metrics. These criteria are necessary; however, they do not provide an answer to the question of how a system will behave over time under conditions of increasing complexity, changes in organisational context, and the accumulation of user adaptations. As a result, solutions that are optimal from the standpoint of individual technical parameters may prove to be non-viable in the long-term perspective.

Within this study, viability is proposed to be considered as a multidimensional engineering criterion that can be used for the comparative assessment of technical solutions at the early stages of design. Within this approach, the evaluation of the viability of technical solutions involves the analysis of at least four interrelated dimensions: design viability (the extent to which the assumptions embedded in the system architecture correspond to real conditions of use; whether the design accounts for variability of scenarios and the role of the human as an adaptive element); operational viability (the ability of the system to support effective operation under changing workloads and contexts; the level of cognitive and operational workload imposed on users over time); adaptive viability (whether the system allows the detection, compensation, and correction of gradual shifts in operation; whether adaptation is not shifted exclusively onto the human); evolutionary viability (the system's capacity for modernisation without uncontrolled growth of complexity; the coherence of changes with accumulated operational experience).

Table 2

Comparison of engineering perspectives on safety and viability

Criterion	Classical safety analysis	Resilience-oriented analysis	Proposed viability framework
Main question	How to prevent failures?	How systems cope with variability?	How design enables long-term viability
Focus	Components, barriers, compliance	Normal work, adaptation	Design assumptions, interaction
Human role	Source of error	Source of resilience	Engineering parameter
Application stage	Late design / operation	Operation / investigation	Early design / concept selection

Unlike classical safety assessment methods focused on component reliability or compliance verification, and resilience-oriented approaches primarily aimed at explaining system behaviour during operation, the proposed viability framework targets design-time decision-making, enabling the early identification of structural conditions that support or constrain long-term system adaptation. Within this study, an original framework model for assessing the viability of complex technical systems is proposed, in which viability is interpreted as a multidimensional engineering criterion suitable for the analysis of technical solutions at the early stages of design.

The proposed framework model can be used as a basis for the comparative assessment of alternative design concepts at the early stages of design. For this purpose, the four dimensions of viability may be represented in the form of a radar diagram, which allows the relative viability profile of different solutions to be visualised without a claim to quantitative precision. The diagram highlights that design concepts optimised primarily for formal safety may exhibit significant weaknesses in adaptive and evolutionary viability, which become critical over long-term operation.

Illustrative example of framework application. To illustrate the proposed viability framework, consider a hypothetical highly automated transport control system that formally complies with safety regulations and demonstrates high component reliability. While its design viability may appear strong due to a well-defined functional architecture, assessment using the framework reveals limitations at other levels. Operational viability may be reduced by elevated cognitive workload caused by fragmented information and frequent manual interventions in non-standard situations. Adaptive viability may be constrained when the system provides limited feedback on the consequences of operator adaptations, shifting responsibility for performance adjustments onto the human. Evolutionary viability may also be affected if system updates increase interface complexity without revising function allocation.

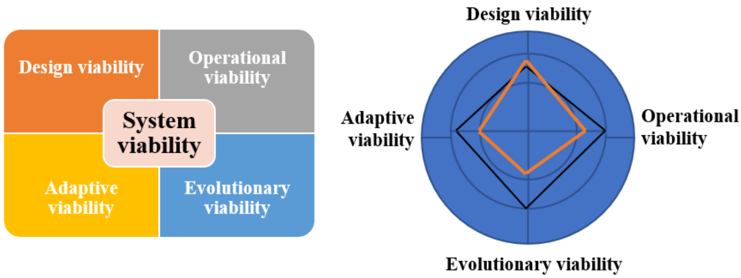

Fig. 7. Multidimensional viability framework and comparative radar profiles of formally safe and human-centred design concepts

A human-centred alternative, evaluated using the same framework, may exhibit lower levels of formal automation but higher operational and adaptive viability due to clearer interaction logic, improved support for situation awareness, and explicit consideration of human adaptation mechanisms. The radar-based representation highlights these trade-offs at early design stages, before implementation decisions become irreversible.

Certain aspects of this approach to viability analysis have been addressed by the author in previous studies devoted to the influence of the human factor and operating conditions on the long-term effectiveness of technical systems[13][14]. The integration of viability as an engineering criterion implies a shift in focus from the assessment of individual components to the analysis of the system as a whole, taking into account its interaction with the human and the environment of use. This entails the need to pose different questions at the design stage: how the system supports user adaptations; which compromises it makes and which it transfers to the human; how cognitive and operational workload change over time; and which mechanisms allow the detection and correction of slow degradation. Considering viability also changes the approach to choosing between alternative technical solutions. Viability becomes a criterion of the long-term quality of engineering solutions, closely linked to economic feasibility, operational stability, and the level of system acceptability for

[13] Mygal G. Transformation of the engineering thinking of complex systems designer. *Municipal Economy*. 2024. Vol. 1. No. 182. Series: Engineering Science and Architecture. P. 20–29. doi: 10.33042/2522-1809-2024-1-182-20-29

[14] 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. doi: 10.20998/2413-4295.2023.04.04

users[15]. An important feature of viability as an engineering criterion is its inseparable connection with the human factor. Since it is humans who ensure system adaptation under real conditions, the assessment of viability without considering their role is impossible. This requires the inclusion of analyses of human behaviour, cognitive limitations, and usage practices within the engineering design cycle, rather than treating them as external or secondary factors. Thus, viability acts as an integral engineering criterion that combines technical, organisational, and human aspects of the functioning of complex technical systems. Its consideration makes it possible to move from reactive mitigation of the consequences of degradation to the design of systems capable of supporting safety and effectiveness throughout the entire life cycle.

2.7. Operationalization of the human factor in engineering models

Within this study, the human factor is considered not as an abstract characteristic or a generalised source of risks, but as an engineering quantity subject to operationalisation and inclusion in models for assessing the viability of complex technical systems. The operationalisation of the human factor is carried out through a set of parameters that have direct engineering significance. In particular, cognitive workload is considered as an indicator of the complexity of human–system interaction, defining the limits of stable decision-making over time[16]. Erroneous actions are interpreted not as individual failures, but as indicators of a mismatch between design assumptions and real operating conditions. That is, errors are indicators of design and organisational constraints rather than individual unreliability. Human adaptability is treated as a mechanism for compensating system limitations, allowing system operability to be maintained under conditions of variability, while at the same time potentially masking the loss of long-term viability. The reliability of human–system interaction is considered as a property of the joint functioning of the human–machine control loop, dependent on the quality of interfaces, procedures, and the organisational context. Operationalising the human factor does not mean measuring the human; rather, it means incorporating parameters of human–system interaction into engineering decisions. Thus, the human factor acts not as an external constraint or a source of errors, but as an integrated engineering parameter that directly influences the viability of technical solutions at different stages of their life cycle.

Conclusions to Chapter 2. Viability is a dynamic life-cycle property formed through the interaction of technical solutions, operating conditions, and the human factor. Its degradation is often embedded at the design stage

---

[15] Baxter G, Sommerville I. Socio-technical systems: from design methods to systems engineering. *Interacting with Computers*. 2011. V.23(1). P.4–17. doi: 10.1016/j.intcom.2010.07.003.

[16] Mygal V.P., Mygal G.V., Mygal S.P. AI: unique opportunities and global challenges – a hybrid approach to modeling reality and its perception. *Qeios*. 2024. doi: 10.32388/GIJ3RI.4

through simplified assumptions about real system use and the role of the human, and is subsequently amplified during operation if design logic is not revised. The human factor plays a key role in maintaining viability by enabling system adaptation, while simultaneously potentially masking structural design limitations when excessive responsibility is shifted onto the human.

Contribution of Chapter 2: a multidimensional framework for viability assessment is proposed (design, operational, adaptive, and evolutionary dimensions), supported by visual tools for comparing alternative concepts; the human factor is operationalised as an engineering parameter of human–system interaction, enabling its integration into assessment models and engineering decision-support processes.

3. Human-Centered Design as an Engineering Methodology for Ensuring Sustainability

3.1. The place of human-centered design in the engineering of complex technical systems

Thus, the key problems of sustainability arise not at the level of individual technical components, but at the level of system interaction with the human under real operating conditions. Formal compliance with standards, high reliability of components, and increasing levels of automation do not in themselves guarantee long-term effectiveness and safety of systems. Therefore, it is necessary to integrate real conditions of use, behavioural characteristics, and human adaptations directly into the design process. Human-centred design, in this sense, appears not as an auxiliary or humanitarian approach, but as a means of extending classical engineering logic by taking into account the role of the human as an active element of a complex technical system[17][18]. In contemporary design practice, the concept of human-centred design is often associated with ensuring usability, improving interfaces, or enhancing the ergonomic quality of technical solutions. Such an interpretation, although not incorrect, significantly narrows the meaning and potential of this approach, reducing it to the level of styling or interaction optimisation at the final stages of system development. In the context of complex technical systems, human-centred design should be considered much more broadly – as an engineering approach to modelling real system use. Its task is not to adapt the human to an already created technical structure, but to design the structure itself with consideration of the role of the human in control loops, decision-making, and adaptation.

[17] Cross N. *Design Thinking: Understanding How Designers Think and Work*. London: Bloomsbury Academic, 2011. ISBN: 978-1847886361

[18] Brown T. Design thinking. *Harvard Business Review*. 2008. Available at: https://hbr.org/2008/06/design-thinking

Human-centred design introduces the human factor directly into the system model. This means that the behaviour of users and operators, their cognitive capabilities, limitations, and typical adaptations are treated as design parameters that influence system architecture, function allocation, and the selection of technical solutions[19][20]. Such an approach is a logical continuation of contemporary safety thinking and the concept of viability. If safety is formed in normal operation, and viability depends on the system's ability to adapt to change, then design must also take into account the mechanisms through which these processes are realised. Ignoring this leads to design solutions that are formally correct but non-viable in operation. Human-centred design makes it possible to reduce the gap between the design model and the system's real operation, decrease the need for hazardous adaptations, and create the prerequisites for long-term safety and sustainability of complex technical systems.

3.2. Man as part of a system model or as a source of unpredictability

Within standard engineering logic, the human factor exists "outside the system model", and its influence is compensated for through organisational measures or automation. Human-centred design proposes a fundamentally different approach, within which the human is regarded as a full-fledged design parameter of a complex technical system. This means that characteristics of human behaviour, cognitive capabilities, limitations, and typical adaptations must be taken into account at the same level as technical characteristics of components, control algorithms, or environmental parameters.

Considering the human as a design parameter implies the inclusion in the system model of such aspects as limited information-processing capacity, variability of decision-making, context dependence, and learning during operation. Unlike technical components, the human changes behaviour with experience, adapts to system constraints, and develops stable usage practices. These characteristics are neither random nor undesirable – they determine the actual behaviour of the system under conditions of uncertainty and change.

An important aspect of treating the human as a design parameter is the presence of cognitive biases that influence information perception, risk assessment, and decision-making. Such biases are systemic in nature and do not depend on the level of training or experience of the user. In complex technical systems, they manifest, in particular, in tendencies toward confirmation of

---

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

[20] Lee J.D., Wickens C.D., Liu Y., Boyle L.N. *Designing for People: An Introduction to Human Factors Engineering*. 3rd ed. CreateSpace Independent Publishing Platform, 2017. Available at: https://www.researchgate.net/publication/319402797

expectations, normalisation of deviations, overreliance on automated solutions, or underestimation of low-probability risks. Ignoring these regularities at the design stage leads to the creation of systems that formally assume "rational" human behaviour but, in real operation, stimulate undesirable adaptations. From an engineering perspective, cognitive biases should be treated not as individual errors, but as parameters that must be accounted for in system architecture and interaction design.

Including the human as a design parameter also changes the approach to the analysis of errors and hazardous situations. User and operator actions are considered not as individual deviations, but as systematic reactions to system structure, interfaces, organisational constraints, and function allocation. An engineering interpretation of the human as a design parameter requires abandoning simplified models of the "ideal user" or "nominal operator". Instead, it is necessary to work with a range of possible behavioural scenarios, typical adaptations, and acceptable workload limits. In this sense, human behaviour becomes a source of information about the quality of design decisions and the correspondence of the system to real conditions of use.

Considering the human as a design parameter is a necessary condition for ensuring the viability of complex technical systems. It makes it possible to integrate real conditions of use into the engineering model of the system and to reduce the gap between design logic and actual operation.

3.3. Integrating a human-centered approach into the classic engineering design cycle

The integration of human-centred design into engineering practice implies the expansion and refinement of the classical approach with consideration of real system use conditions and the role of the human at all stages of the system life cycle. Within the classical engineering cycle, the human-centred approach is integrated at the following key stages:

1) Requirements definition. The human-centred approach makes it possible to move from abstract functional characteristics to the analysis of real system use scenarios. Requirements are formulated with consideration of typical models of human–system interaction, possible variations in user and operator behaviour, as well as the organisational context of operation. Such an approach reduces the risk that a system will formally meet requirements while proving complex or unacceptable in real work.

2) Conceptual design and system architecture. The human-centred approach influences the choice of system architecture and the allocation of functions between technical components and the human. Errors made at this level embed fundamental limitations in system viability and cannot be fully compensated for at later stages.

3) Detailed design and development. At this stage, the approach is implemented through the design of interfaces, procedures, and interaction algorithms that support adequate human actions under conditions of variability and uncertainty. The focus is not only on reducing the probability of errors, but on ensuring the ability to respond flexibly to non-standard situations.

4) System validation and verification. It is necessary to analyse system behaviour under conditions close to real operation, taking into account typical actions of users and operators. Human behaviour is considered as an indicator of the quality of design decisions and their correspondence to real conditions of use.

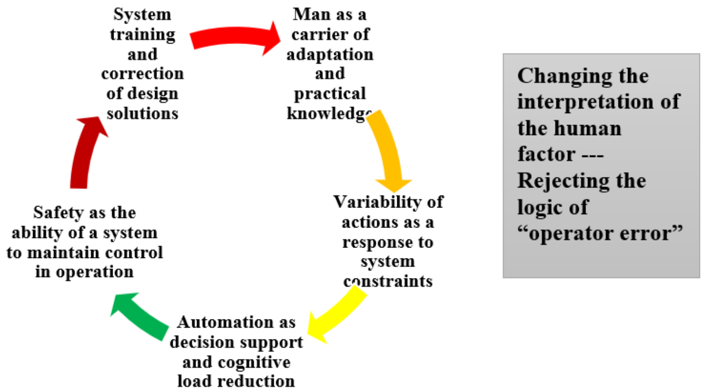

Fig. 8. Breaking the closed loop of safety and sustainability degradation through a human-centred approach to the design and operation of complex technical systems

Within this logic, human-centred design acts not as a separate method, but as a cross-cutting principle of systems engineering. This makes it possible to reduce the gap between the design model and real operation, decrease the need for hazardous adaptations, and increase the long-term viability of complex technical systems.

For the purpose of engineering operationalisation of the human-centred approach, it is appropriate to represent it in the form of a framework model for integrating the human factor into the classical engineering design cycle. Within this framework, the human factor is considered not as an external constraint, but as a design parameter that influences requirements definition, architectural decisions, interaction design, and system validation under conditions close to real operation (Fig. 9). In the proposed dual-loop framework model, human–system interaction parameters (cognitive workload, situation awareness, erroneous actions as indicators, adaptive behaviour, and HMI reliability) are integrated into each phase of the engineering cycle – from requirements definition to operation and organisational learning.

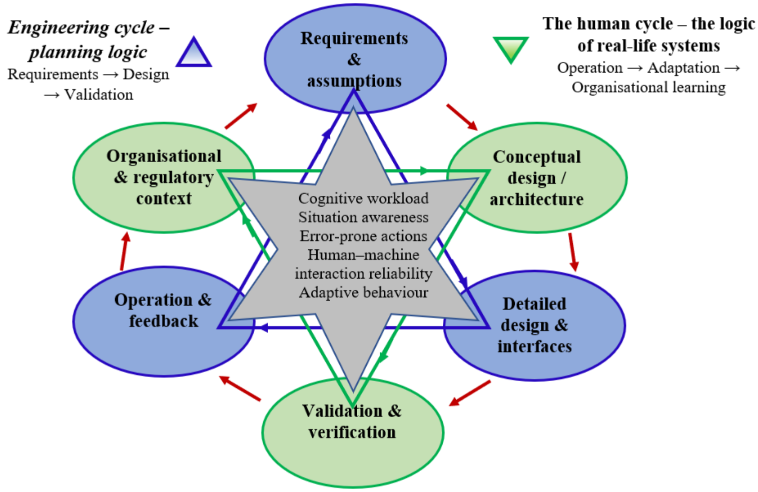

Fig. 9. Dual-loop framework for integrating the human factor into the classical engineering design cycle

The figure illustrates that the human factor is not treated as an external constraint or post-design consideration, but is integrated into key decision points of the engineering lifecycle via measurable interaction-related parameters. To capture the full lifecycle dynamics, the framework is extended by an additional organisational and learning dimension, reflecting how rules, responsibilities, training and accumulated experience shape the long-term behaviour of the system. This dimension connects design decisions with real operational practices and explains why formally correct systems may lose viability over time.

3.4. Human-centered design as a tool for savings, not costs

One of the key differences between human-centred design and the traditional approach is the shift of the focus of human factor analysis to the early stages of the engineering cycle. It is precisely at these stages that system architecture, function allocation, and interaction principles are defined, which subsequently determine both the safety and the viability of the technical solution. Attempts to account for the human factor after the completion of the main design phase are usually cosmetic in nature and are not capable of compensating for fundamental design limitations. This involves analysing what goals people seek to achieve through the system, under what conditions they operate, and which constraints shape their behaviour. In this context, needs should be considered as functional requirements for the system that reflect real usage scenarios rather than only nominal operating modes[21]. Equally important is the early analysis of the constraints within which the user or operator acts. Such constraints include time pressure, cognitive workload, incomplete information, organisational rules, and conflicting goals. If these factors are not incorporated into the design model, the system inevitably shifts their compensation onto the human, forcing the development of informal adaptations. In the short term, this allows operability to be maintained, but in the long term it reduces viability and increases risks. Analysing user behaviour at the early stages of design makes it possible to identify typical interaction scenarios with the system, characteristic points of strain, and potential sources of compromise between safety and effectiveness. Such analysis does not aim to predict every possible human action, but rather to understand the range of likely behavioural strategies. This makes it possible to design the system in such a way that adequate and safe actions are simpler and more likely than undesirable or risky ones. It is fundamentally important that early work with the human factor reduces the cost of design changes. Adjustments to architectural decisions, automation logic, or function allocation at early stages require significantly fewer resources than attempts to mitigate the consequences of design errors after system implementation. In this sense, human-centred design acts not as a source of additional costs, but as a tool for reducing technical, organisational, and operational risks.

3.5. Human-centered design as a factor in the sustainability and acceptability of technical solutions

The resilience and sustainability of complex technical systems are often considered through the lens of technical and environmental indicators, such as energy efficiency, resource conservation, or the reduction of negative environmental impact. However, under real operating conditions, the long-term sustainability of a system is largely determined by whether it is accepted by users and operators and whether they are able to interact with it effectively without excessive effort or risk[22]. In this sense, sustainability appears as a property of

[21] 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 technology. 2023. №4 (18). P. 27-35. ISSN: 2079-5459 (print), 2413-4295 (online). doi:10.20998/2413-4295.2022.04.04

[22] 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. Available at: https://www.redcampussustentable.cl/wp-content/uploads/2022/07/6-CorteseCriticalRoleOfHE.pdf

use rather than solely of design or technology. In various engineering domains, it has repeatedly been observed that technical solutions may meet criteria of energy efficiency, resource conservation, or environmental optimisation at the design level, while simultaneously proving to be unsustainable in real operation. The reason for this lies not in physical limitations of the system, but in the ways it is actually used – simplification of procedures, bypassing of certain functions, or adaptations that alter the intended operating modes.

A similar logic has long been present in contemporary safety and viability thinking, where safety is considered not as a property of the design, but as a result of normal everyday system operation. Transferring this approach to the issue of sustainability makes it possible to argue that sustainability is realised not in the design model, but in the daily actions of people who interact with the system. If safety is "produced" in the course of operation, sustainability is formed in an analogous way.

The design of a technical system shapes the behaviour of users and operators, and it is precisely this behaviour that determines actual operating modes, workload levels, resource use, and patterns of wear. Consequently, sustainability emerges not when a system is potentially capable of operating in a sustainable manner, but when it encourages sustainable behaviour under real operating conditions. Human behaviour determines the actual use of resources and adherence to the principles embedded in the system. A technical solution may be energy-efficient or environmentally optimised by design, yet in real operation these characteristics may fail to materialise due to a mismatch between design logic and practical conditions of use. Human-centred design makes it possible to reduce this gap by making actions that are desirable from a sustainability perspective natural and likely for users. The acceptability of technical solutions also has a temporal dimension. A system may be positively perceived at the implementation stage, but over time lose this support as a result of changing operating conditions, increasing complexity, or the accumulation of minor inconveniences. The human-centred approach allows potential evolution of system use to be taken into account, reducing the risk that its sustainability characteristics will be gradually undermined in the process of adaptation[23].

3.6. Limitations and conditions for the effective application of human-centered design

Despite the significant potential of human-centred design in ensuring the safety, viability, and sustainability of complex technical systems, its application has a number of fundamental limitations. Ignoring these limitations or applying

[23] Mygal S., Mygal V., Mygal G. Mutual enrichment of education, science and technology in post-war Ukraine through self-organized integration of creative individuals. *Art & Design*. 2024. No. 4(28). P. 33–50. doi: 10.30857/2617-0272.2024.4.3

the approach superficially may lead to opposite effects – an increase in complexity, dilution of responsibility, and a reduction in system controllability.

One of the key risks is the reduction of human-centred design to a set of isolated methods or formal procedures. The application of individual tools without their integration into the overall engineering logic of the project creates the illusion of addressing the human factor while failing to influence fundamental design decisions. In such cases, human-centred design becomes a declaration rather than a real mechanism for improving system quality. Another limitation lies in the difficulty of formalising human behaviour. Human-centred design does not aim at full prediction or control of user and operator actions. Attempts at excessive formalisation may lead to oversimplified behavioural models. This requires engineers to accept uncertainty as an inherent characteristic of complex technical systems rather than as a modelling error.

Effective application of the human-centred approach also depends on the level of interdisciplinary interaction. Designing with consideration of the human factor requires coordinated work among engineers, safety specialists, operations personnel, and organisational process experts. In the absence of such interaction, the human factor remains a “no-man’s land”, with responsibility diffused among project participants. Organisational readiness for applying the human-centred approach is no less important. Projects oriented exclusively toward short-term technical or economic indicators usually do not create conditions for systematic consideration of the human factor. In such cases, solutions that enhance long-term viability may be perceived as excessive or unjustified costs. Thus, human-centred design is not a universal or inherently effective solution. Its effectiveness is determined by the depth of its integration into the engineering cycle, readiness to work with uncertainty, and the ability to treat the human factor as a systemic element rather than an external condition.

3.7. Methodological limitations and scope of application

Despite the demonstrated potential of the human-centred approach for enhancing safety, viability, and sustainability of complex technical systems, several methodological limitations should be acknowledged. The proposed framework does not aim to eliminate uncertainty inherent in socio-technical systems and does not provide deterministic predictions of human behaviour. Instead, it offers a structured way to account for variability, adaptation, and constraints at the design stage. The operationalisation of the human factor is based on qualitative and semi-quantitative human–system interaction parameters rather than precise numerical metrics, which limits classical optimisation but reflects the context-dependent nature of real system use. The effectiveness of the approach also depends on organisational readiness to integrate human-centred principles into engineering decision-making; projects driven solely by short-term cost, schedule, or compliance goals may not fully realise its benefits.

Finally, the framework is intended primarily for early design stages and conceptual comparison of alternatives. It complements, rather than replaces, detailed safety analyses and certification procedures by addressing factors typically overlooked in early system development.

Conclusions to Chapter 3. For modern complex technical systems operating under variable conditions and involving active human participation, ignoring human-centred design leads to the accumulation of systemic design constraints and the gradual loss of declared system characteristics. User and operator behaviour serves as an indicator of the adequacy of design decisions and their correspondence to real conditions of use. Sustainability in such systems is formed through real operation rather than being an inherent property of structure or technology. Human-centred design provides an engineering approach for integrating safety, viability, and sustainability across the entire system life cycle.

Contribution of the Chapter: an engineering interpretation of human-centred design as a factor of system viability and sustainability is proposed; sustainability is substantiated as a property of real system use; a framework model for integrating the human factor into the engineering design cycle and its operationalisation through human–system interaction parameters is presented.

CONCLUSIONS

This work examines the role of the human factor in ensuring the safety, viability, and sustainability of complex technical systems. An engineering methodology for integrating the human factor into the assessment of safety, viability, and sustainability of complex technical systems is formulated and substantiated. The main results and contributions are as follows:

1) Reinterpretation of the human factor as a systemic safety resource. A methodological transition is proposed from interpreting the human as a “source of errors” to considering the human as an adaptive element of the control loop. It is shown that under conditions of increasing complexity, safety is formed primarily in the course of normal system operation rather than manifested only in accidents; accordingly, the analysis of everyday operation constitutes a key source of knowledge about mechanisms of resilience and degradation.

2) Substantiation of viability as an integral engineering criterion of long-term solution quality. Viability is defined as a dynamic life-cycle property that emerges through the interaction of technical solutions, operational context, and the human factor. It is shown that formal safety and regulatory compliance do not guarantee viability due to the accumulation of adaptations, compromises, and the “drift” of usage practices.

3) Proposal of a multidimensional framework model for assessing the viability of technical solutions. An original model is developed that includes four interrelated dimensions: design, operational, adaptive, and evolutionary. The model is suitable for the comparative assessment of alternative concepts at early design stages, when key architectural decisions can still be modified.

4) Operationalisation of the human factor as an engineering parameter of "human–system" interaction. An approach is proposed in which the human factor is accounted for not through the evaluation of "human qualities", but through interaction parameters with clear engineering meaning (in particular, cognitive workload; erroneous actions as indicators of a mismatch between the design model and real work; adaptability as a mechanism of compensation and potential drift; and the reliability of the human–machine control loop). This enables the integration of the human factor into engineering decision-making models without reduction to descriptive judgments.

5) Integration of human-centred design into the classical engineering cycle as a methodology for ensuring viability and sustainability. It is shown that the human-centred approach should function not as an "add-on at the end", but as a change in the decision-making perspective at critical points of the design cycle (requirements, architecture/function allocation, interface and procedure detailing, and validation in scenarios close to real operating conditions). This reduces the gap between the design model and real operation and decreases the need for hazardous adaptations.

6) Substantiation of sustainability as a property of real system use. It is demonstrated that sustainable effects are not realised automatically through "correct" design or technology, but are formed in actual operating modes created by the interaction of design, organisational conditions, and human behaviour. Accordingly, human-centred design is considered an engineering factor of long-term acceptability and preservation of the system's declared characteristics over time.

7) Proposal of visual–analytical tools to support engineering decision-making. As a practical outcome, framework schemes and a radar-based representation of the viability profile are proposed, enabling the identification of imbalances between dimensions (for example, "formally safe, but weakly adaptive/evolutionary") prior to system implementation.

Taken together, the obtained results form a coherent engineering framework that integrates safety, resilience/viability, systems engineering, and human factors, and enables the assessment and design of complex technical systems with a focus on long-term viability and sustainability. In summary, it can be stated that ensuring the safety, viability, and sustainable development of complex technical systems is impossible without systematic consideration of the role of the human at all stages of the life cycle. The transition from reactive mitigation of consequences to the design of systems capable of supporting effective and safe operation under real operating conditions represents one of the key challenges of contemporary engineering.

SUMMARY

This work examines the role of the human factor in ensuring the safety, viability, and sustainability of complex technical systems under real operating conditions. The limitations of traditional engineering approaches are demonstrated, within which sustainability and safety are interpreted primarily as properties of structure, technology, or regulatory compliance. Based on the analysis of operational practices, it is substantiated that the long-term effectiveness and robustness of complex technical systems are formed not only by design decisions, but through the interaction of technical architecture, conditions of use, and human behaviour.

Safety is proposed to be considered as a dynamic property of normal system operation, and the human factor – not as an external source of errors, but as an adaptive element of the control loop and a resource for maintaining system functioning under conditions of uncertainty. It is shown that the viability of complex technical systems is a life-cycle characteristic formed through the accumulation of adaptations, compromises, and changes in usage practices, and that it is not guaranteed by formal safety or compliance with standards.

A multidimensional framework model for assessing the viability of technical solutions is proposed, encompassing design, operational, adaptive, and evolutionary dimensions. The human factor is operationalised as an engineering parameter of "human–system" interaction through characteristics such as cognitive workload, erroneous actions as indicators of design mismatch, adaptability, and the reliability of the human–machine control loop.

Human-centred design is substantiated as an engineering methodology for integrating viability and sustainability into the classical development cycle of complex technical systems. It is shown that sustainability should be considered as a property of real system use rather than solely of its structural characteristics. The proposed framework and visual–analytical tools can be used to support engineering decision-making at early design stages, with a focus on long-term viability and system acceptability under real operating conditions.

Bibliography

1. Reason J. Human error. Cambridge: Cambridge University Press; 1990. doi: 10.1017/CBO9781139062367.

2. Reason J. The contribution of latent human failures to the breakdown of complex systems. *Philosophical Transactions of the Royal Society B*. 1990. V.327(1241). P.475–484. doi: 10.1098/rstb.1990.0090.

3. Parasuraman R., Sheridan T., Wickens C. A model for types and levels of human interaction with automation. *IEEE Transactions on Systems, Man, and Cybernetics – Part A*. 2000. V.30(3). P.286–297. doi: 10.1109/3468.844354.

4. 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

5. Rasmussen J. Risk management in a dynamic society: a modelling problem. *Safety Science*. 1997. V.27(2–3). P.183–213. doi: 10.1016/S0925-7535(97)00052-0.

6. Mygal S.P., Mygal V.P., Mygal G.V. A hybrid approach to learning based on emotional experience and the development of innovative metathinking in post-war Ukraine. Art & Design. 2024. No. 3(27). P. 86–97. doi: 10.30857/2617-0272.2024.3

7. Mygal G. Problems of the human factor in transport systems. Transport Technology. 2024. V. 5(1). P. 31–43. doi: 10.23939/tt2024.01.031

8. Hollnagel E., Woods D., Leveson N. Resilience engineering: concepts and precepts. Aldershot: Ashgate; 2006. doi: 10.1201/9781315605685.

9. Hollnagel E. Safety-I and Safety-II: the past and future of safety management. August 2015. Cognition Technology and Work 17(3):461-464. DOI: 10.1007/s10111-015-0345-z

10. Dekker S. Drift into failure: from hunting broken components to understanding complex systems. 2011. DOI: 10.1201/9781315257396

11. Norman D.A. The design of everyday things. Revised and expanded edition. New York: Basic Books; 2013. doi: 10.1080/10447318.2013.835494.

12. Мигаль С., Мигаль В., Мигаль Г. Стратегія розвитку дизайн-освіти в повоєнній Україні: трансдисциплінарний підхід. SA. 2023. Випуск 5, номер 2. С. 119–129. https://doi.org/10.23939/sa2023.02.119

13. Mygal G., Protasenko O., Kobrina N. The eco-ergonomics issues of the digital workplace. In: Nechyporuk M., Pavlikov V., Krytskyi D. (eds). Integrated Computer Technologies in Mechanical Engineering – 2023. Lecture Notes in Networks and Systems, vol. 1008. Springer, Cham, 2024. doi: 10.1007/978-3-031-61415-6_4

14. Protasenko O., Mygal G. Eco-ergonomic thinking under human–machine system design. In: Mleczko K., Płaza G. (eds). Industry Ergonomics: Insights into Industrial Ergonomics. Gliwice: Silesian University of Technology Publishing House, 2024. P. 37–53.

15. Endsley M.R. Toward a theory of situation awareness in dynamic systems. *Human Factors*. 1995. V.37(1). P.32–64. doi: 10.1518/001872095779049543.

16. Snook S. A. Friendly Fire: The Accidental Shootdown of U.S. Black Hawks over Northern Iraq. Princeton University Press, Princeton, NJ, 2000. ISBN: 978-0691016202

17. Leveson N. Engineering a safer world: systems thinking applied to safety. Cambridge, MA: MIT Press; 2012. DOI: 10.7551/mitpress/8179.001.0001

18. Carayon P., Hancock P., Leveson N., Noy I., Sznelwar L., van Hootegem G. Advancing a sociotechnical systems approach to workplace safety. *Ergonomics*. 2015. V.58(4). P.548–564. doi: 10.1080/00140139.2015.1015623.

19. 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. doi: 10.23856/4825

20. Mygal G. Transformation of the engineering thinking of complex systems designer. Municipal Economy. 2024. Vol. 1. No. 182. Series: Engineering Science and Architecture. P. 20–29. doi: 10.33042/2522-1809-2024-1-182-20-29

21. 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. doi: 10.20998/2413-4295.2023.04.04

22. Dul J., Bruder R., Buckle P., Carayon P., Falzon P., Marras W., Wilson J., van der Doelen B. A strategy for human factors/ergonomics: developing the discipline and profession. *Ergonomics*. 2012. V.55(4). P.377–395. doi: 10.1080/00140139.2012.661087.

23. Baxter G., Sommerville I. Socio-technical systems: from design methods to systems engineering. *Interacting with Computers*. 2011. V.23(1). P.4–17. doi: 10.1016/j.intcom.2010.07.003.

24. Mygal V.P., Mygal G.V., Mygal S.P. AI: unique opportunities and global challenges – a hybrid approach to modeling reality and its perception. Qeios. 2024. doi: 10.32388/GIJ3RI.4

25. Cross N. Design Thinking: Understanding How Designers Think and Work. London: Bloomsbury Academic, 2011. ISBN: 978-1847886361

26. Brown T. Design thinking. Harvard Business Review. 2008. Available at: https://hbr.org/2008/06/design-thinking

27. Mygal V.P., Mygal G.V., Mygal S.P. Transdisciplinary convergent approach – human factor. *Radioelectronic and Computer Systems*. 2021. V. 4(100). P. 7–21. doi: 10.32620/reks.2021.4.01

28. Lee J.D., Wickens C.D., Liu Y., Boyle L.N. *Designing for People: An Introduction to Human Factors Engineering*. 3rd ed. CreateSpace Independent

Publishing Platform, 2017. Available at: https://www.researchgate.net/publication/319402797

29. 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 technology. 2023. №4 (18). P. 27-35. ISSN: 2079-5459 (print), 2413-4295 (online). doi:10.20998/2413-4295.2022.04.04

30. 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. Available at: https://www.redcampussustentable.cl/wp-content/uploads/2022/07/6-CorteseCriticalRoleOfHE.pdf

31. Mygal S., Mygal V., Mygal G. Mutual enrichment of education, science and technology in post-war Ukraine through self-organized integration of creative individuals. *Art & Design*. 2024. No. 4(28). P. 33–50. doi: 10.30857/2617-0272.2024.4.3

Information about the author:
Mygal Galyna Valeriivna,
Doctor of Technical Sciences,
Professor at the Department of Transport Technology,
Lviv Polytechnic National University,
12, Stepana Bandery str., Lviv, 79000, Ukraine