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A risk-oriented approach to the development of transport systems with embedded information technologies

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Abstract: The article explores the process of transformation of methodological approaches to ensure safety and reliability of transport systems - from deterministic, tolerance, statistical and probabilistic paradigms to a complex risk-oriented concept, integrated into the life cycle of creating transport objects. The proposed approach aims to achieve a balanced "quality - cost - risk" ratio, which creates the preconditions for increasing the competitiveness of the machine complex products through increased efficiency of intellectual activity in the design stages, production and operation of technical systems. The analysis of current problems was carried out, prospective directions of methodology were considered, as well as models and methods for justifying the permissibility of design-technological risks. Examples of the implementation of risk-oriented strategies and tactics at different stages of the life cycle of transport systems are given.

Keywords: risk-oriented concept, life cycle, digital twins, mathematical model, rail transport, technological systems, information technology

1. Introduction

The development of rail transport as an integral part of the system of machine science and mechanical engineering has historically focused on solving a complex of interconnected tasks: optimizing resource consumption in all stages of the creation of machinery, Ensuring the required level of reliability and safety of technical systems and technological processes, studying cause-and-effect relationships of degradation phenomena (including analysis of damage mechanisms of both individual elements and complex technical complexes), as well as automating the processing of datasets to reduce the time to market for new products. The creation and application of intelligent systems is of particular importance in modern times, which inevitably generates new classes of risk and requires the development of adequate methods to manage them [1-4].

As a priority for the development of transport systems, and in particular its key component - rail transport, the further development and implementation of a risk-based approach is currently being considered. The evolution of methodology, which has been in full development since the early 2000s, involves a gradual shift from traditional deterministic, tolerant, statistical, and probabilistic methods (including predictions of reliability) to holistic risk assessment and management. This paradigm has been reflected in both basic scientific research and applied industry development - from the implementation of unique projects to the organization of serial production within the full life cycle of technical objects [4].

The particular relevance and specificity of a risk-based approach for the railway industry is due to:

- increased requirements for the safety of the transport process;
- the complexity and interdependence of infrastructure facilities and rolling stock;
- Long service life and the need for risk management at all stages of the life cycle: from conception, design and manufacturing to repair and disposal;
- the existence of a regulatory framework based mainly on deterministic and statistical paradigms, with the simultaneous need to optimize maintenance costs.

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The aim of this work is to analyze existing methods and develop conceptual models and methodologies for applying a risk-based approach in order to ensure an acceptable level of risks when increasing the productivity of intellectual activities in the process of building transport systems. The solution to this problem aims at optimizing the "quality-cost-risk" relationship and achieving an acceptable level of risk (i.e. acceptable probability and integral damage) for failures at different stages of the life cycle of transport systems.

2. Research methodology

The following areas of study are identified in the context of the life cycle of transport systems and related risks [4]:

- normalization and standardization of terminology, including the conceptual range in the field of artificial intelligence, as well as regulating the application of information systems at all stages of the life cycle;
- numerical modeling of physical processes as a tool to reduce resource costs and accelerate the preparation of new technology production;
- the duality of risks arising from the interaction of hardware and information subsystems;
- risk management based on the application of built-in monitoring systems for degradation processes.

There is now an intensive introduction of integrated information systems in the technical complex [3, 5] as a means to increase the productivity of intellectual activity - both during the design phase and during operation. The main source of risks leading to natural, man-made and social damage is inappropriate or insufficiently reliable information (figure 1).

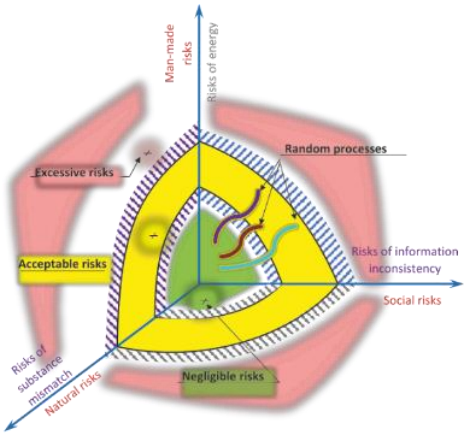


Fig. 1. Presentation of the risk analysis structure of a process using a hybrid system based on a risk-based design and process approach: challenges, threats, vulnerabilities and damages

To implement risk-oriented thinking, a hyperbolic model developed by the authors is proposed that describes the relationship between potential damage and an acceptable probability of non-compliance (figure 2). The underlying principle is that significant damage should be less likely to materialize than less significant damage. This ensures that an acceptable or required probability of identified damage is achieved. To facilitate risk analysis in practical activities, including management of the life cycle of a socio-technical system, continuous hyperbolic dependence can be presented as a step function (score on the parameters "probability - priority/damage significance"), which allows for the ranking of priorities and their corresponding acceptable probabilities of discrepancies. Accordingly, a system for identifying the scores of significance of consequences is introduced in the design and technology and other documentation.

With a view to harmonizing and ensuring the universal application in managed environments of information systems for "second nature" objects - techniques and technologies - a series of international and national standards are being developed, defining:

— Terminology and conceptual provisions (for example ISO/IEC 22989:2022);

— Impact assessment processes (ISO/IEC 38507:2022);

— Requirements for the organization's management system (ISO/IEC FDIS 42001);

— Risk identification methodology (ISO/IEC 22894:2022).

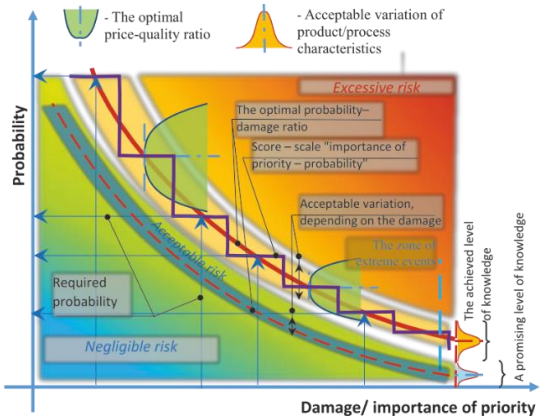


Fig. 2. Fundamental five-component model of optimization of "probability - damage" - "quality - value" - "variation - damage" dependencies

National standards are also being developed to apply terms and definitions correctly. In particular, GOST R 57188 presents a terminology apparatus for modeling physical processes, and GOST R 57412 identifies applicable electronic models in the processes of product development, production and operation. Standards are developed in the supply chain to ensure that technical systems with embedded software complete their life cycle stages efficiently and effectively. Thus, the GOST series P 57700 regulates software certification and validation systems.

2.1 Regulatory framework and standardization of modelling

It should be noted that the methods of interlinked risk management of physical and information systems are still insufficient for widespread practical application. Moreover, the term "artificial intelligence" (AI) is still not definitively defined even in ISO/IEC 22989. In the standards STB 1694 and STB 2582 (developed with the authors of this article) for the English term "artificial intelligence" is proposed the phrase "means of supporting intellectual activity" (MSIA), which, in our view, more accurately reflects the essence of this concept. This interpretation is not misleading, as it is with AI as a kind of "miracle," but makes a valid analogy with the means to support human physical activity - the creation of machines (such as machine tools) and tools that enhance productivity.

Currently, to reduce development and production lead times [1-4], for example, within the GOST series P 15,000,

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a set of standards regulating the implementation of numerical modeling of technical products has been developed. An analysis of these documents leads to the following conclusions.

The GOST series R 57700 defines requirements for numerical modeling systems, including software certification and validation processes. In particular, GOST R 57700.10 regulates the processes of verification and validation of numerous models of complex structural elements in the elastic area, as well as requirements for software of computer models used in product development and acceptance, qualification, series and other tests, as well as at later stages of the life cycle.

The classification of computer models is presented in GOST R 57700.22, general provisions on the use of digital twins of articles - in GOST R 57000.37. This standard introduces the following key concepts:

— Model adequacy - compliance of the model with the modelled article (process, phenomenon) according to the substantiated list of characteristics;

— Digital product model - a system of mathematical and computer models, as well as electronic product documents, describing the structure, functionality, and behavior of a product being developed or operated at various stages of the life cycle, for which, based on the results of digital and (or) other tests for GOST 16504 have been evaluated for compliance with the requirements;

— Digital product twins - a system consisting of the digital model of the product and bilateral information links with the product (if any) and/or its component parts;

— Model is the entity that reproduces a real-world phenomenon, object, or property of an object;

— Mathematical model - a model in which information about the modeling object is presented as mathematical characters and expressions.

2.2 Hybrid systems risk analysis issues

Because all socio-technical systems are subject to degradation processes, the entire life cycle - from marketing research to disposal - should be considered in assessing adequacy risks. Risk analysis includes steps to assess threat, damage and vulnerability scenarios. To ensure universal application, a series of international and national standards are being developed that define the terminology apparatus, concepts, impact assessment processes, management system requirements, and risk identification methodology for information technology applications.

The full risk analysis of technical systems using electronic models requires further development of appropriate methodologies and methods that take into account the stages of assessing threat, damage and vulnerability scenarios.

At the present stage of development, experimental tests are partly replaced or supplemented by calculation models. The use of such models makes it possible to predict the behavior of machines and systems in service conditions, assess their strength, durability, energy efficiency and safety, and conduct scenario analysis without the need to perform expensive or potentially dangerous physical tests.

The most important task is to define the conditions of use of digital twins, which allow experiments to be replaced by calculated models, taking into account the completeness, accuracy, and reliability of the results obtained. The key point is to select an appropriate criterion for evaluating model results. Researchers have pointed out the lack of a hierarchical framework for regulatory and technical documents that allow and regulate the application and scope of digital technologies. Thus, there is an objective need to describe the conditions of application of calculation models in regulatory and technical documentation, justification and legitimization of digital tests. Decisions to replace physical tests with calculation models must be made based on identification of local damage zones using documents in which risk indicators depend on assigned points (figure 2), to determine the significance of risks in deciding whether to conduct a physical experiment, computational simulation, or a combination thereof. The risk assessment for a point system is based on conventional approaches but requires verification and analysis of the effects of changing operating conditions [3, 6].

In order to achieve an acceptable level of risks for technical systems with embedded software, a graphical process risk analysis model using a hybrid (material and information) system based on a risk-oriented project-processing approach has been proposed (figure 3). The model takes into account challenges, threats, vulnerability and damage. Each of the subsystems - physical (machinery, design) and information (software) - is characterized by its own risks of non-compliance.

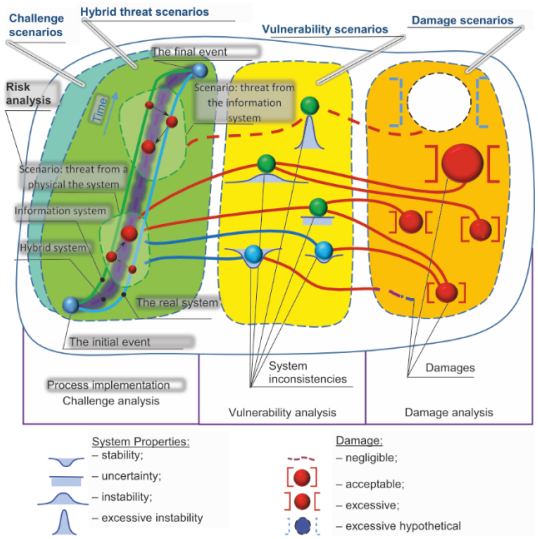


Fig. 3. Graphical risk analysis model of the technical system with hybrid - material and information - subsystem

It is necessary to consider a series of scenarios for identifying both the individual vulnerabilities of the hardware and information subsystems, and their mutual vulnerability due to the mutual influence of threats and vulnerabilities in each. A separate issue is the need to re-perform risk analysis because information systems may have adaptive functions; moreover, both stakeholder requirements and regulatory requirements change in the operation of technical systems. As a result, the vulnerabilities of hybrid systems are also transforming, necessitating a reassessment of whether an acceptable level of risk has been reached. For risk management of technical systems with built-in software, it is proposed to use the series of standards STB 1506, STB 2582 developed with the participation of authors, as well as the methodology of risk analysis FMEA.

In implementing a risk-based approach, the most important step is to synthesize design and engineering activities in the supply chain to reduce vulnerability. The

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decision to allocate resources for technological improvements is determined by the degree of unacceptability of potential damage. The relationship between risk management at the strategic, operational, programmatic and project levels should be considered, since the acceptability of integrated risks is determined by the configurator, i.e. a system of a higher level than the one under consideration [7-10].

Risk-oriented thinking allows for the consideration of ways to reduce product and process risks by diagnosing and monitoring degradation processes, thereby preventing critical situations from occurring. Thus, acceptable risk is achieved without increasing product strength inventories - at the expense of timely prevention of adverse events. Figure 4 presents a developed model for achieving acceptable damage by preventing excessive risk through diagnostics and monitoring.

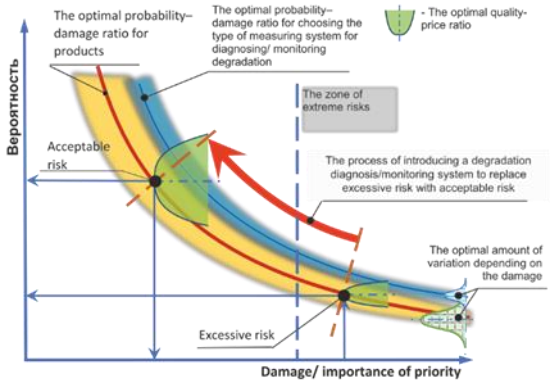


Fig. 4. Model for preventing excessive damage by diagnosing and monitoring degradation processes by changing the significance of consequences

Excessive damage can be prevented and reduced to an acceptable or negligible level by diagnosing and monitoring degradation processes using appropriate types and variations of measurement systems. The extrinsic hyperbolic "probability-damage" dependence is characteristic of a monitoring system. The parabolic dependence "quality - value" depends on the size of the damage and its significance, with the steepness of this dependence increasing as the significance of the damage increases. The acceptability of variation in product or process characteristics is reduced depending on the significance of damage and priorities. In conditions of high uncertainty, congestion and service life, an additional system of diagnostics and monitoring can reduce the cost of product creation and achieve replacement of excessive operational risk with acceptable.

3. Conclusion

The analysis confirms that the shift to a risk-oriented paradigm in transport engineering, and particularly in the railway industry, is an objective necessity. This necessity stems from the increasing complexity of technical systems, the integration of intelligent components, and the need to optimize costs while maintaining safety. Development of the methodological base, including harmonization of terminology, improvement of normative documentation and development of practical methods for risk assessment and management of hybrids (material-information) systems, provides a framework for achieving acceptable risk levels at all stages of the life cycle. Especially important are the validation and verification of digital models, the definition of conditions for their application in place of field tests, as well as the consideration of risk dualism when interaction between physical and information components. The models and approaches proposed in the work, including the hyperbolic "probability-damage" dependence, a point system for assessing the significance of risks and the concept of preventing excessive damage by means of monitoring, can serve as a basis for further research and practical implementation of risk-oriented design in transport engineering.

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CONTENT / MUNDARIJA

O. Berdiev, O. Zafarov, E. Urishbaev
Complex chemical admixture intended for improving the properties of concrete mixture……168

I. Kavaliova, A. Panov, E. Romashova, U. Ziyamukhamedova, L. Marchenko, Y. Podgornaya, V. Podgornaya
A risk-oriented approach to the development of transport systems with embedded information technologies……175