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PROCESS VULNERABILITY OF RAILWAY TRANSPORT ENTERPRISES: ESSENCE, ASSESSMENT, AND DIRECTIONS FOR MINIMIZATION

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The article is devoted to the study of process vulnerability of railway transport enterprises under conditions of increasing environmental turbulence, growing complexity of intersystem interactions, and a higher level of risk intensity in economic processes. It is substantiated that traditional management approaches, primarily focused on achieving operational efficiency, do not ensure an adequate level of enterprise resilience, as they fail to account for latent internal dysfunctions within the process architecture. In this context, the need to develop proactive management models aimed at the timely identification and minimization of internal sources of instability is emphasized. The paper clarifies the essence of process vulnerability as an integral multidimensional characteristic of business processes, reflecting their susceptibility to degradation under the influence of internal and external disturbances. Its distinction from related categories such as flexibility and adaptability is defined, which deepens the theoretical understanding of this economic concept. A systematic approach to the identification of process vulnerability is proposed, involving the decomposition of business processes, detection of bottlenecks, and classification of vulnerabilities into structural,

resource, informational, and managerial types. A methodological approach to assessing process vulnerability is developed based on a system of quantitative and qualitative indicators, including time characteristics, variability, reliability, and workload levels of processes. An integral index of process vulnerability is proposed, enabling the aggregation of partial indicators, monitoring of the process system state, and identification of critical areas within the enterprise. It is substantiated that the application of this toolkit provides a foundation for the transition from reactive to proactive management. Key directions for minimizing process vulnerability are identified, involving the formation of a comprehensive system of managerial measures aimed at increasing the reliability, balance, and adaptability of business processes. The obtained results have both theoretical and practical significance and can be used to improve management systems of railway transport enterprises in a transformational economy.

Keywords: process vulnerability, railway transport enterprises, business processes, resilience, operational efficiency, risk-oriented management, bottlenecks, process architecture, integral vulnerability index, adaptive management, system stability, uncertainty.

ПРОЦЕСНА ВРАЗЛИВІСТЬ ПІДПРИЄМСТВ ЗАЛІЗНИЧНОГО ТРАНСПОРТУ: СУТНІСТЬ, ОЦІНЮВАННЯ ТА НАПРЯМИ МІНІМІЗАЦІЇ

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У статті досліджено теоретико-методичні положення процесної вразливості підприємств залізничного транспорту в умовах зростаючої турбулентності зовнішнього середовища, ускладнення міжсистемних зв'язків та підвищення рівня ризиконасиченості бізнес-процесів. Обґрунтовано, що традиційні підходи до управління, орієнтовані переважно на досягнення операційної ефективності, не забезпечують належного рівня стійкості функціонування підприємств, оскільки не враховують наявність прихованих внутрішніх дисфункцій у процесній архітектурі. Актуалізовано необхідність формування проактивних моделей управління, спрямованих на своєчасне виявлення та мінімізацію внутрішніх джерел нестійкості. Уточнено сутність процесної вразливості як інтегральної багатовимірної характеристики бізнес-процесів, що відображає їх схильність до деградації під впливом внутрішніх і зовнішніх збурень. Запропоновано системний підхід до ідентифікації процесної вразливості, який передбачає декомпозицію бізнес-процесів, виявлення «вузьких місць» та класифікацію вразливостей за структурними, ресурсними, інформаційними та управлінськими ознаками. Розроблено методичний підхід до оцінювання процесної вразливості на основі системи кількісних і якісних індикаторів, що охоплюють часові характеристики, варіативність, надійність та рівень навантаження процесів. Запропоновано інтегральний індекс процесної вразливості, який дозволяє узагальнити часткові показники, здійснювати моніторинг стану процесної системи та ідентифікувати критичні зони в межах підприємства. Обґрунтовано, що застосування такого інструментарію створює підґрунтя для переходу від реактивного до проактивного управління. Визначено ключові напрями мінімізації процесної вразливості, які передбачають формування комплексної системи управлінських впливів, спрямованих на підвищення надійності, збалансованості та адаптивності бізнес-процесів. Отримані результати мають теоретичне та прикладне значення і можуть бути використані для вдосконалення систем управління підприємствами залізничного транспорту в умовах трансформаційної економіки.

Ключові слова: процесна вразливість, підприємства залізничного транспорту, бізнес-процеси, стійкість, операційна ефективність, ризик-орієнтоване управління, вузькі місця, процесна архітектура, інтегральний індекс вразливості, адаптивне управління, системна стійкість, невизначеність

Problem statement. The modern macroeconomic environment is characterized by increasing turbulence, fragmentation of the market environment, and the growing complexity of intersystem interactions. Under such conditions, traditional approaches to managing enterprise performance prove to be insufficient, as they are primarily focused on optimizing results rather than identifying hidden structural vulnerabilities of business processes. This problem becomes particularly acute for railway transport enterprises, which function as complex socio-technical systems with a high level of infrastructural inertia, significant capital intensity, and a critical dependence on process continuity. Vulnerability of individual elements of the process architecture in such systems can transform into systemic failures with a multiplicative effect, posing threats not only to operational efficiency but also to the safety of transportation processes and the strategic stability of the industry as a whole.

It is also important to emphasize that the growing impact of external shocks, the digitalization of management practices, and the increasing role of risk-oriented thinking intensify the need to develop new analytical tools capable of identifying, measuring, and forecasting process vulnerability in dynamics. Therefore, the study of the essence of process vulnerability, the determination of effective approaches to its assessment, and the substantiation of directions for its minimization acquire not only theoretical but also significant practical importance, forming the basis for the transition to proactive management models of railway transport enterprises in a transformational economy.

Analysis of recent research and publications. Theoretical foundations and applied approaches to business process management have been repeatedly highlighted in the works of Dykan V. L., Tokmakova I. V., Ovchynnikova V. O., Obruch H. V., Korin M. V., Teplyuk M. A., Koval A. Yu., Zubko Ye. V., Martsenyuk L. V., Kalycheva N. Ye., Maslova V. O., and others [1–8]. However, the issue of a comprehensive theoretical understanding of process vulnerability as an integral characteristic of business processes remains insufficiently explored, as well as the development of a systematic approach to its identification and structuring, and the formation of methodological tools for its quantitative assessment and the substantiation of effective directions for its minimization, taking into account the industry-specific features of railway transport enterprises.

The purpose of the article. The aim of the article is to develop theoretical and methodological provisions of process vulnerability of railway transport enterprises.

Presentation of the main material. The current stage of development of economic systems is characterized by increasing turbulence, a growing level of uncertainty, and a significant rise in the risk intensity of the external environment [9]. The nonlinearity of economic processes, the acceleration of technological changes, the fragmentation of market linkages, and increased sensitivity to exogenous shocks form a fundamentally new configuration of enterprise functioning, in which traditional forecasting and management tools become insufficient [10]. Under such conditions, the importance increases not only of organizations' adaptive capabilities but also of their ability to identify hidden internal vulnerabilities that may act as catalysts of systemic failures.

This issue becomes particularly complex in the field of railway transport, which functions as a multi-level infrastructure system with a high degree of technological interdependence among elements, significant capital intensity, and strict requirements for continuity and safety of operational processes.

In such systems, even minor deviations in individual elements of the process architecture are capable of generating cascading effects that transform into large-scale functional disruptions [11]. Therefore, the resilience of railway transport enterprises is determined not only by the level of their resource provision or the efficiency of individual processes, but primarily by the degree of their internal balance and their ability to resist the accumulation of latent dysfunctions.

At the same time, in contemporary management theory [1] and practice, there is a prevailing focus on achieving operational efficiency, which typically involves cost optimization, reducing process time parameters, and increasing productivity. However, such logic often ignores the fact that excessive optimization may be accompanied by growing process fragility (reduced buffers, increased dependence on individual resources or critical nodes, and a narrowing of maneuvering space in the case of deviations). As a result, a situation emerges in which a formally efficient system becomes unable to adequately respond to disturbances, thereby undermining its real resilience.

In this context, the problem of the absence of a holistic, systematically structured understanding of process vulnerability as an internal source of risk becomes increasingly relevant. Process vulnerability is not limited to individual «bottlenecks» but represents an integral characteristic of the process architecture, reflecting the system's tendency toward degradation under the influence of external and internal factors. Its neglect leads to managerial decisions being based on simplified perceptions of stability, without accounting for the accumulation of latent threats. Thus, efficiency achieved without considering process vulnerability has an illusory nature: it reflects only the current state of the system in the absence of significant disturbances, but does not guarantee its ability to maintain functional integrity in a dynamic environment. This necessitates a shift from the paradigm of optimization to the paradigm of resilience, within which the key object of management becomes not only process performance, but also their internal reliability, adaptability, and ability to resist vulnerabilities. This is particularly relevant given the specifics of the railway sector as critical infrastructure, where process interdependence, technological complexity, and high requirements for operational continuity result in increased sensitivity to internal dysfunctions. The absence of a comprehensive approach to analyzing process vulnerability in this field not only limits the ability to adequately assess risks but also hinders the formation of proactive resilience management mechanisms.

The fundamental difference between process vulnerability and flexibility and adaptability lies in the fact that the latter characterize the system's ability to change and adjust, whereas vulnerability is a measure of its potential inability to withstand disturbances. In other words, flexibility and adaptability reflect the strength of response, while vulnerability represents the «weakness of the structure». Moreover, excessive emphasis on efficiency and optimization may paradoxically increase vulnerability by reducing reserves and strengthening dependence on critical process elements. Overall, process vulnerability emerges as a multidimensional category encompassing both latent and explicit aspects of process system functioning, as well as their dynamic interaction. Its conceptualization allows shifting the management focus from responding to already realized risks to the proactive identification and neutralization of internal sources of instability, which is fundamentally important for ensuring long-term efficiency and safety of railway transport enterprises.

The identification and structuring of process vulnerability involves a transition from an abstract understanding of instability to its concretization within the enterprise's process architecture. This does not merely involve the identification of isolated problem areas, but rather a systematic detection of internal characteristics of business processes that create preconditions for their degradation under disturbance impacts.

The starting point of such analysis is the decomposition of business processes, which allows revealing the internal logic of enterprise functioning as a set of interconnected operations, subprocesses, and functional blocks. At this stage, it is important to move away from a formal description of processes and instead carry out their real «layering» (identifying responsibility transfer points, information flows, time parameters, and resource dependencies). Such detailing makes it possible to identify hidden asymmetries, duplication of functions, excessive complexity, or, conversely, a critical concentration of operations in key nodes.

Next, the logical step is the identification of «bottlenecks», which represent concentrated manifestations of process vulnerability. Their essence is not limited to restricted throughput capacity, but also includes increased sensitivity to changes in workload, resource shortages, or information disruptions. In the context of railway transport enterprises, such bottlenecks are often formed at the interfaces between technological and organizational processes - at points of traffic coordination, information processing, and resource allocation. It is important to emphasize that a bottleneck is not a static characteristic: it may change its location depending on the operating conditions of the system, which necessitates its dynamic monitoring.

To ensure a systematic analysis, it is appropriate to classify process vulnerabilities (structural, resource, informational, managerial), which allows not only their ordering but also the identification of adequate managerial intervention mechanisms. Thus, the identification and structuring of process vulnerability enables a shift from a fragmented perception of problems to the formation of a holistic view of the enterprise's internal instability. It creates an analytical basis for further vulnerability assessment, determination of its critical zones, and development of targeted managerial decisions aimed at improving the resilience and reliability of railway transport enterprises.

The assessment of process vulnerability of railway transport enterprises should be based on a transition from descriptive and fragmented evaluations to a systematic, formalized, and dynamic diagnosis that reflects the real state of the process architecture over time and under changing external conditions.

The starting element of such an approach is the formation of a system of evaluation indicators that allows both quantitative and qualitative representation of different aspects of business process functioning. The basic groups of indicators should include time characteristics (process duration, delays, cyclicity of operations), variability indicators (degree of deviation from normative parameters, instability of process execution), reliability indicators (frequency of failures, level of fault tolerance of process units), and load indicators (intensity of resource utilization, level of workload of process nodes). The combination of these parameters forms a multidimensional evaluation space that reflects not only efficiency but also the internal stability of the process system.

The next stage is the construction of an integrated assessment of process vulnerability, implemented through the development of a generalized vulnerability index. Such an index serves as a synthetic indicator that aggregates partial metrics while taking into account their weights and interdependencies. Its conceptual purpose is to transform disparate characteristics into a unified analytical assessment that allows comparison of different processes and identification of the most critical areas within the enterprise's process architecture. Importantly, the integral index should not be treated as a static value, but as a dynamic parameter sensitive to fluctuations in both internal and external environments. The following formula is proposed for calculating the integral process vulnerability index (I_{vuln}):

$$I_{\text{vuln}} = \frac{\alpha \cdot T_{\text{norm}} + \beta \cdot V_{\text{norm}} + \gamma \cdot F_{\text{norm}} + \delta \cdot L_{\text{norm}}}{\alpha + \beta + \gamma + \delta}$$

where: T_{norm}- normalized time indicator (for example, the ratio of actual process duration to planned duration, or the ratio of average process duration over a period to a benchmark value; the higher the value, the higher the vulnerability);

V_{norm} - normalized variability indicator (for example, the coefficient of variation of duration or quality of execution; characterizes process instability);

F_{norm} - normalized unreliability indicator (frequency of failures/errors per unit of time or workload; may be the inverse of mean time between failures);

L_{norm} - normalized load indicator (ratio of actual intensity of resource utilization to their capacity; reflects the level of workload of process nodes);

$\alpha, \beta, \gamma, \delta$ - weighting coefficients determined through expert judgment or analytical hierarchy methods (pairwise comparisons), depending on safety priorities and the specifics of railway transport.

The value of the indicator I_{vuln} close to 0 indicates a low level of process vulnerability (high resilience), while values approaching 1 indicate a critical level requiring immediate managerial intervention.

Thus, the proposed methodological approach forms a holistic analytical framework for the identification, measurement, and monitoring of process vulnerability, ensuring a transition from reactive management to a proactive model focused on anticipating risks in the operations of railway transport enterprises.

The final stage is the formulation of directions for minimizing process vulnerability, which should be considered not as a set of isolated managerial measures, but as an interconnected multi-level system of transformations aimed at reducing the structural, resource, and informational sensitivity of business processes within railway transport enterprises. Accordingly, it is appropriate to develop a coherent architecture of managerial interventions that ensures a shift from reactive elimination of disruptions to proactive prevention of their occurrence.

Conclusion. As a result of the conducted research, a theoretical and methodological foundation of process vulnerability of railway transport enterprises has been formed as a key factor in ensuring their functional resilience under conditions of increasing uncertainty and risk intensity of the environment. It has been proven that the dominance of the efficiency paradigm, focused on cost optimization and productivity improvement without considering internal imbalances in the process architecture, may lead to the formation of hidden sources of instability and increased system fragility. The economic essence of process vulnerability has been clarified as an integral characteristic reflecting the potential inability of business processes to maintain functional integrity under the influence of disturbances. This made it possible to propose a logic for identifying process vulnerability, which involves the decomposition of business processes, identification of critical points, and classification of vulnerabilities into structural, resource, informational, and managerial types. This, overall, ensures a transition from fragmented analysis to a holistic understanding of the enterprise's internal instability. A methodological approach to assessing process vulnerability has been developed based on a system of relevant indicators and an integral index, which allows for quantitative representation of vulnerability levels, comparative analysis of processes, and identification of priority areas for managerial intervention. A key advantage of the proposed approach is its dynamic nature and its ability to take into account changes in both the internal and external environment. It is substantiated that the minimization of process vulnerability should be based on the formation of a system of coordinated managerial measures aimed at reducing dependence on critical elements, increasing process reliability, developing reserves, and ensuring the flexibility of the process architecture. This creates prerequisites for a transition to a proactive management model focused on preventing disruptions rather than merely eliminating their consequences.

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