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A SET-THEORETIC APPROACH TO MODELING CASCADING DERIVATIVE RISKS IN SOCIO-TECHNICAL SYSTEMS

The article addresses a pressing scientific and applied problem: modeling complex hierarchical relationships among risk factors arising in the operation of high-tech, socially oriented systems. The object of the study is a network of sorting stations, considered as a complex dynamic system with distributed business processes. The relevance of the research is driven by the high level of turbulence in the external environment and the need to move from qualitative descriptions of risks to their digital formalization and quantitative measurement. The proposed approach is grounded in systems analysis, which enabled a multi-level decomposition of the organizational structure into subsystems of financial planning, logistics, sales, and marketing. Set theory was employed as the mathematical framework to describe the interactions among these subsystems. This made it possible to represent the cascading development of risks as a sequence of system states in which the emergence of a primary threat (funding shortfall) initiates a set of derivative risks, ranging from technological degradation of sorting lines to the loss of intellectual capital. The scientific novelty of the work lies in the further development of set-theoretic membership models that establish logical relationships between the causes and consequences of critical situations in a format suitable for automated processing. For the first time, an algorithm for the quantitative assessment of cascading impacts has been proposed through an integral indicator of Expected Risk Value (ERV), based on a combination of probabilistic characteristics and degrees of influence on the system's target performance indicators. The practical significance of the research is realized in the form of a strategic management map-scheme representing a set of algorithmized response strategies (avoidance, mitigation, acceptance). The proposed measures integrate both managerial decisions and technical-technological innovations, including the use of robotic systems to automate sorting processes. This reduces critical dependence on the human factor and minimizes operational risks. The application of the developed models creates a mathematical foundation for the design of intelligent Decision Support Systems (DSS) capable of predictive monitoring of complex systems and the automatic generation of cascading threat neutralization scenarios. The use of such digital tools ensures not only the short-term stabilization of business entities but also creates conditions for their sustainable development and enhanced competitiveness in the context of the economy's digital transformation.

Key words: *systems analysis, set-theoretic approach, mathematical modeling, derivative risks, cascading threats, socio-technical systems, expected risk value (ERV), management algorithmization, operational resilience, waste sorting.*

Зюзюн В. І., Щербак Д. Д. Теоретико-множинний підхід до моделювання каскадних похідних ризиків у соціально-технічних системах

У статті розв'язано актуальну науково-прикладну задачу моделювання складних ієрархічних зв'язків між факторами ризику, що виникають у діяльності високотехнологічних соціально-орієнтованих систем. Об'єктом дослідження обрано мережу сортувальних станцій, яка розглядається як складна динамічна система із розподіленими бізнес-процесами. Актуальність дослідження обумовлена високим рівнем турбулентності зовнішнього середовища та необхідністю переходу від якісного опису ризиків до їхньої цифрової формалізації та кількісного вимірювання. В основу запропонованого підходу покладено метод системного аналізу, який дозволив здійснити багаторівневу декомпозицію структури організації на підсистеми фінансового планування, логістики, збуту та маркетингу. Для математичного опису взаємодії між цими підсистемами використано апарат теорії множин. Це дозволило представити каскадний розвиток ризиків як послідовність станів системи, де виникнення базової загрози (дефіциту фінансування) ініціює множину похідних ризиків: від технологічної деградації ліній сортування до втрати інтелектуального капіталу. Наукова новизна роботи полягає у подальшому розвитку теоретико-множинних моделей належності, які дозволяють встановити логічні зв'язки між причинами та наслідками розвитку критичних ситуацій у форматі, придатному для автоматизованої обробки. Вперше запропоновано алгоритм кількісного оцінювання каскадних впливів через *інтегральний показник очікуваної величини ризику (ОВР), що базується на комбінації ймовірнісних характеристик та ступенів впливу на цільові показники системи. Практична значущість дослідження реалізована у вигляді стратегічної карти-схеми управління, яка є набором алгоритмізованих стратегій реагування (уникнення, зменшення, прийняття). Запропоновані заходи інтегрують у собі як управлінські рішення, так і техніко-технологічні інновації, зокрема використання роботизованих комплексів для автоматизації сортування, що дозволяє знизити критичну залежність від людського фактора та мінімізувати операційні ризики. Застосування розроблених моделей створює математичний фундамент для створення інтелектуальних систем підтримки прийняття рішень (DSS), здатних здійснювати предиктивний моніторинг стану складних систем та автоматично формувати сценарії нейтралізації каскадних загроз. Використання таких цифрових інструментів забезпечує не лише короткострокову стабілізацію об'єктів господарювання, а й створює умови для їхнього сталого розвитку та підвищення конкурентоспроможності в умовах цифрової трансформації економіки.*

Ключові слова: *системний аналіз, теоретико-множинний підхід, математичне моделювання, похідні ризики, каскадні загрози, соціально-технічні системи, очікувана величина ризику (ОВР), алгоритмізація управління, операційна стійкість, сортування відходів.*

Introduction. The current state of nonprofit organizations and social enterprises operating in Ukraine's environmental sector is characterized by a high level of turbulence in the external environment and a critical dependence on the stability of financial inflows. The distinctive feature of such business entities lies in the combination of a social mission with the necessity of maintaining a costly technical and technological infrastructure, including a network of sorting stations and waste management centers. The effective operation of these facilities requires continuous resource support to cover expenses related to complex logistics, compensation for qualified personnel, and the technological maintenance of equipment.

The research problem stems from the cascading nature of threat development, whereby the emergence of a primary external risk in the form of insufficient funding triggers an entire system of derivative risks capable of paralyzing sorting lines and degrading key business processes. Traditional risk management approaches often fail to account for the complex hierarchical relationships between external factors and the internal structure of environmental projects, making it difficult to identify the system's most vulnerable points. The absence of an adapted toolkit for the quantitative assessment of Expected Risk Value deprives management personnel of the ability to objectively prioritize threats – from the risk of staff reductions at stations to the complete loss of reputation and organizational dissolution.

In this context, there is an urgent scientific and practical need to apply a set-theoretic approach to modeling the parameters of external impact development. This would enable the formalization of sorting stations' operational activities and the development of a strategic management map-scheme for derivative risks, thereby ensuring their long-term resilience under conditions of financial instability.

Analysis of recent research and publications. The issue of enterprise and project risk management remains the subject of active scholarly inquiry, encompassing a broad spectrum of theoretical and applied approaches. The fundamental principles concerning the transformation of external threats into internal risks were substantiated in [1], which demonstrated the decisive role of the external environment in shaping a company's development strategy. The author proposed a mathematical formalization of risk using the apparatus of set theory and introduced the indicator of expected risk value (ERV), enabling the ranking of threats according to their level of severity.

The further development of a systems-based approach to managing environmental project risks was presented in [2], which formulated a systemic model for environmental risk management in projects. The study substantiated the expediency of comprehensively accounting for interrelationships among risk factors and elements of the project environment, thereby establishing a methodological foundation for assessing the resilience of environmental initiatives under conditions of uncertainty.

The significance of external factors in the functioning of modern enterprises was emphasized in [3], highlighting the necessity of their systematic consideration in the process of strategic management. At the same time, study [4] demonstrated that an effective internal control system serves as a key instrument for the timely identification and monitoring of risks affecting enterprise performance outcomes.

The integrative nature of risk management was explored in [5], which established a close interconnection among crisis management, economic security management, and risk management. A further development of conceptual foundations was presented in [6], whose authors propose viewing the management of risk-related losses as an extension of classical risk management, thereby enhancing the effectiveness of managerial processes.

Important methodological aspects of risk management standardization were highlighted in [7], which substantiated the feasibility of applying the PDCA cycle to enhance the coherence of IT service management, quality management, project management, and information security. The financial dimension of risk management was examined in [8], which proposed a financial engineering approach to mitigating currency risks through the use of information technologies.

A distinct line of research is associated with digital transformation and the risks of the IT environment. In particular, study [9] proposed an enterprise risk management model under conditions of digital transformation using artificial intelligence algorithms, significantly improving the accuracy of threat identification.

Applied aspects of risk management in IT projects have been addressed in a number of studies. Work [10] analyzed the risks of implementing DevOps in corporate IT infrastructures and identified conditions for their minimization. Article [11] substantiated the effectiveness of simulation modeling for supporting managerial decision-making in IT project management. Study [12] focused on the integration of Lean Six Sigma into the Scaled Agile Framework (SAFe), thereby enhancing the effectiveness of risk management in agile IT projects.

Work [13] examined the application of a set-theoretic approach to the mathematical description of the design of an information IoT system for environmental protection purposes.

Thus, contemporary research has established a substantial theoretical and methodological foundation for risk management across enterprises and projects of various natures. At the same time, an analysis of scholarly sources reveals insufficient attention to the problem of the cascading development of derivative risks in socio-environmental projects under conditions of chronic financial instability. In particular, further development is required in adapting the set-theoretic approach to the specific operational context of sorting station networks and in formulating applied map-schemes for responding to derivative risks. These gaps determine the relevance of the present study.

The purpose of the research. The purpose of this research is to provide scientific substantiation and to develop an information technology framework for modeling cascading derivative risks in complex socio-technical systems based on a set-theoretic approach. The primary focus is placed on formalizing the processes through which external destabilizing influences are transformed into internal systemic threats, as well as on creating algorithmic support for managerial decision-making aimed at ensuring the operational resilience of environmental infrastructure facilities under conditions of resource constraints.

Presentation of the main material. Despite the substantial theoretical foundation established in [1] regarding the mathematical modeling of derivative risks and their strategic significance for business entities, a number of applied aspects remain insufficiently explored.

First, further specification is required in adapting the developed set-theoretic model to the distinctive business processes of environmental organizations. Most existing studies focus on classical manufacturing or commercial enterprises, whereas the activities of sorting stations are characterized by a unique business process structure (recyclable logistics, high-temperature incineration, environmental education), in which risks exhibit a high degree of interdependence.

Second, the issue of the practical ranking of derivative risks remains unresolved in situations where the primary external influence (insufficient funding) operates on a permanent basis. It is necessary to determine how the prioritization of response strategies shifts when the expected risk value (ERV) reaches critical levels in such sensitive domains as organizational reputation and the preservation of human capital in environmental projects.

Third, there is a need to develop specific applied management algorithms (response map-schemes) that integrate managerial decisions aimed at risk mitigation with the technical and technological capabilities of sorting stations, such as automation and the implementation of KPI systems for frontline personnel. These aspects define the necessity of the present study and its focus on addressing gaps in the practical risk management toolkit for socio-environmental enterprises.

Let us conduct an analysis of the factors and parameters of the development of the external influence «insufficient funding» on the operations of a typical organization engaged in waste sorting and secondary material processing, using set theory.

To conduct a detailed study, it is first necessary to define the structure of the object and identify the key nodes of risk emergence. Table 1 presents the results of a systemic decomposition of the impact of financial deficit on the organization's functional subsystems.

Table 1

System and subsystem table

System / component name	Symbol
System name	
Insufficient funding	LF
Subsystem name	
Low adoption of paid services among visitors	RA
Reliance on limited funding sources	RB
Low customer traffic at the "No waste shop"	RC
Ineffective financial planning	RD

This distribution provides a clear distinction between areas of responsibility and allows for the identification of primary entry points for external threats into the project's internal environment.

A more in-depth analysis requires moving from general subsystems to specific sets of elementary factors that shape the risk landscape. The composition of these sets for each identified subsystem is categorized in Table 2.

Table 2

Subsystem set classifications

Subsystem name	Set name	Symbol
Low adoption of paid services among visitors	Low station attendance	RAA
	Low user purchasing power	RAB
	Low public awareness of services	RAC
Low customer traffic at the “No waste shop”	High product prices	RBA
	Low store foot traffic	RBB
	Competition	RBC
Ineffective financial planning	Inaccurate expense estimation	RCA
	Partial record-keeping	RCB
Reliance on limited funding sources	–	–

The established subsystem sets serve as the foundation for the subsequent mathematical formalization of cause-and-effect relationships.

A key stage of the study involves determining the logical dependence between root causes and the consequences of destabilization. Table 3 presents the results of formalizing these connections using membership models and corresponding hierarchical equations.

The transition from verbal descriptions to set-theoretic representations minimize subjectivity when evaluating complex systems. This creates the necessary conditions for further computer data processing and the development of automated models for predicting the objects state.

Table 3

Analysis of causes and consequences of problem impact

№	Problem	Causes / consequences of problem development	Equation	Explanation	Membership models
1	Low station visitor volume	Causes	$RAAR = \{RAAR_1, RAAR_2, RAAR_3\}$	$RAA_1 \rightarrow$ low brand awareness	$RAAR_1 = \{RAAC_1, RAAC_2\}$ $RAAR_2 = \{RAAC_2\}$ $RAAR_3 = \{RAAC_2\}$ or $RAAC_1 \in \{RAAR_1\}$ $RAAC_2 \in \{RAAR_1, RAAR_2, RAAR_3\}$
				$RAA_2 \rightarrow$ insufficient environmental education	
				$RAA_3 \rightarrow$ inconvenient location	
		Consequences	$RAAC = \{RAAC_1, RAAC_2\}$	$RAAC_1 \rightarrow$ loss of cooperation and partnership opportunities	
				$RAAC_2 \rightarrow$ loss of potential users	
2	Insufficient service awareness	Causes	$RBBR = \{RBBR_1, RBBR_2, RBBR_3\}$	$RBBR_1 \rightarrow$ low public awareness of the shop’s existence	$RBBR_1 = \{RBBC_1, RBBC_3\}$ $RBBR_2 = \{RBBC_3\}$ $RBBR_3 = \{RBBC_2, RBBC_3\}$ or $RBBC_1 \in \{RBBR_1\}$ $RBBC_2 \in \{RBBR_3\}$ $RBBC_3 \in \{RBBR_1, RBBR_2, RBBR_3\}$
				$RBBR_2 \rightarrow$ low awareness of the product range	
				$RBBR_3 \rightarrow$ insufficient communication	
		Consequences	$RBBC = \{RBBC_1, RBBC_2, RBBC_3\}$	$RBBC_1 \rightarrow$ weak reputation and trust	
				$RBBC_2 \rightarrow$ poor understanding of service value	
				$RBBC_3 \rightarrow$ loss of potential users	
3	Low shop visitor	Causes	$RACR = \{RACR_1, RACR_2, RACR_3\}$	$RACR_1 \rightarrow$ insufficient advertising and marketing	$RACR_1 = \{RACC_1, RACC_2\}$ $RACR_2 = \{RACC_1, RACC_2\}$ $RACR_3 = \{RACC_2\}$ or $RACC_1 \in \{RACR_1, RACR_2\}$ $RACC_2 \in \{RACR_1, RACR_2, RACR_3\}$
				$RACR_2 \rightarrow$ poor communication	
				$RACR_3 \rightarrow$ inaccessibility of detailed service descriptions and pricing	
		Consequences	$RACC = \{RACC_1, RACC_2\}$	$RACC_1 \rightarrow$ necessity to allocate additional marketing and advertising resources	
				$RACC_2 \rightarrow$ loss of potential users	
4	Inaccurate cost estimation	Causes	$RCAR = \{RCAR_1, RCAR_2, RCAR_3\}$	$RCAR_1 \rightarrow$ insufficient analytics	$RCAR_1 = \{RCAC_1\}$ $RCAR_2 = \{RCAC_2\}$ $RCAR_3 = \{RCAC_1, RCAC_2\}$ or $RCAC_1 \in \{RCAR_1, RCAR_3\}$ $RCAC_2 \in \{RCAR_2, RCAR_3\}$
				$RCAR_2 \rightarrow$ accounting errors	
				$RCAR_3 \rightarrow$ unexpected events or crises	
		Consequences	$RCAC = \{RCAC_1, RCAC_2\}$	$RCAC_1 \rightarrow$ decline in competitiveness	
				$RCAC_2 \rightarrow$ loss of development opportunities	

The modeling results confirm the hypothesis regarding the cascading nature of risk propagation, where a single negative factor initiates a chain reaction across adjacent subsystems.

Given the established cause-and-effect relationships between primary external influences and the internal processes of the object under study, the next stage involves the systematic identification of derivative risks. This identification allows for the structuring of the potential threat landscape, categorizing them into respective classes, and determining the business processes upon which they may exert the most critical impact. The results of this identification are presented in Table 4.

We will proceed by identifying potential derivative risks stemming from external influences, determining their classification, and establishing which business processes of the study object they may consequently affect.

Table 4

Identification of derivative risks

№	Derivative risk identification	Risk class	Business process impacted by the derivative risk
1	Decrease in operational volume	Organizational risk	1. Sale of recyclables. 2. Sale of reusable goods
2	Staff reductions (layoffs)	Stakeholder risk	1. Sorting of recyclables
3	Decline in service quality	Technological risk	1. Sorting and sale of recyclables. 2. Educational activities
4	Accrual of debt	Financial risk	1. Sale of reusable goods
5	Threat to organizational viability	Organizational risk	All
6	Reputational damage	Marketing risk	1. Lobbying and advocacy. 2. Educational activities

The results indicate the multi-level nature of derivative risk formation and their close alignment with the core business processes of the sorting infrastructure. The established risk structuring provides a foundation for the further analysis of potential development scenarios and the assessment of their possible consequences.

Based on the identified derivative risks, it is appropriate to analyze their potential development scenarios, which allows for an evaluation of the depth of destructive impacts on the system. A summary of these scenarios is provided in Table 5.

Table 5

Development scenarios for derivative risks

№	Risk name	Potential hazardous consequence scenarios
1	Decrease in operational volume	1. Loss of development opportunities. 2. Necessity to attract new partners/users
2	Staff reductions (layoffs)	1. Increased workload on remaining staff. 2. Internal tension and morale decline
3	Decline in service quality	1. Loss of existing partners and clients. 2. Reputational damage
4	Accrual of debt	1. Deterioration of relationships with partners 2. Loss of development opportunities. 3. Necessity to seek additional funding sources
5	Threat to organizational viability	1. Dissolution of the organization
6	Reputational damage	1. Loss of existing and potential users. 2. Loss of cooperation and partnership opportunities. 3. Necessity to allocate new resources for reputation recovery

Scenario analysis demonstrates that even localized derivative risks can trigger cascading negative effects across interconnected subsystems. This justifies the need for a quantitative assessment of their hazard levels and ranking them by priority for management response.

To quantify these parameters, we use the values provided in Table 6.

The expected risk value (ERV) is defined as the product of the risk impact value and its probability of occurrence.

To determine the risk rank, we use the data from Table 7.

To objectively prioritize the management of identified risks, a qualitative and quantitative assessment was conducted using the expected risk value (ERV) indicator. This approach facilitates a transition from descriptive analysis to the formalized ranking of threats. The calculation results are presented in Table 8.

Table 6

Risk assessment indicators

Risk impact level indicator for project implementation		**Project risk probability of occurrence indicator**	
0,05	Low	0,2	Low
0,1	Minor	0,35	Moderately low
0,2	Moderate	0,5	Moderate
0,4	Major	0,65	High
0,8	Critical	0,8	Very high

Table 7

Definition of the ERV indicator

Value	**ERV**
Up to 0,15	Low-risk zone (Rank 3 risks)
From 0,15 to 0,25	Moderate-risk zone (Rank 2 risks)
From 0,25 to 1,0	High-risk zone (Rank 1 risks)

Table 8

Derivative risk assessment

№	**Risk name**	**Impact (consequence)**	**Probability of occurrence**	**Impact level on business process execution**	**ERV**	**Rank**
1	Decrease in operational volume	Loss of development opportunities	0,8	0,05	0,04	3
		Necessity to attract new partners/users	0,95	0,1	0,095	3
2	Staff reductions (layoffs)	Increased workload on remaining staff	0,95	0,4	0,38	1
		Internal tension	0,6	0,2	0,12	3
3	Decline in service quality	Loss of existing partners and clients	0,5	0,4	0,2	2
		Reputational damage	0,9	0,2	0,18	2
4	Accrual of debt	Deterioration of relationships with partners	0,7	0,4	0,28	1
		Loss of development opportunities	0,9	0,05	0,045	3
		Necessity to seek additional funding sources	0,95	0,1	0,095	3
5	Threat to organizational viability	Dissolution of the organization	0,5	0,8	0,4	1
6	Reputational damage	Loss of existing and potential users	0,5	0,6	0,3	1
		Loss of cooperation and partnership opportunities	0,5	0,4	0,2	2
		Necessity to allocate resources for reputation recovery	0,8	0,2	0,16	2

The resulting ranking confirms the uneven distribution of hazard levels among derivative risks and highlights critical areas requiring management attention. This provides an analytical foundation for developing targeted response strategies.

Based on the identification, scenario analysis, and quantitative ranking of risks, a strategic management roadmap for derivative risks has been developed. This roadmap integrates specific response strategies tailored to their level of criticality. The generalized roadmap is presented in Table 9.

The proposed strategic roadmap provides a formalized toolset for decision support under conditions of financial instability, enhancing the operational resilience of the system under study. These results serve as the foundation for the study's generalized conclusions.

The proposed information technology for systems analysis integrates the stages of identification, modeling, and quantitative measurement, allowing for a comprehensive overview of the project's risk security. Utilizing the expected risk value (ERV) as a key indicator ensures the dynamic adaptation of management strategies to shifting environmental conditions.

Conclusions and prospects. This scientific study performs a systematic formalization of the emergence and progression of cascading derivative risks within complex socio-technical systems, using environmental projects as a case study. The application of set theory facilitates a transition from qualitative threat descriptions to the construction of mathematical membership models. These models reflect the logic of transforming external financial

Table 9

Development of a strategic management roadmap for derivative risks stemming from external influences

№	Derivative risk name	Impacted business process	Response strategy	Recommended response algorithm (actions)
1	Decrease in operational volume	1. Sale of recyclables 2. Sale of reusable goods	Avoidance	1. Partner with companies to manage their waste for a fee. 2. Organize "Eco-toloka" (community clean-ups) across Ukraine. 3. Launch ad campaigns to attract new station visitors. 4. Offer "No Waste Shop" discounts to new users after their first successful sorting visit. 5. Implement a bonus system convertible into shop discounts or partner perks
2	Staff reductions (layoffs)	1. Sorting of recyclables	Mitigation	1. Engage volunteers and eco-activists for station operations. 2. Optimize labor-intensive processes (e.g., investing in sorting robotics). 3. Implement KPIs for all staff members. 4. Establish a reward system for exceeding work quotas. 5. Develop a support plan for employees affected by layoffs
3	Decline in service quality	1. Educational activities	Mitigation	1. Identify root causes of quality decline. 2. Provide professional development and upskilling for service staff. 3. Implement an internal penalty system for user complaints
4	Accrual of debt	1. Sale of reusable goods	Mitigation	1. Conduct cost analysis and optimization. 2. Identify and onboard new business partners. 3. Secure additional investment sources
5	Reputational damage	1. Lobbying and advocacy 2. Educational activities	Avoidance	1. Ensure transparent financial reporting. 2. Host charitable educational events. 3. Organize community eco-cleanups. 4. Actively grow social media presence. 5. Collaborate with influencers and corporate partners. 6. Develop an informational portal/blog
6	Threat to organizational viability	All	Avoidance	1. Proactively avoid or mitigate Risks № 1, 4, and 5, as their cumulative impact leads to this risk

deficits into internal technological and organizational degradation. The developed methodological approach, based on the calculation of expected risk value (ERV), provides an objective foundation for algorithmic management decisions and the optimal allocation of limited resources.

The practical significance of these results is confirmed by the creation of a strategic roadmap containing clear response algorithms for critical risks – specifically through the implementation of KPI systems and the automation of production lines using robotic sorters. This not only minimizes the negative impact of resource shortages but also enhances the system's operational resilience in highly turbulent environments. Future research prospects lie in integrating these set-theoretic models into specialized decision support systems (DSS), enabling real-time monitoring of derivative risks and the automated adaptation of protection strategies.

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