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CAUSAL ANALYSIS OF RISK FACTORS IN AUTONOMOUS MARITIME PLATFORMS USING THE DEMATEL METHOD

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Autonomous platforms are increasingly used in maritime industry where permanent crew presence is limited or impossible. At the same time, the growth in autonomy creates a complex risk environment characterized by the close interaction of technical, organizational, and informational factors. Traditional risk assessment methods, typically focused on linear cause-and-effect relationships, are not able to fully capture the systemic and interdependent nature of these interactions. This paper proposes a DEMATEL-oriented approach to analysing cause-and-effect relationships between key risk factors of autonomous maritime platforms. The methodology is based on expert assessments and enables the quantitative identification of both direct and indirect influences among factors, allowing the determination of causal and dependent elements within the risk structure. The analysis considers factors reflecting the specifics of autonomous operation, including computerization, autonomous decision-making capability, response time, emergency management, and the potential need for platform abandonment. The practical implementation of the approach is demonstrated through a numerical example involving the construction of direct and total influence matrices, calculation of prominence and causal role indices, and visualization via a cause-effect diagram and a threshold influence network. The results show that autonomous decision-making act as system-forming drivers of risk, while emergency response and platform evacuation are predominantly dependent factors. The proposed approach can be applied as a decision-support tool in the design, operation, and safety management of autonomous maritime platforms and can serve as a basis for further integration with fuzzy and dynamic risk analysis models.
Ключові слова: *autonomous shipping; operational risk; maritime transport; ship systems; autonomous platforms; DEMATEL; risk analysis; cause-and-effect relationships; maritime safety; decision-making.*

Problem statement

The active development of Autonomous Maritime Platforms (AMP) is significantly changing approaches to offshore operations, reducing or completely eliminating the crew on board reduces risks to personnel, but at the same time creates new systemic threats related to autonomous decision-making, digital infrastructure, and remote control.

Unlike traditional offshore facilities, autonomous platforms function as complex cyber-physical systems in which technical, organizational, and informational factors are closely interrelated. Failure of one element can cause cascading effects, leading to emergencies, delays in response, or even the need to abandon the platform.

Classic risk assessment methods, such as FMEA or fault tree analysis, are usually based on linear cause-and-effect relationships and do not adequately account for the mutual influence of factors and feedback loops. In this context, it is advisable to use multi-criteria decision analysis methods capable of modeling complex cause-and-effect structures.

Analysis of recent studies and publications

Contemporary research on maritime security focuses heavily on the issues of autonomous shipping and autonomous systems. The authors note that autonomy reduces the influence of the human factor, but at the same time increases dependence on digital technologies, decision-making algorithms, and the reliability of communication channels. Some studies focus on cyber risks, software failures, and situational awareness issues in autonomous systems. However, most existing approaches consider risks in isolation, without taking into account their mutual influence.

Systemic cause-and-effect risk analysis for autonomous maritime platforms is based on several interrelated blocks of literature, which together justify the applicability of the DEMATEL method. First, studies on global security management, hybrid threats, terrorism, barriers to sustainable development, and evacuation planning based on AIS data show that risks in the maritime industry are multi-level and polycentric in nature and depend on both politics and the spatial organization of infrastructure [1-7].

Against this backdrop, a large family of DEMATEL-oriented approaches (classical, fuzzy, grey, neutrosophic DEMATEL, as well as combined schemes DEMATEL-ISM/ANP, DEMATEL-BN, DEMATEL-FT-BN, etc.) has been formed, which are used to identify and quantitatively assess causal relationships between factors of accident rates, man-made incidents, human errors, organizational barriers, and digital limitations in various industries-from maritime transport, fires, and explosions to steelmaking, hydrogen infrastructure, and construction [8, 9-19]. For autonomous and semi-autonomous platforms, these tools are applied to the technical research base covering new AUV/USV control algorithms, collision avoidance models, reliable communications and radar-sensor systems, energy efficiency of ship installations, use of alternative fuels, hull design optimization, and hull structure integrity [20-22].

The DEMATEL method is widely used to analyze complex systems in the fields of transport, energy, safety management, and risk engineering. Its advantage lies in the ability to identify causal factors (drivers) and dependent factors (outcomes), as well as in constructing a visual map of cause-and-effect relationships. Despite the potential of DEMATEL, its application for analyzing the risks of autonomous maritme platforms remains limited, which determines the scientific novelty of this study.

Purpose of the article

The purpose of this work is to develop and apply the DEMATEL method to analyze the cause-and-effect relationships between key risk factors for autonomous platforms in order to support effective safety management.

The main scientific results of this study are as follows:

- a structured approach based on the DEMATEL method is proposed for analyzing cause-and-effect relationships between risk factors for autonomous offshore platforms;
- it has been identified that digitalization and autonomous decision-making are key causal factors, while emergency response, platform abandonment, and response time are mostly dependent;
- a numerical implementation of DEMATEL is demonstrated through the construction of cause-and-effect diagrams, ensuring clarity and reproducibility of results;
- the practical applicability of the proposed approach in supporting management decisions related to autonomous offshore platform safety is demonstrated.

Methods and materials

In this study, a clear distinction is made between the concepts of *risk* and *risk factors*. Risk is understood as the probability and consequences of undesirable events affecting the safety or performance of autonomous maritime platforms. In contrast, risk factors are interpreted as causal drivers that influence the emergence and evolution of such risks. Thus, the DEMATEL method is applied to identify and analyze the interdependencies between risk factors rather than to quantify risks directly.

The Decision-Making Trial and Evaluation Laboratory (DEMATEL) method used is this study to analyze the cause-and-effect relationships between risk factors for autonomous maritime platforms (AMP). DEMATEL is a multi-criteria decision analysis method that allows identifying both direct and indirect interactions between elements of complex systems.

The main advantage of the DEMATEL method is its ability to structure expert knowledge into a formalized model of cause-and-effect relationships, which is critically important for the analysis of autonomous platforms as cyber-physical systems with a high level of interdependence between technical, information, and management components.

The application of DEMATEL in this work is carried out in several consecutive stages:

- identification of key risk factors;
- formation of a matrix of direct influences based on expert assessments;
- normalization of the matrix to ensure the convergence of calculations;
- calculation of the matrix of general influences;
- determination of integral indicators of influence and dependence;
- interpretation of results in the form of cause-and-effect diagrams.

This approach ensures transparent calculations, reproducible results, and practical application of the conclusions obtained in the risk management of autonomous platforms.

The general sequence of DEMATEL analysis implementation for autonomous offshore platforms is shown in Figure 1. The diagram shows the stages of forming a set of factors, collecting expert assessments, constructing a matrix of direct influences, normalizing, calculating a matrix of general influences, and determining the integral indices D, R, $D+R$, and $D-R$. The construction of a cause-and-effect diagram and (if necessary) a threshold influence network is used to interpret the results and determine risk management priorities.

Within the operational context of autonomous maritime platforms, the primary risks include loss of operational control, delayed response to failures, emergency escalation, mission interruption, and the need for platform evacuation. These risks arise as consequences of interactions between technological, organizational, and digital factors. Therefore, the analysis focuses on identifying the key risk factors that act as precursors to these adverse outcomes.

At the first stage, a list of risk factors characterizing the safety of AMP was compiled. The factors were selected based on an analysis of scientific publications, industry standards, and expert experience in the field of offshore operations and autonomous systems.

The final set of factors included the following key aspects: the need to leave the platform, response time to failures, the system's ability to make autonomous decisions, the effectiveness of emergency management, and the level of digitalization of the platform. The selected factors cover both technical and organizational components of the system and reflect the specifics of operating AMP without a permanent crew presence.

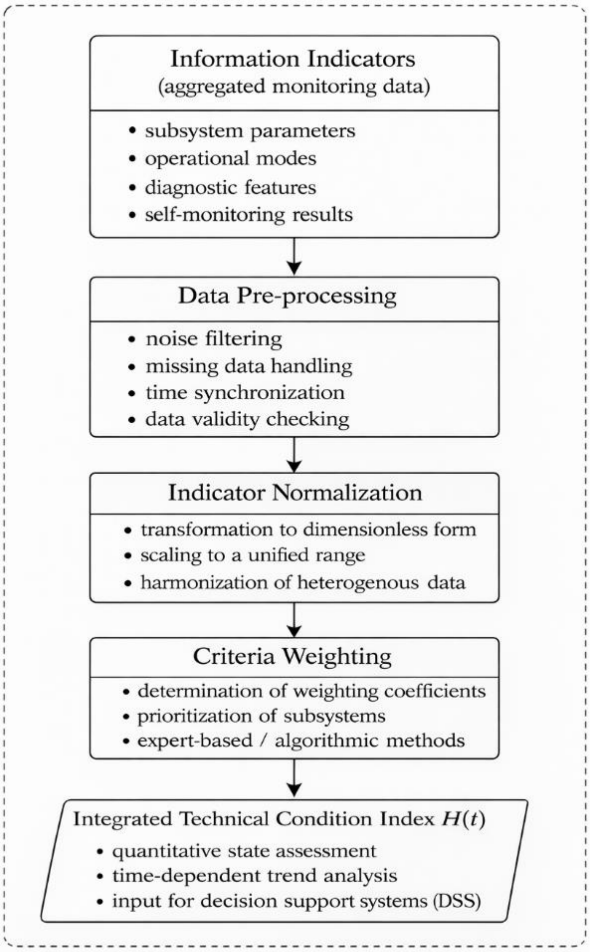

Fig. 1 – DEMATEL-based risk analysis workflow for autonomous maritime platforms (The workflow includes factor selection, expert elicitation, matrix normalization, computation of the total-relation matrix, derivation of prominence and relation indices, and visualization via the cause-effect diagram.)

The mutual influence between risk factors was assessed with the involvement of experts in the fields of marine engineering, offshore operations, and autonomous control systems. The experts were asked to assess the degree of influence of each factor on other factors on a discrete scale from 0 to 4, where 0 means no influence and 4 means a very strong influence. In order to reduce the subjectivity of the assessments, individual expert matrices were aggregated by averaging, which made it possible to obtain a generalized matrix of direct influences for further analysis.

After forming the matrix of direct influences, the standard computational procedure of the DEMATEL method was implemented. At this stage, the matrix is normalized, the matrix of total influences is calculated, and quantitative indicators of influence and dependence are determined for each factor.

The calculations were performed using software implementations in MATLAB and Python environments. The numerical results obtained became the basis for constructing cause-and-effect diagrams and threshold influence networks, which allows for a visual interpretation of the risk structure of AMP.

DEMATEL Framework

3.1 Definition of the Factor Set. Let the system consist of a finite set of risk-related factors:

$$\boldsymbol{F} = \{f_1, f_2, \dots, f_n\}, \tag{1}$$

where n denotes the total number of factors. In this study, the following factors are considered: f_1: Abandonment, f_2: Timing of response, f_3: Decision-making capability, f_4: Emergency handling, f_5: Digitalization level.

3.2 Direct-Relation Matrix. Expert evaluations are collected to assess the influence of factor f_i on factor f_j using a discrete scale from 0 (no influence) to 4 (very high influence). The direct-relation matrix is defined as:

$$\boldsymbol{A} = [a_{ij}]_{n\times n}, \quad a_{ij} \in [0,4], \quad a_{ii} = 0. \tag{2}$$

3.3 Normalization. The matrix is normalized to ensure convergence:

$$s = max_i \sum_{j=1}^{n} a_{ij}, \qquad \boldsymbol{X} = \frac{\boldsymbol{A}}{s}. \tag{3}$$

3.4 Total-Relation Matrix. The total-relation matrix is computed as:

$$\boldsymbol{T} = \boldsymbol{X}(\boldsymbol{I} - \boldsymbol{X})^{-1}, \tag{4}$$

where **I** - identity matrix.

3.5 Influence and Dependence Measures. The influence vector **D** and dependence vector **R** are defined as:

$$D_i = \sum_{j=1}^{n} t_{ij}, \quad R_i = \sum_{j=1}^{n} t_{ji}. \tag{5}$$

3.6 Causal Indicators. Two indices are derived:

$$M_i = D_i + R_i, \quad C_i = D_i - R_i. \tag{6}$$

where M_i represents factor prominence and C_i determines causal role.

4. Case study of an autonomous platform

The proposed approach was applied to a hypothetical AMP operating without a permanent crew. Expert assessments were obtained from specialists in the fields of marine engineering, offshore operations, and autonomous systems.

DEMATEL calculations (normalization, construction of the general influence matrix, and calculation of the D, R, $D+R$, and $D-R$ indices) were performed using software implementation in MATLAB/Python. The complete script is provided in Appendix A / in the supplementary materials.

Table 1
Risk factors considered in the DEMATEL analysis

Code	Factor name	Description
F1	Abandonment	Loss of operational control requiring evacuation
F2	Response timing	Time required to initiate corrective actions
F3	Decision-making	Autonomous or remote decision capability
F4	Emergency handling	Ability to manage abnormal situations
F5	Digitalization	Level of digital integration

Numerical example of the application of the DEMATEL method

To demonstrate the practical implementation of the proposed DEMATEL approach, a numerical example was performed for five risk factors of an AMP: abandonment (F1), response timing (F2), decision-making (F3), emergency handling (F4), and digitalization (F5).

At the first stage, based on expert assessments, a matrix of direct influences A was formed, in which each element a_{ij} reflects the intensity of the influence of factor F_i on factor F_j on a scale from 0 to 4. The diagonal elements of the matrix are zero, which corresponds to the absence of self-influence of factors.

Next, matrix A was normalized by dividing it by the maximum sum of the row elements, which ensured that the DEMATEL method convergence condition was met. The resulting normalized matrix X. The values of the elements of the matrix X are in the interval [0;1], which allows both direct and indirect relationships between factors to be correctly taken into account.

The matrix of total influences T, which reflects the cumulative effect of direct and indirect interactions, was calculated according to the classical DEMATEL formula. Analysis of the matrix T indicates the presence of significant indirect influences that cannot be detected based solely on the matrix of direct estimates.

Based on the T matrix, the indicators of total influence D, total dependence R, as well as the integral indices of prominence (D+R) and relation ($D-R$) were calculated for each factor. The indicator $D+R$ characterizes the overall involvement of the factor in the risk system, while $D-R$ determines its causal role.

The results of the analysis show that the factors Digitalization (F5) and Decision-making (F3) have positive values of the indicator $D-R$, which allows them to be classified as causal factors (cause group). This means that these factors form the initial risk impulses and have the greatest systemic impact on other elements.

On the other hand, the factors Emergency handling (F4), Abandonment (F1), and Response timing (F2) are characterized by negative values of $D-R$, which indicates their dependent nature (effect group). In particular, the emergency handling factor has the lowest value $D-R$, indicating its high sensitivity to changes in the autonomous control system and digital infrastructure.

A graphical representation of the results in the form of a cause-and-effect diagram is shown in Figure 2, where the prominence indicator (D+R) is plotted on the x-axis and the relation indicator ($D-R$) is plotted on the y-axis. The diagram clearly demonstrates the division of factors into causal and dependent groups, as well as the central role of factors F3 and F5 in the risk structure.

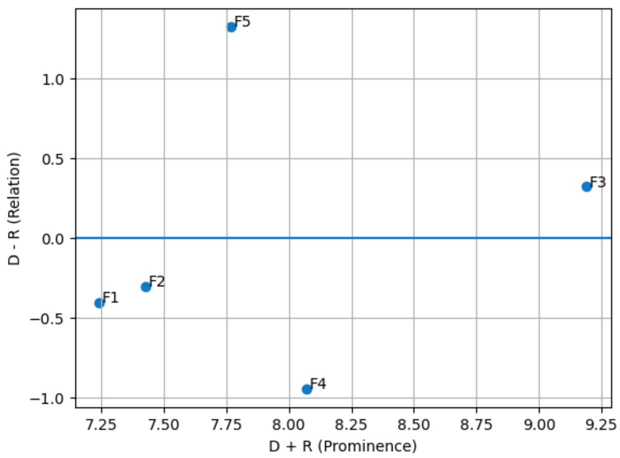

Fig. 2 – Cause-effect diagram of risk factors (DEMATEL)

As shown in Figure 2, the factors Decision-making (F3) and Digitalization (F5) are located at the top of the diagram, indicating their causal nature in the risk structure of an AMP. In contrast, the factors Emergency handling (F4), Abandonment (F1), and Response timing (F2) belong to the group of dependent factors.

For additional interpretation, a threshold cause-and-effect network was constructed (Figure 3), which takes into account only those connections whose values exceed the average value of the elements of the T matrix. The resulting network clearly illustrates the dominant channels of influence in the system and confirms the system-forming role of digitalization and autonomous decision-making.

Figure 2 shows a threshold-based cause-effect network derived from the total-relation matrix using a threshold value α equal to the mean of the matrix T. The resulting network confirms the system-forming role of the Digitalization (F5) and Decision-making (F3) factors. In general, the numerical example confirms the feasibility of using the DEMATEL method for analyzing the risks of autonomous platforms and demonstrates its ability to identify key risk drivers that should be priority targets for management intervention.

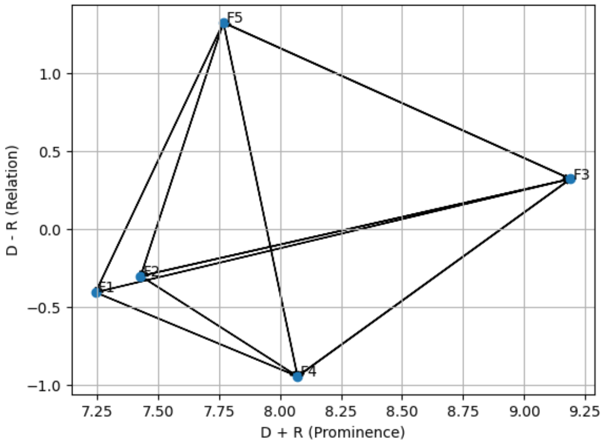

Fig. 3 – Threshold-based causal network

Results and discussion

The results of the DEMATEL analysis indicate the presence of a clearly defined cause-and-effect structure between the risk factors of autonomous offshore platforms. Based on the $D-R$ index values, the factors Digitalization (F5) and Decision-making (F3) are classified as cause group factors, which means they have a dominant influence on the formation of the system's risk profile.

The factors Emergency handling (F4), Abandonment (F1), and Response timing (F2) are characterized by negative $D-R$ values and belong to the effect group. This indicates that their status is largely determined by the quality of the digital infrastructure and the effectiveness of autonomous decision-making.

The values of the $D+R$ indicator show that the Decision-making (F3) factor has the highest integral significance, i.e., it is most involved in the system of interactions and plays a central role in the risk structure.

The results confirm that for autonomous maritime platforms, the key sources of risk are not individual accidents, but systemic factors related to digitalization and autonomous decision-making algorithms. This is consistent with current research in the field of autonomous and cyber-physical offshore system safety, where digital components are considered to be the main drivers of risk.

The identification of Emergency Handling and Abandonment as dependent factors indicates the limited effectiveness of purely reactive safety measures. Instead, the results of the DEMATEL analysis point to the advisability of proactive risk management by increasing the reliability of digital systems, reducing autonomous response times, and improving decision-making logic.

Thus, the DEMATEL method allows not only to identify critical risk factors, but also to justify the priorities of managerial influence, focusing on causal factors rather than their consequences. The proposed DEMATEL-oriented methodology provides the possibility of systematic analysis of the relationships between risk factors and allows determining their cause-and-effect hierarchy. The results confirm that investments in the development of digital infrastructure, autonomous decision-making algorithms, and predictive monitoring systems have a significantly greater impact on safety than traditional reactive emergency response measures.

The DEMATEL method can be effectively used as an analytical tool to support management decisions in the design, certification, and operation of autonomous platforms. For regulatory authorities and developers, this creates a basis for integrating causal risk analysis into regulatory and technical standards and procedures for assessing the safety of new-generation systems.

Conclusions

The paper develops and tests a DEMATEL-oriented approach to analyzing cause-and-effect relationships between risk factors for autonomous offshore platforms. The proposed methodology allows for a quantitative assessment of both direct and indirect interactions between factors and the formation of a hierarchy of causal and dependent elements in the risk structure. The results of a numerical example showed that the factors of digitalization and autonomous decision-making play a system-forming role and are the main drivers of risk, while emergency response, platform abandonment, and response time are predominantly dependent. This indicates the advisability of focusing safety management measures on proactively improving the reliability of digital and control components of autonomous offshore platforms. The limitations of the study are the use of expert assessments and the static nature of the model. Further research may be aimed at expanding the proposed approach by applying fuzzy or dynamic DEMATEL, as well as integrating it with other risk analysis methods and using real operational data.

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ПРИЧИННИЙ АНАЛІЗ ФАКТОРІВ РИЗИКУ В АВТОНОМНИХ МОРСЬКИХ ПЛАТФОРМАХ З ВИКОРИСТАННЯМ МЕТОДУ DEMATEL

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Швидкий розвиток автономних морських платформ суттєво трансформує підходи до виконання офшорних та морських операцій, зменшуючи участь людини та підвищуючи ефективність функціонування систем. Водночас зростання рівня автономності формує складне середовище ризиків, що характеризується тісною взаємодією технічних, організаційних та інформаційних факторів. Традиційні методи оцінювання ризиків, орієнтовані на лінійні причинно-наслідкові залежності, не дозволяють повною мірою врахувати системний характер таких взаємодій. У статті запропоновано DEMATEL-орієнтований підхід до аналізу причинно-наслідкових зв'язків між ключовими факторами ризику в автономних морських платформах. Методологія базується на експертних оцінках та дозволяє кількісно визначити як прямі, так і непрямі впливи між факторами з подальшим виділенням причинних і залежних елементів у структурі ризиків. До аналізу включено фактори, що відображають специфіку експлуатації автономних засобів, автономне прийняття рішень, час реагування, управління аварійними ситуаціями. Практична реалізація підходу продемонстрована на числовому прикладі з побудовою матриць прямих і загальних впливів, розрахунком індексів значущості та причинної ролі, а також візуалізацією результатів у вигляді діаграми причинно-наслідкових зв'язків і порогової мережі впливу. Отримані результати свідчать, що інтелектуальні технології та автономне прийняття рішень відіграють системну та утворюючу роль і є ключовими драйверами ризику, тоді як аварійне реагування та процес залишення платформи мають переважно залежний характер. Запропонований підхід може бути використаний як інструмент підтримки управлінських рішень у процесах проєктування, експлуатації та управління безпекою автономних морських платформ, а також слугувати основою для подальших досліджень у напрямі інтеграції нечітких та динамічних моделей аналізу ризиків.

Keywords: *автономне судноплавство; експлуатаційний ризик; морський транспорт; системи судна; автономні морські платформи; DEMATEL; аналіз ризиків; причинно-наслідкові зв'язки; морська безпека; прийняття рішень.*

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