



# Dynamic Scenario-Based DEMATEL for Modeling Time-Evolving Risk Topology in Autonomous Maritime Platforms



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## Abstract

Autonomous maritime platforms operate in complex and potentially hazardous environments where the risk structure is not constant but varies depending on the system's operating mode. The traditional DEMATEL approach assumes a fixed cause-and-effect topology and does not consider the transformation of relationships between factors during transitions from normal to degraded or emergency modes. This paper proposes a dynamic scenario-oriented modification of the DEMATEL method for analyzing the evolution of the risk structure of autonomous maritime platforms. The methodology is based on constructing separate direct-relation matrices for normal, degraded, and emergency operating scenarios. For each scenario, total-relation matrices and causal indicators are calculated. New dynamic metrics are introduced, including a scenario transformation operator, a scenario instability index, and an integral dynamic criticality index. These indicators enable quantitative assessment of changes in causal dominance across operating modes. Numerical modeling demonstrates that autonomous decision-making mechanisms may dominate in normal mode, while emergency response and critical event management mechanisms become key drivers in crisis conditions. The results confirm that the risk topology of autonomous maritime platforms is inherently scenario-dependent and should be modeled dynamically to support adaptive safety management strategies.

**Keywords:** Dynamic DEMATEL; Scenario-based modeling; Risk topology; Autonomous maritime platforms; Causal analysis; Operational regimes; System resilience

## Introduction

Autonomous maritime platforms are complex cyber-physical systems in which technical, informational, and organizational components interact in real time. Unlike traditional maritime facilities, autonomous platforms are characterized by a high level of digitalization and automated decision-making, which creates a new risk structure.

The DEMATEL method is widely used to model cause-and-effect relationships and risk interdependencies in complex systems. Huang et al. [1] provide a comprehensive overview of

risk assessment approaches in the maritime industry, highlighting the growing need for integrated and dynamic maritime transport safety modeling methods.

Recent studies show that the DEMATEL method has grown through its application to hybrid models and industry-specific models. The researchers Zhang et al. [2] developed a grey-DEMATEL method which they applied to manufacturing systems in their study. Zhou et al. [3] used DEMATEL together with STPA-FTA to create a method which enabled them to measure risks in

shale gas extraction operations. Similar hybridizations include fuzzy DEMATEL for sustainable supply chains [4], DEMATEL-FT-BN for life-cycle risk evaluation [5], and DEMATEL-ANP for governance complexity modeling [6].

In the context of safety-critical infrastructures, fuzzy and hybrid DEMATEL-based risk frameworks have been applied to gas pipeline shutdown operations [7], maritime collision accident evolution [8], and system dynamics integration for cost prediction [9]. Emerging applications also extend to ESG-driven logistics systems [10] and healthcare 4.0 monitoring environments [11].

Despite this broad methodological development, most existing applications treat the total-relation matrix as structurally invariant and focus on static causal configurations. Even when hybridized, DEMATEL is typically applied within a single operational context. The problem of explicitly modeling regime-dependent structural transformations of risk topology remains insufficiently addressed, particularly in autonomous maritime systems.

Most existing studies use static cause-and-effect analysis, including the classic DEMATEL method, which allows identifying drivers and dependent risk factors. However, this approach does not consider changes in the relationships between factors in different operating modes. In real conditions, the risk structure of an autonomous platform in normal mode can differ significantly from the risk structure in a degraded or emergency state.

The DEMATEL method has been widely applied for modeling causal relationships in complex systems and risk analysis. However, most existing applications assume structural invariance of the total-relation matrix and focus on static cause-effect configurations. In maritime and cyber-physical systems, where operational regimes dynamically evolve, such assumptions may lead to incomplete representation of risk interactions. This creates the need for a scenario-dependent extension of DEMATEL capable of capturing time-evolving causal structures.

The purpose of this work is to develop a dynamic scenario-oriented DEMATEL approach that allows modeling the evolution of cause-and-effect relationships between risk factors of autonomous maritime platforms depending on the system's operating mode.

### Dynamic Scenario-Based DEMATEL Framework

#### Scenario-dependent direct-relation matrices

A matrix of direct impacts is determined for each operational scenario:

$$A^{(k)} = [a_{ij}^{(k)}], \quad k \in \{1, 2, 3\}, \quad (1)$$

where:  $k=1$  - Normal mode,  $k=2$  - Degraded mode,  $k=3$  - Emergency mode

$$a_{ij}^{(k)} \in [0, 4], \quad a_{ii}^{(k)} = 0. \quad (2)$$

#### Scenario-based total-relation matrices

For each scenario:

$$s^{(k)} = \max_i \sum_{j=1}^n a_{ij}^{(k)} \quad (3)$$

$$X^{(k)} = \frac{A^{(k)}}{s^{(k)}} \quad (4)$$

$$T^{(k)} = X^{(k)} \left( I - X^{(k)} \right)^{-1} \quad (5)$$

#### Dynamic causal indicators

$$D_i^{(k)} = \sum_{j=1}^n t_{ij}^{(k)} \quad (6)$$

$$R_i^{(k)} = \sum_{j=1}^n t_{ji}^{(k)} \quad (7)$$

$$Rel_i^{(k)} = D_i^{(k)} - R_i^{(k)} \quad (8)$$

$$Prom_i^{(k)} = D_i^{(k)} + R_i^{(k)} \quad (9)$$

#### Scenario Transformation Operator

To quantitatively describe changes in the cause-and-effect structure between scenarios, a scenario transformation operator is introduced:

$$\Delta T^{(k \rightarrow l)} = T^{(l)} - T^{(k)}, \quad (10)$$

where:

$k, l \in \{1, 2, 3\}, k \neq l, T(k)$  – total – relation matrix for scenario  $k$

Element  $\Delta t_{ij}^{(k \rightarrow l)}$  reflects the change in the influence of factor  $i$  on factor  $j$  during the transition between modes.

For an aggregated assessment of the transformation, we introduce the matrix norm:

$$\|\Delta T^{(k \rightarrow l)}\|_F = \sqrt{\sum_{i=1}^n \sum_{j=1}^n \left( \Delta t_{ij}^{(k \rightarrow l)} \right)^2}. \quad (11)$$

This indicator characterizes the intensity of structural restructuring of the risk system.

#### Scenario Instability Index

For each factor, the scenario instability index is determined:

$$SI_i = \sqrt{\frac{1}{m} \sum_{k=1}^m \left( Rel_i^{(k)} - \overline{Rel_i} \right)^2}, \quad (12)$$

where:

$$\overline{Rel}_i = \frac{1}{m} \sum_{k=1}^m Rel_i^{(k)}. \quad (13)$$

Thus  $m=3$  - number of scenarios,  $SI_i$  - sensitivity of factor  $i$  to operational regime. The greater the value of  $SI_i$ , the less stable the role of the factor in different modes of operation.

### Dynamic Criticality Index

The integral assessment of the importance of a factor, considering its instability, is determined as:

$$DCI_i = Prom_i \cdot (1 + SI_i), \quad (14)$$

where

$$Prom_i = \frac{1}{m} \sum_{k=1}^m Prom_i^{(k)}. \quad (15)$$

Thus: high values of  $Prom_i$  indicate the systemic significance of the factor; high values of  $SI_i$  indicate its sensitivity to changes in operating modes; high values of  $DCI_i$  characterize the factor as strategically critical.

### Discussion and Practical Implications

The proposed dynamic scenario-oriented DEMATEL approach extends the classical static formulation of the problem by introducing explicit modeling of structural changes in cause-and-effect relationships depending on the system's operating mode. Unlike traditional approaches, in which the matrix of general influences  $T$  is considered invariant, in the proposed model it is defined as a scenario-dependent operator  $T^{(k)}$ , which reflects the current operational state of the autonomous platform. Introduction of the scenario transformation operator allows quantitative comparison of risk topology between modes. Frobenius norm  $\|\Delta T^{(k \rightarrow l)}\|_F$  is used as an integral measure of the intensity of structural restructuring of the system. High values of this indicator indicate a significant redistribution of causal dominance among risk factors. The scenario instability index  $SI_i$  allows identifying factors whose role is most sensitive to changes in the operating mode. Such factors can act as hidden triggers for the system to transition to a degraded or emergency state.

The integral indicator of dynamic criticality  $DCI_i$  combines the structural significance of a factor with its mode instability, forming a more reasonable criterion for prioritizing safety management measures. The results of numerical modeling demonstrate a structural inversion of the causal role of factors: autonomous decision-making mechanisms dominate in normal mode, while in emergency mode, response and critical event management mechanisms become the key drivers. This confirms that the risk topology of autonomous maritime platforms is highly scenario-dependent.

### Conclusion

Main results of the study: a formalism of scenario-dependent matrices of direct and complete influences has been developed. A scenario transformation operator for quantitative analysis of structural changes has been proposed. A scenario instability index has been formed to assess the sensitivity of factors to operating modes. An integral indicator of dynamic criticality has been introduced to support management decisions. It has been shown that the causal dominance of factors varies depending on the operating scenario. The results obtained indicate that the use of static risk analysis methods can lead to an underestimation of structural transformations that occur during transitions between system operating modes. Considering the dynamic nature of cause-and-effect relationships allows for increased adaptability of safety management strategies and strengthened resilience of autonomous maritime platforms. Further research may be directed toward expanding the model in the direction of probabilistic or fuzzy DEMATEL, as well as integrating the approach with real-time systems for adaptive risk monitoring.

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