ACCSCIENCE PUBLISHING

Asian Journal of Water, Environment and Pollution

ORIGINAL RESEARCH ARTICLE

# A bibliometric analysis of natural gas transportation research: From risk analysis to route optimization

**Na Li, Yidan Tang, Xiaoming Wu***

Department of Petroleum Engineering Management, School of Economics and Management, Southwest Petroleum University, Chengdu, Sichuan, China

## Abstract

Under the transition toward low-carbon energy systems, natural gas transportation has attracted increasing attention with respect to transportation safety, operational coordination, and intelligent decision-making. Based on 1,687 publications retrieved from the Web of Science Core Collection database between 2008 and 2025, we conducted a bibliometric and knowledge graph analysis of natural gas transportation research using CiteSpace. Keyword co-occurrence analysis, cluster analysis, and temporal evolution analysis were employed to examine the knowledge structure, research hotspots, and evolutionary characteristics of the field. The results indicate that natural gas transportation research has gradually evolved into three major research streams: transportation risk analysis, coordinated operation and scheduling, and intelligent optimization. Early studies mainly focused on engineering-oriented safety analysis, while recent research has increasingly emphasized integrated energy coordination, uncertainty-aware decision-making, and intelligent transportation optimization under complex energy environments. Risk-related research has expanded from traditional accident investigation to quantitative risk assessment and risk propagation analysis. Coordinated operation research increasingly focuses on integrated energy systems and operational scheduling under uncertainty. Intelligent optimization research has developed rapidly in routing optimization, intelligent algorithms, and dynamic decision-making methods. Despite the rapid growth of these research streams, their integration remains limited. In particular, the interaction between transportation risk analysis and intelligent optimization has not been sufficiently incorporated into existing transportation decision-making frameworks. Future research should further integrate risk analysis, intelligent optimization, and real-time transportation decision-making to support the low-carbon energy transition.

***Keywords:*** Natural gas transportation; Transportation risk; Intelligent optimization; Knowledge graph; Multi-objective optimization

***Corresponding author:**
Xiaoming Wu
(wuxiaoming028@163.com)

**Citation:** Li N, Tang Y, Wu X. A bibliometric analysis of natural gas transportation research: From risk analysis to route optimization. *Asian J Water Environ Pollut*. 2026;23(4):026130087. doi: 10.36922/AJWEP026130087

**Received:** March 26, 2026

**Revised:** June 18, 2026

**Accepted:** June 18, 2026

**Published online:** July 6, 2026



## 1. Introduction

With the accelerating transition toward a low-carbon energy system, natural gas has increasingly served as a key transitional energy source. Its role in peak shaving in power systems, industrial fuel substitution,[1] and urban gas supply has become progressively more prominent. Compared with other fossil fuels, natural gas offers advantages in reducing carbon emissions and improving the energy structure,[2] and its reliable supply has become essential for maintaining the stable operation of regional energy systems.

From the perspective of the energy supply chain, the transportation stage acts as a critical link connecting resource supply and end-use consumption, thereby ensuring the continuity of energy delivery.[3] Traditionally, natural gas has been transported primarily through pipeline systems, particularly in large-scale gathering, transmission, and distribution networks.[4] Studies on wellbore and subsea gathering systems further demonstrate the dominant role of pipeline-based transportation infrastructure in natural gas production and delivery processes.[5,6] However, due to constraints such as geographical conditions, long construction cycles, and high investment costs, pipeline networks are often unable to achieve full spatial coverage within a limited timeframe. Under such conditions, liquefied natural gas (LNG) road transportation, characterized by high flexibility and wide accessibility, has gradually emerged as an important supplement to pipeline transport. It plays a vital role in supplying remote areas, supporting emergency response, and enabling peak demand regulation.[7]

Despite these advantages, LNG tanker transportation exhibits typical characteristics of hazardous materials transport. Its operation involves multiple risk factors, including cryogenic storage, high-pressure equipment, and complex traffic environments. Accidents in this context may lead not only to casualties and environmental damage but also to cascading impacts on regional energy supply systems.[8] Consequently, with the continuous expansion of natural gas transportation networks, improving transportation efficiency while ensuring safety has become a critical issue in the energy logistics domain.[9] Existing studies have addressed this issue from three main perspectives. First, research on transportation risk focuses on risk identification and assessment, emphasizing risk sources, accident mechanisms, and quantitative evaluation methods. Second, studies on coordinated operation in natural gas systems explore the functional complementarity and scheduling mechanisms between pipeline transport and non-pipeline modes. Third, intelligent optimization and route optimization research, typically based on vehicle routing problem models, aims to enhance transportation efficiency and service performance through multi-objective optimization approaches. These studies have made meaningful progress in both methodological development and practical applications, providing important support for analyzing natural gas transportation systems.

However, from a holistic perspective, a certain degree of fragmentation remains among these research streams. On one hand, risk-related studies tend to focus on identification and assessment, primarily describing accident probabilities and potential consequences.[10] On the other hand, intelligent optimization and route optimization research often prioritize economic or temporal objectives, with limited consideration of transportation safety risks in a systematic manner.

The role of risk factors in routing decisions has not been fully elucidated, which constrains the explanatory power and practical applicability of existing optimization models in hazardous materials transportation contexts. At the same time, with the development of multi-energy systems and intelligent optimization methods, natural gas transportation problems are increasingly characterized by multiple constraints, multiple objectives, and high levels of uncertainty.[11] The interactions among risk, efficiency, and system coordination are becoming more complex, making traditional single-objective analytical frameworks insufficient for practical decision-making. In this context, incorporating transportation risk into routing decision frameworks and developing risk-constrained multi-objective optimization models have gradually emerged as important research directions.

Motivated by these considerations, this study adopts a bibliometric perspective and employs knowledge graph techniques to investigate the knowledge structure and evolutionary patterns of natural gas transportation research. The analysis focuses on identifying research themes, knowledge structures, and their evolutionary patterns, with particular attention to the connections between risk analysis and intelligent transportation optimization. On this basis, existing research gaps are highlighted, and potential future research directions are discussed, with the aim of providing theoretical support for further studies on risk-constrained route optimization in natural gas transportation systems. This study mainly focuses on knowledge structure and research trends rather than detailed technical modeling.

## 2. Data sources and methodology

### 2.1. Data sources

To systematically examine the knowledge structure, research hotspots, and evolutionary trajectories of natural gas transportation research, this study employed the Web of Science Core Collection as the primary data source, including the Science Citation Index Expanded (SCI-EXPANDED) and the Social Sciences Citation Index (SSCI).[12]

A retrieval strategy was developed around core themes such as natural gas transportation, transportation risk, and route optimization. The time span was set to cover the period from 2008 to 2025, and only articles were retained to ensure the academic rigor and representativeness of the dataset. The search strings were constructed using combinations of representative keywords, including “natural gas transportation,” “LNG transportation,” “transportation risk,” “risk assessment,” “route optimization,” “vehicle routing,” “intelligent optimization,” “coordinated scheduling,” and “energy.” Specifically, Boolean logic operators such as AND and OR were employed to construct the retrieval expressions. Representative search expressions included: (“natural gas transportation” OR “LNG transportation”) AND (“transportation risk” OR “risk assessment”); (“natural gas transportation” OR “LNG transportation”) AND (“route optimization” OR “vehicle routing” OR “intelligent optimization”); and (“natural gas transportation” OR “LNG transportation”) AND (“coordinated scheduling” OR “energy coordination”). These retrieval expressions correspond respectively to the three thematic research streams of transportation risk analysis, coordinated operation and scheduling, and intelligent optimization, respectively.

Inclusion criteria included peer-reviewed journal articles within the defined time span, while non-relevant and duplicate records were excluded. To improve the precision and thematic relevance of the retrieved literature, multiple rounds of screening and refinement were conducted. Studies focusing exclusively on electricity dispatching, smart grid optimization, or general energy efficiency analysis without explicit relevance to natural gas transportation processes were excluded. Duplicate records, weakly related studies, conference abstracts, and non-peer-reviewed publications were also removed.

The dataset was subsequently organized into three thematic research streams based on title- and abstract-based relevance screening of the retrieved literature: (i) transportation risk identification and assessment, (ii) coordinated operation and scheduling related to natural gas transportation systems, and (iii) intelligent optimization research involving routing optimization and data-driven decision-making methods.

After the initial screening process, additional preprocessing procedures were conducted to improve dataset consistency. First, irrelevant records were excluded based on keyword matching and topic relevance assessment. Second, duplicate entries were identified and removed. Third, keyword normalization was performed by unifying synonyms, abbreviations, and variations in expression to minimize semantic bias in subsequent analyses. In addition, manual screening was conducted to remove weakly related studies, thereby improving the precision of the dataset.

In this study, weakly related studies refer to publications that mention natural gas only in a broad energy context but do not focus on natural gas transportation processes, LNG transportation, transportation safety, transportation scheduling, routing optimization, or risk-constrained decision-making. For example, studies focusing exclusively on natural gas power generation, smart grid optimization, or general energy efficiency evaluation without explicit relevance to transportation-related processes were excluded during the manual screening process. After these procedures, a refined dataset was obtained for further analysis.

It should be noted that a small proportion of the retrieved studies are related to power system scheduling. This is mainly because the data collection employed keywords associated with transportation, optimization, and risk analysis, within the broader energy system context. Given the methodological similarities between power system scheduling and natural gas transportation—particularly in optimization methods and risk-constrained decision-making—these studies were retained based on their methodological relevance.

Given the multidimensional nature of the research topic, the dataset was further divided into three thematic subsets:

(i) Studies on natural gas transportation risk identification and assessment.
(ii) Studies on coordinated operation and scheduling related to natural gas transportation systems.
(iii) Studies on the application of intelligent optimization algorithms in natural gas transportation.

This classification is intended for thematic analysis rather than strict technical categorization, and facilitates targeted analysis from different research perspectives while providing a basis for subsequent cross-domain comparisons.[13]

### 2.2. Methodology

This study adopted a bibliometric approach combined with knowledge graph techniques to conduct a structured analysis of research on natural gas transportation. By examining keyword co-occurrence relationships and their temporal distribution, the method enables a systematic exploration of the knowledge structure and evolutionary patterns of the research field, thereby providing methodological support for identifying the interconnections among different research directions.[14] CiteSpace (version 6.3.R1, Drexel University, USA) was employed to perform visual and quantitative analysis of the dataset. Two main analytical techniques were implemented: keyword clustering analysis and temporal evolution (time–zone) analysis. It should be emphasized that CiteSpace was used as a data processing and visualization tool, while the analytical contribution of this study lies in the interpretation and synthesis of the generated results.

#### 2.2.1. Keyword clustering analysis

Based on the keyword co-occurrence network, clustering algorithms were applied to group high-frequency keywords, which enables identification of core research themes and their structural distribution within the field. The clustering results are typically presented in a modular structure, where each cluster represents a distinct research direction. The size and density of clusters reflect the level of research activity and the strength of internal associations within each thematic area.[15]

By examining cluster labels—such as natural gas, risk management, and Bayesian networks—the major knowledge domains in natural gas transportation research can be identified and further synthesized. This facilitates a deeper understanding of the structural characteristics of the field and the relationships among different research themes.

#### 2.2.2. Temporal evolution analysis

To capture the dynamic development of research topics, a time–zone view was constructed based on the temporal distribution of keywords. This approach visualizes the emergence and persistence of keywords over time, thereby revealing the evolution of research themes from initial exploration to subsequent expansion. It also enables the identification of stage-specific hotspots and potential emerging frontiers within the field.[16]

#### 2.2.3. Integrated analytical framework

By integrating the above methods, this study analyzed natural gas transportation research from both structural and evolutionary perspectives. Specifically, keyword clustering was used to reveal the knowledge structure of the field, while temporal evolution analysis was employed to capture the dynamic progression of research hotspots. The combination of these approaches provides a comprehensive understanding of how the field has evolved from early-stage risk identification and assessment toward more advanced topics such as route optimization and decision support.

## 3. Research hotspots and knowledge structure analysis

### 3.1. Keyword clustering analysis

Based on the bibliographic dataset, a keyword co-occurrence network was constructed, and clustering techniques were applied to reveal the structural organization of research on natural gas transportation. This approach enables the identification of major research themes and their corresponding knowledge structures within the field.[17]

To improve the specificity and accuracy of thematic identification, clustering analysis was further conducted across different research directions. This strategy allows for a more refined interpretation of thematic distributions and helps to capture the distinct structural characteristics associated with each research direction.

In addition, rather than relying solely on cluster labels, the analysis further considers the relationships among clusters to provide a more structured understanding of the knowledge domain. Overall, the clustering results across different research streams reveal three major research orientations, with noticeable interconnections and evolutionary relationships among them.

#### 3.1.1. Research on natural gas transportation risk identification and assessment

Using the Web of Science Core Collection as the retrieval platform, a topic-based search was conducted in the SCI-EXPANDED and SSCI databases with the keywords "transportation risk" and "natural gas." The document type was restricted to Article, and the time span was set to cover the period from 2008 to 2025. Duplicate records and studies with low thematic relevance were removed to improve data quality.

A total of 370 valid publications were obtained after a structured screening process based on title and abstract evaluation. Based on the refined dataset, CiteSpace was employed to construct a keyword co-occurrence network and perform clustering analysis, as illustrated in Figure 1.

As shown in Figure 1, the clustering results indicate that research on natural gas transportation risk is mainly concentrated in several well-defined thematic areas. Cluster #0 is primarily associated with the application of Bayesian network models in risk identification and quantitative assessment. Representative keywords in this cluster include "Bayesian network," "risk assessment," and "natural gas," indicating the increasing application of probabilistic and data-driven methods in transportation risk analysis.[18] Cluster #1 focuses on natural gas transportation systems and associated risk contexts, emphasizing the interaction between energy system characteristics and transportation safety. Representative keywords in this cluster include "natural gas," "transportation safety," and "risk management," reflecting the close relationship between transportation system operation and safety management.[19] Cluster #2 represents an emerging research direction

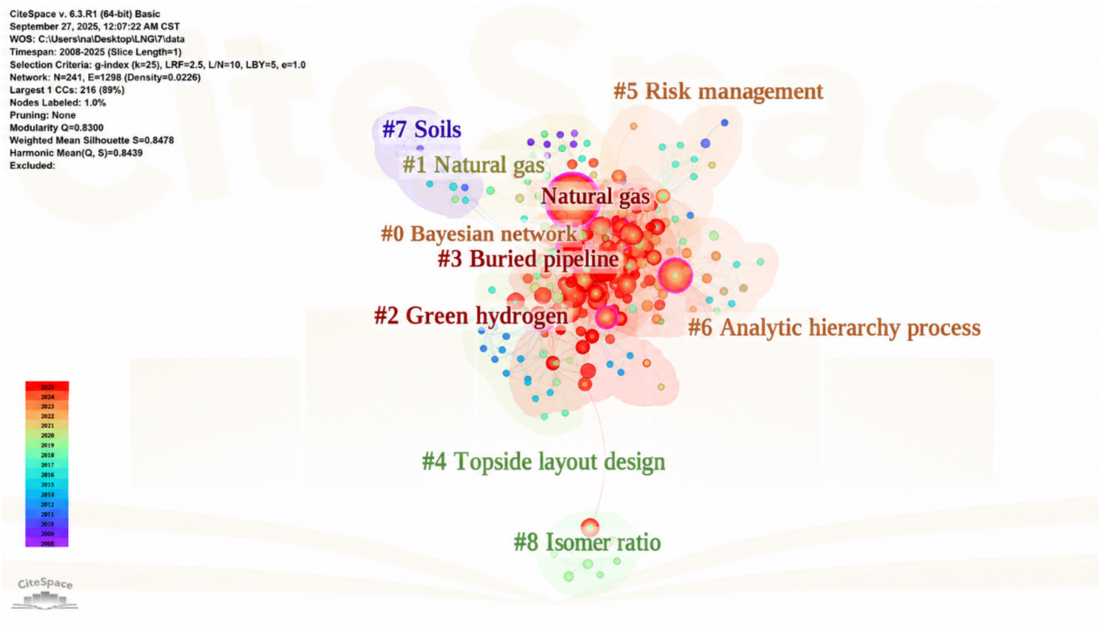


**Figure 1.** Keyword clustering map of natural gas transportation risk identification and assessment

related to green hydrogen, highlighting the growing influence of the energy transition on transportation risk studies. In particular, it involves comparative risk analyses under hydrogen–natural gas coupling scenarios and cross-energy system interactions.

Additionally, Cluster #3 is mainly concerned with the safety and integrity of pipeline infrastructure, including leakage risks, geohazards, and long-distance transmission safety, reflecting the engineering-oriented foundation of early research in this field. Cluster #4 is associated with facility-level safety, focusing on layout optimization and risk control in LNG receiving terminals, storage systems, and offshore structures. Cluster #5 emphasizes risk management frameworks and decision-making mechanisms, including emergency response strategies and multi-level approaches to transportation risk control. Finally, Cluster #6 reflects the application of traditional multi-criteria decision-making methods, such as the analytic hierarchy process, in constructing risk evaluation systems. Some relatively small clusters are more specialized and fragmented, particularly those related to soil–pipeline interaction and compositional factors. These clusters were retained only when they contributed to understanding specific risk mechanisms, while overly heterogeneous clusters were simplified during the analysis.

To further evaluate the reliability of the clustering results, clustering quality metrics were calculated. The Modularity $Q$ value was used to evaluate the overall network structure, while the Mean Silhouette value was used to assess the internal consistency of clusters. In this study, the Modularity $Q$ value of 0.54 indicates a significant clustering structure, and the Mean Silhouette value of 0.85 indicates high cluster consistency. The Mean Silhouette values of the three thematic datasets were all above 0.7, suggesting acceptable reliability of the clustering results. The obtained Modularity $Q$ value (>0.3) indicates a significant clustering structure, while the Mean Silhouette value (>0.7) suggests that the clusters are highly consistent and reliable.

Furthermore, the identified clusters can be grouped into three higher-level thematic categories: (i) risk identification and assessment, focusing on probabilistic modeling and quantitative analysis; (ii) infrastructure and system safety, emphasizing pipeline integrity, facility safety, and environmental interaction; and (iii) decision-making and management approaches, including multi-criteria evaluation and risk control strategies. This hierarchical organization enhances the coherence of the clustering results and provides a clearer understanding of the knowledge structure and research evolution in the field of natural gas transportation risk.

Overall, the clustering structure indicates that research on natural gas transportation risk has evolved into a multi-dimensional analytical framework, integrating probabilistic modeling, infrastructure safety, environmental interaction, and decision-making approaches.

### *3.1.2 Research on coordinated operation and scheduling in energy systems related to natural gas transportation*

To systematically examine the research landscape of coordinated scheduling in energy systems, a topic-based search was conducted in the Web of Science Core Collection using the keywords "coordination scheduling" AND "energy." The data sources included SCI-EXPANDED and SSCI, with the document type limited to Article and the time span set from 2008 to 2025.

A total of 1,374 publications were initially retrieved. After data cleaning and duplicate removal, 1,165 valid records were retained for subsequent analysis. Based on this dataset, CiteSpace was employed to generate a keyword clustering network, as shown in Figure 2.

As illustrated in Figure 2, the research hotspots of coordinated scheduling are mainly concentrated in several thematic clusters. Cluster #0 (power generation) represents the core research area, emphasizing the efficient operation of generation units through coordinated scheduling within energy systems, while simultaneously considering cost, risk, and environmental factors.[20] Representative keywords in this cluster include "power generation," "economic dispatch," and "unit commitment," reflecting the central role of generation scheduling in coordinated energy system operation. Cluster #1 (smart grid) highlights the deep integration of power systems and information technologies, focusing on energy scheduling and distributed optimization under the smart grid paradigm. Representative keywords in this cluster include "smart grid," "distributed optimization," and "energy management," reflecting the increasing integration of digital technologies and intelligent control methodologies in coordinated scheduling research.

Cluster #2 (demand response) addresses user-side participation in scheduling, exploring mechanisms such as pricing and incentives to achieve peak shaving and load balancing. Cluster #3 (optimization) constitutes a methodological cluster, encompassing approaches such as linear programming, mixed-integer programming, and multi-objective optimization, which provide fundamental tools for solving scheduling problems. Cluster #4 (uncertainty) emphasizes modeling under conditions of renewable energy integration and demand fluctuations, promoting the development of robust and stochastic optimization methods. Cluster #5 (energy efficiency) focuses on improving overall system efficiency and reducing carbon emissions through coordinated operation, reflecting the orientation toward low-carbon energy strategies. Cluster #6 (stochastic programming) represents advanced methodological developments for handling uncertainty in power systems and multi-energy scheduling problems. Cluster #7 (Lagrangian

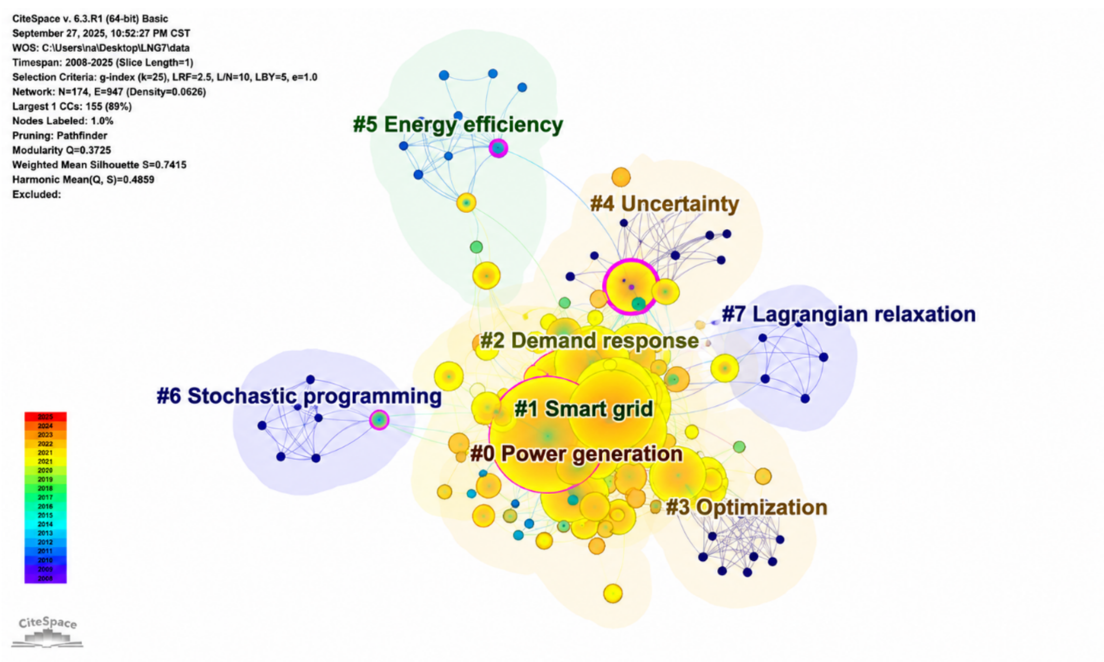


**Figure 2.** Keyword clustering map of coordinated operation and scheduling in energy systems

relaxation) reflects the importance of decomposition and approximation techniques in solving large-scale scheduling problems, highlighting the role of algorithmic research in this domain.

Overall, the clustering results indicate that research on coordinated energy operation is predominantly system-oriented and method-driven, with a strong emphasis on power systems, uncertainty modeling, and optimization techniques.[21] Compared with studies on natural gas transportation, this research stream focuses more on integrated energy system coordination at a macro level, while relatively limited attention has been given to the operational coordination between pipeline and non-pipeline transportation modes in natural gas systems.

#### *3.1.3. Research on the application of intelligent optimization algorithms in natural gas transportation*

To systematically explore the application of intelligent optimization methods in natural gas transportation and utilization, a topic-based search was conducted in the Web of Science Core Collection using the keywords "intelligent optimization" AND "natural gas." A total of 152 relevant publications were retrieved.

Based on this dataset, CiteSpace was employed to generate a keyword clustering network, as shown in Figure 3.

As illustrated in Figure 3, the application of intelligent optimization methods in the natural gas domain is mainly concentrated in several research directions. Cluster #0 (energy efficiency evaluation) represents a core application area, focusing on the quantitative assessment of energy efficiency in natural gas transportation, storage, and utilization processes.[22] Representative keywords in this cluster include "energy efficiency evaluation," "optimization algorithm," and "natural gas," indicating the growing importance of efficiency-oriented performance assessment in natural gas systems. Cluster #1 (multi-agent systems) emphasizes multi-entity coordination modeling within natural gas networks and broader energy systems, reflecting the integration of artificial intelligence and complex system theory. Representative keywords in this cluster include "multi-agent systems," "coordination," and "distributed control," highlighting the increasing application of intelligent coordination mechanisms in energy transportation systems.

Cluster #2 (adaptive neuro-fuzzy inference system) combines neural networks with fuzzy logic, enhancing inference and prediction capabilities under uncertain conditions. Cluster #3 (neural networks) is widely applied to nonlinear modeling tasks such as risk prediction, demand forecasting, and transportation scheduling, highlighting the growing importance of data-driven approaches. Cluster #4 (hybrid intelligent models) integrates metaheuristic algorithms—such as genetic algorithms and particle swarm optimization—with machine learning

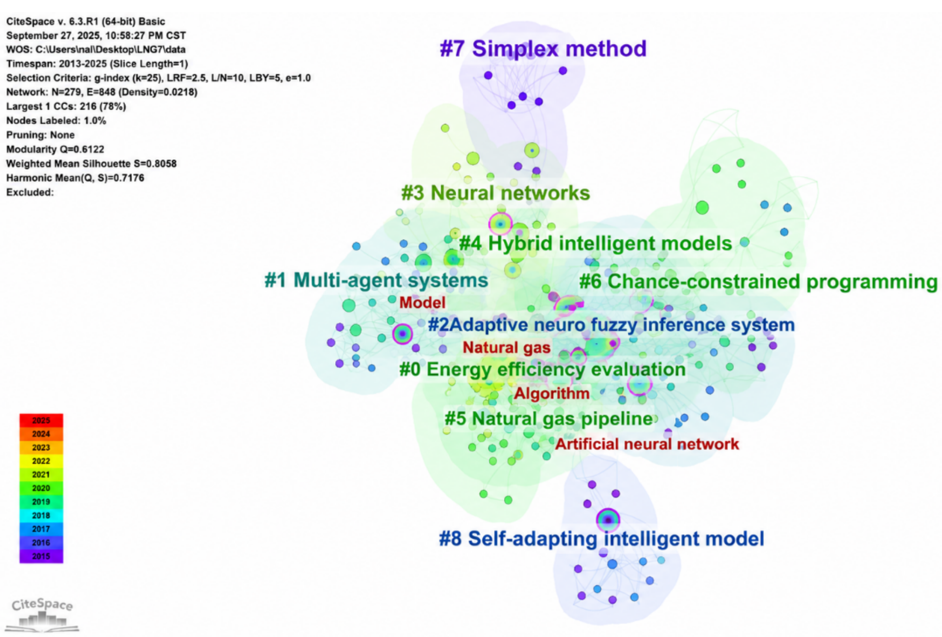


**Figure 3.** Keyword clustering map of intelligent optimization applications in natural gas transportation

techniques, improving the performance of solving large-scale and complex optimization problems. Cluster #5 (natural gas pipeline) focuses on infrastructure-related applications, including risk prediction, leakage detection, and operational optimization of pipeline systems.

Cluster #6 (chance-constrained programming) is extensively used in uncertainty modeling, particularly for addressing demand fluctuations and supply risks in natural gas systems. Clusters #7 (simplex method) and #8 (self-adaptive intelligent model) reflect the integration of traditional mathematical programming with adaptive intelligent optimization methods, indicating a continuous expansion and hybridization of methodological frameworks in this field. From a comparative perspective, the clusters exhibit distinct yet interrelated research focuses. However, a certain degree of fragmentation remains, particularly in the limited integration between risk analysis and route optimization.

Overall, the clustering results reveal that research on intelligent optimization in natural gas systems has evolved into a multi-layered framework encompassing energy efficiency evaluation, risk prediction, multi-agent coordination, and hybrid optimization approaches.[23] However, it can also be observed that existing studies tend to emphasize algorithmic performance and computational efficiency, while the incorporation of transportation risk into optimization models remains relatively limited.[24] In particular, risk factors are often treated as external parameters rather than being explicitly embedded into the decision-making structure. This limitation highlights the need to develop risk-constrained optimization frameworks that can more effectively capture the trade-offs between safety and operational efficiency in natural gas transportation systems.

From a broader perspective, the clustering results reveal several major research orientations in the field of natural gas transportation. In addition, the relationships among different clusters were examined to provide a more integrated understanding of the knowledge structure of the field. Rather than being entirely independent, these clusters exhibit varying degrees of thematic connections and evolutionary linkages. It should also be noted that clustering based on titles and keywords may introduce a certain degree of semantic overlap, which is an inherent limitation of bibliometric analysis. Therefore, the clustering results are interpreted at a macro level, focusing on general research trends rather than strictly bound conceptual categories.

### 3.2. Temporal evolution analysis

The temporal evolution analysis was divided into five-year stages to better capture the evolution of research hotspots over time. This division generally corresponds to major energy policy cycles, technological development phases, and the gradual transition of natural gas transportation research from engineering-oriented safety analysis to intelligent and uncertainty-aware decision-making.

Building upon the keyword clustering analysis, this section further examines the temporal evolution of different research streams to reveal the stage-wise development of research hotspots. It should be noted that the temporal analysis reflects thematic evolution at the field level based on keyword patterns rather than direct technical progression.

#### *3.2.1. Research on natural gas transportation risk identification and assessment*

Based on the dataset described in Section 3.1.1, CiteSpace was employed to generate a time–zone visualization, as shown in Figure 4.

As illustrated in Figure 4, the evolution of research on natural gas transportation risk exhibits a clear transition from traditional approaches toward more intelligent and integrated frameworks. During the 2008–2012 period, research was primarily centered on keywords such as "risk analysis," "accidents," and "pipeline," reflecting an early focus on accident case analysis and pipeline transportation risks. From 2013 to 2017, the introduction of keywords such as "buried pipeline," "risk assessment," and "analytic hierarchy process" indicates a shift toward more quantitative and multi-criteria evaluation methods. This stage marks the gradual development of systematic risk assessment frameworks. From 2018 to 2025, research attention has increasingly shifted toward topics such as "Bayesian network," "green hydrogen," and "risk management," highlighting the growing importance of intelligent modeling approaches, low-carbon energy transition, and integrated risk governance. In particular, the emergence of hydrogen-related topics suggests that research has expanded beyond conventional natural gas transportation toward multi-energy systems and cross-energy comparative analysis.

Overall, the temporal evolution demonstrates a clear progression from engineering-oriented risk analysis toward data-driven, multi-dimensional, and system-integrated research paradigms.

#### *3.2.2. Research on coordinated operation and scheduling in energy systems related to natural gas transportation*

Using the validated dataset described in Section 3.1.2 ($n$ = 1,165), CiteSpace was applied to construct a time–

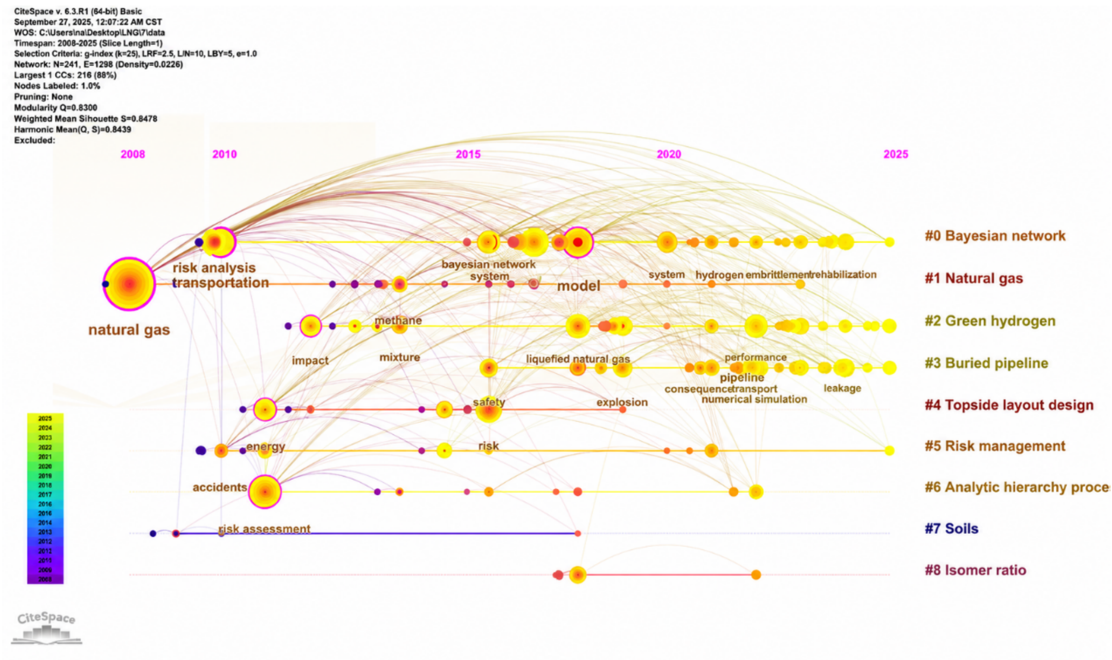


**Figure 4.** Time–zone evolution map of natural gas transportation risk research

zone visualization illustrating the temporal evolution of coordinated scheduling research in energy systems (Figure 5).

As illustrated in Figure 5, the evolution of coordinated scheduling research exhibits clear stage-wise characteristics. During the 2008–2012 period, research focused on foundational methods and application domains, with keywords such as "optimization" and "power generation" dominating the field. This stage primarily relied on traditional operations research approaches to address scheduling problems in power generation and electricity systems. From 2013 to 2017, the emergence of "smart grid" and "demand response" reflects the increasing integration of power systems with communication and information technologies. During this stage, user-side participation was gradually incorporated into scheduling frameworks, marking a shift toward more interactive and flexible system operation. From 2018 to 2025, research attention has increasingly shifted toward "uncertainty," "stochastic programming," and "energy efficiency," indicating a dual emphasis on managing variability introduced by renewable energy integration and improving system efficiency under low-carbon transition goals.[25] This stage highlights the growing importance of uncertainty modeling and sustainability-oriented optimization in coordinated energy systems.

Overall, the temporal evolution demonstrates a transition from method-oriented optimization in power systems to integrated, uncertainty-aware, and low-carbon-oriented coordination frameworks. However, it is noteworthy that existing studies are largely centered on electricity systems and integrated energy systems at a macro level, while relatively limited attention has been paid to the operational coordination between pipeline and non-pipeline transportation modes in natural gas systems.

#### ***3.2.3. Research on the application of intelligent optimization algorithms in natural gas transportation***

Based on the dataset described in Section 3.1.3, CiteSpace was employed to generate a time–zone visualization illustrating the evolution of intelligent optimization research in natural gas transportation and utilization, as shown in Figure 6.

As illustrated in Figure 6, the development of intelligent optimization research in the natural gas domain exhibits a clear evolutionary trajectory. During the 2008–2012 period, research was primarily centered on "optimization" and "artificial neural networks," focusing on the application of traditional optimization techniques and neural networks in pipeline transportation and storage systems. From 2013 to 2017, research expanded toward "adaptive neuro-fuzzy inference systems" and "hybrid intelligent models," indicating a growing trend of integrating intelligent optimization with machine learning methods.[26] From 2018 to 2025, research attention shifted toward "energy efficiency evaluation," "multi-agent systems," and "chance-

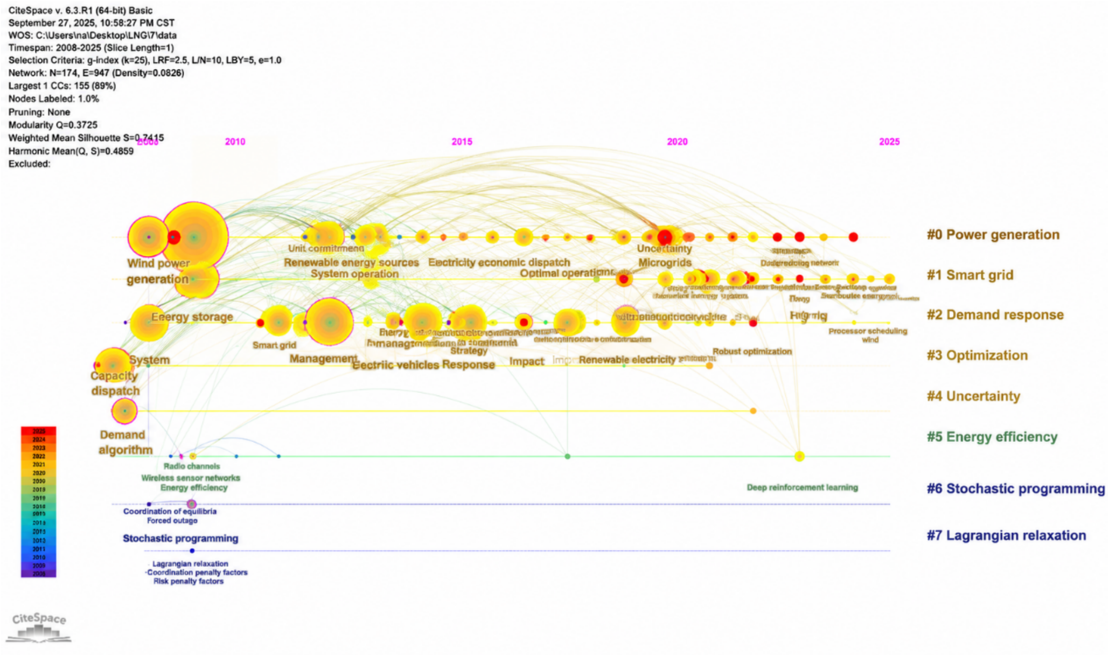

**Figure 5.** Time–zone evolution map of coordinated operation and scheduling in energy systems

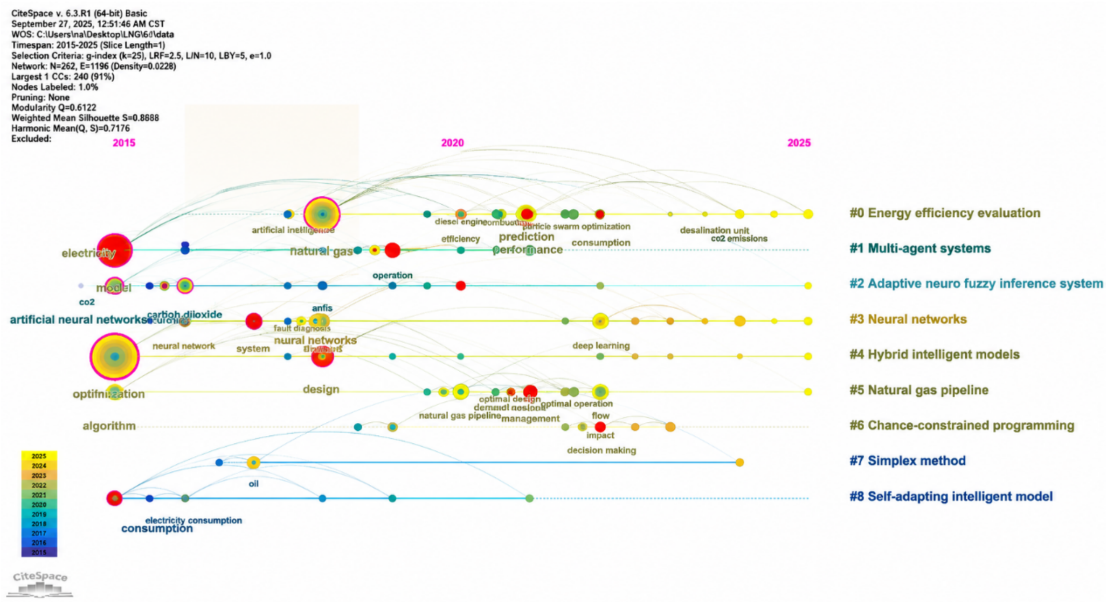

**Figure 6.** Time–zone evolution map of intelligent optimization in natural gas transportation

constrained programming," highlighting an increasing emphasis on energy efficiency and risk management under low-carbon transition contexts. At the same time, intelligent optimization models have evolved to address uncertainty constraints and the complexity of multi-network systems.[27]

Overall, the temporal evolution demonstrates a transition from single-method applications to hybrid intelligent optimization frameworks, and further toward multi-objective and uncertainty-aware optimization paradigms. However, similar to other research streams, the explicit integration of transportation risk into optimization models remains limited.[28] Risk factors are often incorporated indirectly or treated as external constraints, rather than being embedded within the core decision-making structure.

## 4. Conclusion

We conducted a bibliometric and knowledge graph analysis of natural gas transportation research based on 1,687 publications retrieved from the Web of Science Core Collection database from 2008 to 2025. The results show that the field has gradually formed three major research streams: transportation risk analysis, coordinated operation and scheduling, and intelligent optimization.

From the perspective of knowledge structure, risk-related studies have established analytical frameworks grounded in probabilistic modeling and multi-criteria evaluation, with significant advances in quantitative risk assessment and propagation analysis. Research on coordinated operation emphasizes structural optimization and operational coordination within multi-energy systems. Meanwhile, route optimization research, largely based on vehicle routing problem models, has continuously expanded in terms of modeling complexity and solution techniques, evolving toward multi-objective optimization and intelligent algorithms.

Overall, the research evolution demonstrates a transition from fragmented and single-objective studies toward integrated, intelligent, and uncertainty-aware analytical frameworks. Risk analysis primarily focuses on safety assessment, route optimization emphasizes efficiency improvement, and coordinated operation primarily focuses on system-level structures. A unified analytical framework integrating these dimensions has yet to be established. In particular, the integration between transportation risk and route optimization remains limited, and the integration of risk factors into routing decision models remains insufficient.

Future research should focus on the integration of risk analysis and route optimization and on the development of more comprehensive analytical frameworks. Specifically, further efforts may explore data-driven risk modeling, scenario-based optimization under uncertainty, and the incorporation of real-time operational data into routing decision processes. These directions can enhance the practical applicability of optimization models and support safer and more efficient natural gas transportation systems.

## Acknowledgments

None.

## Funding

None.

## Conflict of interest

The authors declare that they have no conflict of interest.

## Author contributions

*Conceptualization:* Na Li
*Data curation:* Na Li, Yidan Tang
*Formal analysis:* Na Li
*Methodology:* Na Li
*Project administration:* Xiaoming Wu
*Visualization:* Yidan Tang
*Writing–original draft:* Na Li
*Writing–review & editing:* Xiaoming Wu

## Availability of data

Data supporting the findings of this study are available from the corresponding author upon reasonable request.

## References

1. Liu F, Wang Y, Lang X, *et al*. Fundamentals and economic analysis of hydrate-based carbon dioxide sequestration. *Carb Neutrality*. 2025;4(1).

   doi: 10.1007/s43979-025-00134-x

2. Jordaan SM, Ruttinger AW, Surana K, *et al*. Global mitigation opportunities for the life cycle of natural gas-fired power. *Nat Clim Chang*. 2022;12(11):1059-1067.

   doi: 10.1038/s41558-022-01503-5

3. Yuan J, Shi X, He J. LNG market liberalization and LNG transportation: Evaluation based on fleet size and composition model. *Appl Energy*. 2024;358:122657.

   doi: 10.1016/j.apenergy.2024.122657

4. Li M, Liu J, Xia Y. Risk Prediction of Gas Hydrate Formation in the Wellbore and Subsea Gathering System of Deep-Water Turbidite Reservoirs: Case Analysis from the South China Sea. *Reserv Sci*. 2025;1(1):52-72.

   doi: 10.62762/rs.2025.567907

5. Zhou X, Yang F, Chen Z, *et al*. Mechanistic Insights and Engineering Strategies for Wellbore Integrity Control in Polar Permafrost Reservoirs. *Reserv Sci*. 2026;2(2):126-150.

   doi: 10.62762/rs.2025.816374

6. Brantson ET, Obeng SDA, Ocran D, *et al*. Evaluating Enthalpy Production in Geothermal Reservoirs: Insights from Response Surface Methodology and Advanced Machine Learning Techniques. *Reserv Sci*. 2026;2(2):151-171.

   doi: 10.62762/rs.2026.366192

7. Hoseinzadeh S, Pourfayaz F. Comparative techno-economic analysis of using multisource renewable energy with flexible storage systems for various environments. *Environ Prog Sustain Energy*. 2025;44(2).

doi: 10.1002/ep.14544

8. Xu Y, Peng P, Xie X, *et al*. Structural analysis and robustness assessment of global LNG transport network from 2013 to 2023. *Ocean Coast Manag*. 2025;263:107619.

   doi: 10.1016/j.ocecoaman.2025.107619

9. Wu J, Bai Y, Zhao H, *et al*. A quantitative LNG risk assessment model based on integrated Bayesian-Catastrophe-EPE method. *Saf Sci*. 2021;137:105184.

   doi: 10.1016/j.ssci.2021.105184

10. Tian AQ, Wang XY, Xu H, *et al*. Multi-objective optimization model for railway heavy-haul traffic: Addressing carbon emissions reduction and transport efficiency improvement. *Energy*. 2024;294:130927.

    doi: 10.1016/j.energy.2024.130927

11. Park C, Han C. Case Study on Optimization of Send-out Operation in Liquefied Natural Gas Receiving Terminal. *Korean Chem Eng Res*. 2015;53(2):150-155.

    doi: 10.9713/kcer.2015.53.2.150

12. Ho YS. Comments on Yang and Meng (2020) "The evolution and research framework of carbon footprint: Based on the perspective of knowledge mapping" [Ecol. Indic., 112, 106125]. *Ecol Indic*. 2021;129:107978.

    doi: 10.1016/j.ecolind.2021.107978

13. Lo HW, Lin SW. A hybrid Bayesian BWM-machine learning framework for university digital transformation assessment: Integrating expert clustering and predictive validation. *Technol Soc*. 2026;85:103170.

    doi: 10.1016/j.techsoc.2025.103170

14. Stathakis KG, Papageorgiou G, Tjortjis C. Identifying Methodological Language in Psychology Abstracts: A Machine Learning Approach Using NLP and Embedding-Based Clustering. *Big Data Cogn Comput*. 2025;9(9):224.

    doi: 10.3390/bdcc9090224

15. Lu H, Xiao C, Jiao L, *et al*. Spatial-temporal evolution analysis of the impact of smart transportation policies on urban carbon emissions. *Sustain Cities Soc*. 2024;101:105177.

    doi: 10.1016/j.scs.2024.105177

16. Chaugule PV. Modulo Search Trees (Plain and Z-Overlapped). *IOSR J Comput Eng*. 2014;16(3):47-51.

    doi: 10.9790/0661-16384751

17. Zhang G, Wang L, Chen T. Complexity analysis of network-based dynamical systems. *J Syst Sci Complex*. 2011;24(3):413-432.

    doi: 10.1007/s11424-011-8173-6

18. Gao Y, Luo Z, Bi A, *et al*. A New Method for Evaluating Natural Gas Pipelines Based on ICEEMDAN-LMS: A View of Noise Reduction in Defective Pipelines. *Appl Sci*. 2023;13(17):9670.

    doi: 10.3390/app13179670

19. Fan H, Enshaei H, Jayasinghe SG. Formation of Dataset for Fuzzy Quantitative Risk Assessment of LNG Bunkering SIMOPs. *Data*. 2022;7(5):60.

    doi: 10.3390/data7050060

20. Chen Y, Zhou X, Chen S, *et al*. LNG Freight Rate and LNG Price, Carbon Price, Geopolitical Risk: A Dynamic Connectedness Analysis. *SSRN*. Preprint posted 2024.

    doi: 10.2139/ssrn.4678229

21. Zafar K, Baig AR. Optimization of route planning and exploration using multi agent system. *Multimed Tools Appl*. 2012;56(2):245-265.

    doi: 10.1007/s11042-010-0585-0

22. Zhang L. A comprehensive analysis of natural gas reserve policies: Global comparison, quantitative analysis, and strategic insights. *Energy*. 2025;320:135253.

    doi: 10.1016/j.energy.2025.135253

23. Javeed MA, Li D, Ashraf MA. Urban city data delivery optimization in VNDN using a route-based caching approach with content-type awareness in intelligent transportation system. *J Supercomput*. 2025;81(6).

    doi: 10.1007/s11227-025-07250-6

24. Yangin VB, Yalcin Y, Akalin O. A tunable explicit nonlinear MPC for a vehicle considering improved path tracking performance and computational efficiency. *J Mech Sci Technol*. 2025;39(5):2877-2888.

    doi: 10.1007/s12206-025-0446-4

25. Woo C, Chung Y, Chun D, *et al*. The static and dynamic environmental efficiency of renewable energy: A Malmquist index analysis of OECD countries. *Renew Sustain Energy Rev*. 2015;47:367-376.

    doi: 10.1016/j.rser.2015.03.070

26. Zhu D, Han Z, Du X, *et al*. Hybrid Model Integrating Fuzzy Systems and Convolutional Factorization Machine for Delivery Time Prediction in Intelligent Logistics. *IEEE Trans Fuzzy Syst*. 2025;33(1):406-417.

    doi: 10.1109/tfuzz.2024.3472043

27. Qu K, Fan X, Xu X, *et al*. Improving transportation network redundancy under uncertain disruptions via retrofitting critical components. *Transp Res B Methodol*. 2025;194:103174.

    doi: 10.1016/j.trb.2025.103174

28. Chiou SW. A learning optimization for resilience enhancement of risk-informed traffic control system with hazardous materials transportation under uncertainty. *Reliab Eng Syst Saf*. 2024;252:110425.

    doi: 10.1016/j.ress.2024.110425