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# Safety risks assessment of infrastructure challenges in liquid hydrogen transport in a multimodal network: an ISM-FIS-based analysis

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## ABSTRACT

This study assesses the risk probabilities/levels of infrastructural challenges in liquid hydrogen ($LH_2$) transportation within a multimodal network that extends from hydrogen production plants in the Gulf countries to the corridor's refueling stations. The methodology integrates Interpretive Structural Modeling (ISM) and MATLAB®-based Fuzzy Inference System (FIS) to provide a structured and quantifiable risk analysis. ISM is applied to analyze interdependence among the key infrastructure challenges and safety risk factors. The results reveal that insufficient hydrogen-ready infrastructure at ports and hubs is the foundational issue. Four challenges: limited cryogenic maintenance, poor emergency response, weak digital monitoring, and material degradation of storage tanks, emerging as intermediate. Six safety risks, including flammability and explosion, leak detection issues, high-pressure storage, cryogenic hazards, vapor clouds, and electrostatic discharge, are the most dependent. The FIS results show that transportation risk levels/probabilities increase significantly with greater severity or concurrent occurrence of these challenges. For a demonstrative analysis, we consider two sub-challenges: the lack of a high-safety transport container design and material fatigue caused by fluctuating conditions. The results indicate that the probability of flammability and explosion risk remains relatively low (approximately 45%) when both factors are at low severity levels. The probability rises to a moderate level (55–65%) when either challenge is rated as medium and peaks at 70–75% when both are severe. This study contributes theoretically by integrating ISM and FIS to develop a systemic framework for assessing $LH_2$ transportation risks in a multimodal network and offers practical recommendations for mitigating key infrastructure challenges.

## Introduction

The Gulf-Europe corridor emerges as a strategic trade and transport link between the Gulf region and European markets. Its primary goal is to facilitate the seamless movement of goods, fuel, and industrial materials, thereby supporting economic growth, fostering regional integration, and advancing sustainable transportation practices [1–4]. Designed as a multimodal network, it combines overland trucking, maritime shipping, and terminal logistics, positioning the corridor as a vital mechanism for enhancing cross-border freight efficiency and strengthening supply chain resilience [2]. As $LH_2$ gains momentum globally as a clean energy carrier, the corridor offers a critical pathway for hydrogen exports from the Gulf to Europe [3]. But $LH_2$ transport poses some infrastructural challenges due to its cryogenic nature (−253 °C) [5–7], high-pressure storage requirements [8,9], and chemical volatility [10]. These conditions introduce significant risks, including material degradation [11,12], leakage [11], flammability [13,14], vapor cloud formation [13,15], and limited emergency response capacity [16] across modes and hubs. If not properly managed, these risks could undermine operational safety and energy sustainability goals [17]. However, leveraging this corridor for $LH_2$ transport offers strong sustainability benefits, supporting the global shift toward low-carbon energy and reducing long-term dependence on fossil fuels [2,18,19]. By enabling large-scale hydrogen logistics, the corridor can significantly lower greenhouse gas emissions from freight transport and help position the Gulf region as a clean energy export hub.

The motivation of this study is to assess the risk levels arising from infrastructure challenges in $LH_2$ transportation in the corridor's multimodal network, spanning from hydrogen production plants in the Gulf Cooperation Council (GCC) countries to the corridor's hydrogen refueling stations (HRSs). $LH_2$ is particularly promising for long-distance and large-scale transport due to its high energy density [8,20].

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Though the corridor presents a strategic opportunity to establish a clean hydrogen export route from the Gulf region to European markets [2,3], realizing this vision depends on overcoming critical infrastructural challenges associated with a complex multimodal network [17,20–22]. This study is driven by the need to ensure the safe and efficient movement of $LH_2$ throughout this corridor. While previous research has theoretically and empirically explored the impacts of infrastructure challenges or sub-challenges to hydrogen logistics [3,21,23–25], a significant gap remains in understanding qualitatively and analytically the combined impact of those challenges on transportation safety. This study adds a new dimension by addressing both challenges and safety risks. Unlike earlier studies that often examine these issues in isolation or only at a conceptual level, this research adopts an integrated approach. Specifically, it (1) employs ISM to analyze the interdependencies among infrastructure challenges and safety risks, and (2) uses FIS modeling to quantify transportation risks resulting from these challenges, as illustrated in the research model in Fig. 1. The research questions (RQs) this study aims to address are:

RQ1. What are the key infrastructural challenges and safety risks associated with $LH_2$ transportation within the multimodal network of the Gulf-Europe corridor?

RQ2. How do these challenges and risks interrelate and influence each other across the network, and what dependencies emerge from these interactions?

RQ3. To what extent do varying combinations and intensities of these challenges impact transportation safety risks?

ISM is employed to identify and structure interrelationships among the challenges and risks. Expert consultations guide the development of a Structural Self-Interaction Matrix (SSIM), which is then converted into a binary reachability matrix [26,27]. After transitivity checks and level partitioning, a multi-level hierarchy is established, categorizing challenges as foundational, intermediate, or highly dependent. The ISM results reveal that limited hydrogen-ready infrastructure at ports and hubs is the foundational challenge, while safety-related issues, such as flammability risk, vapor cloud formation, and electrostatic discharge, are among the most dependent. Subsequently, FIS modeling is used to evaluate the transportation risks arising from the identified infrastructure sub-challenges [28–30], with two of these sub-challenges assessed as a demonstrative example. The FIS results show that risk remains low (~45 %) when two selected sub-challenges (transport containers lack design for high safety standards and fluctuating conditions accelerate material fatigue) are minor, rises to a moderate level (55–65 %) when one is in a medium range, and peaks at 70–75 % when both are high/severe. This integrated ISM–FIS approach enables a comprehensive, scenario-based risk assessment to support strategic infrastructure and safety planning. The key contributions of this study are:

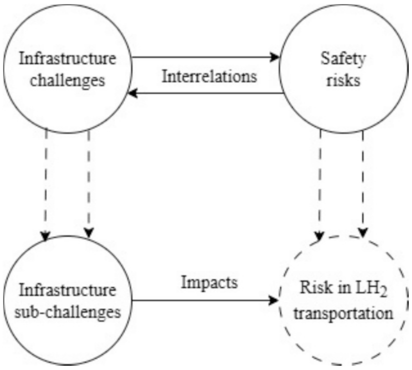

**Fig. 1.** The research model.

- This study uniquely combines ISM and FIS to address both infrastructure challenges and safety risks in $LH_2$ transport. ISM reveals the hierarchical interdependencies among them, while FIS enables precise risk assessment, providing a comprehensive assessment framework.
- The proposed FIS model enables scenario-based assessment of transportation risks arising from infrastructure challenges. This approach provides policymakers and planners with actionable insights to prioritize infrastructure investments and implement targeted safety measures across the corridor.

The novelty of this study lies in its integrated methodological framework that uniquely combines ISM and FIS. While previous research on hydrogen logistics has often examined risks or challenges in isolation, this study provides a comprehensive, system-level perspective that addresses both structural interdependencies and transportation risks. The ISM approach reveals hierarchical relationships among key challenges and risks which are essential for designing targeted infrastructure and safety interventions. Coupled with FIS, the study enhances risk assessment by quantifying how varying intensities and combinations of challenges influence risk levels. This scenario-based evaluation equips decision-makers with the insights needed to prioritize investments and implement safety measures under complex, real-world conditions. As such, the study contributes a novel analytical toolset for hydrogen transport risk management, with direct implications for emerging hydrogen corridors/routes worldwide.

The following sections of this paper are structured as follows. Section 2 provides an overview of the corridor, the potential adoption of hydrogen fuel cell vehicles (HFCVs), its multimodal transportation network, and the associated challenges and risks. Section 3 reviews the relevant literature and highlights key research gaps. Section 4 describes the research methodology, detailing the step-by-step procedures employed in the study. Section 5 presents the findings along with a comprehensive analysis. Finally, Section 6 concludes the paper by discussing its limitations and offering directions for future research.

## Overview of the corridor, potential adoption of HFCVs, its multimodal transportation network, and aggregation of challenges and risks

### *Corridor's overview, potential adoption of HFCVs, and multimodal transportation network*

**Corridor overview:** On April 22, 2024, an agreement was signed by Qatar, Iraq, Türkiye, and the United Arab Emirates (UAE) to begin a major infrastructure initiative known as the Gulf-Europe transportation corridor, also referred to as the Iraq development road project [31]. This collaborative effort aims to significantly upgrade transport connectivity between the Gulf nations and Europe, with Iraq and Türkiye serving as vital linkage points along the corridor, as depicted in Fig. 2. The project involves the development of approximately 1,200 km (745 miles) of rail and highway infrastructure to enable more efficient goods movement between the regions [31,32]. The planned route will begin in Kuwait and traverse Saudi Arabia, Qatar, Bahrain, the UAE, and Oman, eventually extending into Türkiye. The agreement also emphasizes the expansion of Al-Faw Port in Basra, Iraq's strategic seaport, which will be directly connected to the corridor leading to Türkiye [3,32,33]. Once completed, the corridor is expected to play a key role in facilitating trade, improving regional logistics systems, and deepening economic cooperation between the Gulf region and Europe [2,4].

**Corridor's potential adoption of HFCVs:** This corridor presents significant potential for the adoption of HFCVs as a sustainable alternative to diesel-powered freight transport. Building on the suggestions of Rahman & Baldacci [2] and Rahman et al. [3], this approach is inspired by successful implementations in other regions, such as the Los Angeles–San Francisco freight route (approximately 612 km) and the

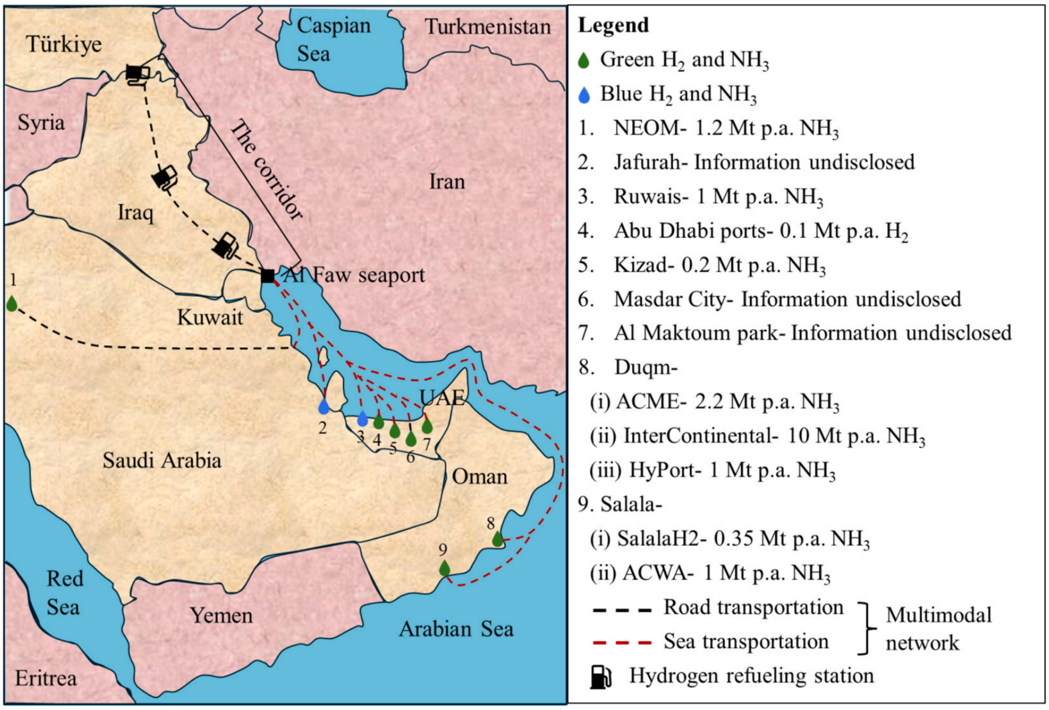

**Fig. 2.** The Gulf-Europe corridor, multimodal network and hydrogen production facilities in GCC countries ( adapted from Rahman & Baldacci [2])

longer Houston–Los Angeles corridor (around 2,300 km). These corridors have effectively introduced hydrogen-powered heavy-duty trucks, significantly contributing to the reduction of greenhouse gas emissions [22,34]. In particular, the Los Angeles–San Francisco corridor supports hydrogen mobility with over 50 HRSs [35], enabling both passenger and freight vehicle operations. Similarly, the Gulf-Europe corridor, which spans key economies across the Gulf, Iraq, and Türkiye, presents a valuable opportunity for hydrogen adoption in long-haul freight. To achieve decarbonization targets in the region's freight sector, this study recommends deploying HFCVs for medium- and heavy-duty transport along with the development of hydrogen refueling infrastructure. Such initiatives, as emphasized by Rahman & Baldacci [2] and Ma et al. [19], could play a vital role in reducing transport-related emissions [23,36] while strengthening cross-border freight operations.

**Corridor's multimodal transportation network:** Fig. 2 shows the corridor and highlights key hydrogen production facilities across the GCC countries. These production sites offer a significant opportunity to supply hydrogen per annum (p.a.), either in its liquid form or as ammonia ($NH_3$) [37–39], to refueling stations located along the corridor. To facilitate this distribution, a multimodal transportation network is essential, combining road and maritime [2]. Initially, hydrogen can be transported from inland or coastal production plants via cryogenic trucks to major seaports. From there, it can be shipped using marine-grade cryogenic vessels equipped with boil-off gas management systems. Upon reaching designated terminals closer to refueling infrastructure, hydrogen can again be transferred by trucks for final distribution. This multimodal network needs to ensure safe, efficient, and scalable hydrogen transport, supporting the deployment of HFCVs and enhancing energy sustainability along the corridor.

### *Corridor's multimodal transport requirements*

Fig. 3 illustrates the multimodal transportation modes involved in $LH_2$ transport along the corridor, while Table 1 outlines the key requirements that must be maintained in trucks and ships during transit. As shown in Fig. 2, the multimodal network includes overland trucking, maritime shipping, and final distribution stages, each of which presents complex technical and safety challenges due to the extreme physical conditions required for $LH_2$ handling. Specifically, $LH_2$ must be

**Table 1**
Technical requirements along with temperature and pressure constraints in transporting $LH_2$.

| Stage | Temperature constraint | Pressure constraint | Technical requirements |
|---|---|---|---|
| Truck (1st leg) | $< -253\ ^\circ C$ ($< 20$ K) | ~ 1–10 bar | Requires vacuum-insulated cryogenic tanks with multi-layer insulation to prevent heat ingress and minimize boil-off during overland transport [40,41,9]. |
| Ship | $< -253\ ^\circ C$ ($< 20$ K) | ~ 1–10 bar | Requires marine-grade cryogenic storage systems; includes onboard boil-off gas management systems to safely vent, compress, or reliquefy vaporized hydrogen [43,45]. |
| Truck (2nd leg) | $< -253\ ^\circ C$ ($< 20$ K) | ~ 1–10 bar | Requires portable cryogenic tanks with stable insulation for short-haul distribution to HRS; minimal exposure time is critical to reduce losses [7,9,41]. |

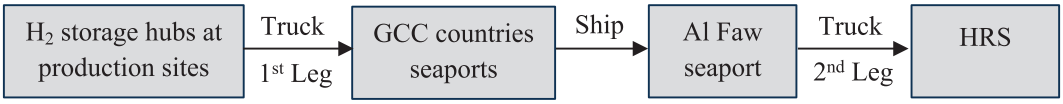

**Fig. 3.** Multimodal transportation of $LH_2$ in the Gulf-Europe corridor.

maintained at an ultra-low temperature of –253 °C and within a pressure range that typically remains between 1 and 3 bar, although certain operational conditions or specialized systems may experience pressures approaching 10 bar [9,40]. These demanding conditions necessitate the use of highly specialized, cryogenic vacuum-insulated tanks with multi-layer insulation to minimize heat ingress and reduce hydrogen boil-off [41,42]. Onboard ships, additional systems are needed to safely manage boil-off gases, through venting, compression, or re-liquefaction, to mitigate the risk of fire or explosion [43]. Similarly, trucks operating in the initial and final legs of the corridor require portable, stable cryogenic equipment designed to ensure minimal exposure times, reduce product loss, and maintain operational safety [11,44].

### *Challenges and risk factors aggregation*

We have aggregated the infrastructure challenges and safety risk factors associated with $LH_2$ transportation in the Gulf-Europe corridor, which are briefly described in Tables 2 and 3, respectively.

## Related studies and research gap

Table 4 summarizes previous studies that addressed INF1–INF5 and SAF1–SAF6. It also highlights how our study uniquely integrates those while quantifying the associated transportation safety risks, thereby

**Table 2**
List of infrastructure challenges.

| Challenges | Description |
|---|---|
| INF1- Limited ready infrastructure at ports and hubs | Ports and inland logistics hubs along this corridor may lack dedicated hydrogen-handling infrastructure, including cryogenic tanks, compressors, transfer lines, leak detection systems, and fire suppression setups. This infrastructure gap can complicate modal transitions during multimodal transport, increase operational delays, and significantly elevate safety risks, particularly when managing large volumes of $LH_2$ [7,14]. |
| INF2- Material degradation of storage tanks | Prolonged exposure to hydrogen can cause embrittlement in metallic tank materials, weakening their structural integrity and increasing the risk of failure during storage or transit [11,12]. Identifying and implementing materials that offer a balance of safety, long-term durability, and economic feasibility remains a significant technical and logistical challenge for this corridor. |
| INF3- Limited cryogenic maintenance facilities | Maintaining cryogenic tankers and transfer systems demands specialized workshops, equipment, and trained personnel to handle ultra-low temperatures and prevent system failures [46,47]. The limited presence of such facilities along this corridor may hinder consistent operations, reduce system reliability, and result in increased downtime and higher maintenance-related costs. |
| INF4- Inadequate emergency response infrastructure | In the event of a leak or fire in the tanks, traditional firefighting systems will not be effective [13,16]. Logistics hubs lack hydrogen-specific emergency response infrastructure, including specialized sensors, fire suppression systems, and trained personnel, which poses a significant challenge along this corridor. |
| INF5- Insufficient digital monitoring and data integration | Real-time monitoring of tank pressure, temperature, and potential leaks is essential for ensuring the safety and integrity of $LH_2$ during transit [48,49]. However, the absence of Internet of Things (IoT) enabled infrastructure for digital integration across transport modes can limit operational visibility, hinder proactive risk management, and compromise overall transport reliability along the corridor. |

**Table 3**
List of safety risk factors.

| Risk factors | Description |
|---|---|
| SAF1- Flammability and explosion risk | Hydrogen is extremely flammable and can ignite from even a minor spark or small leak, posing serious safety risks [13,14,50]. During multimodal transport involving trucks and ships, frequent handling, loading, and unloading operations significantly increase the chances of accidental ignition, making the prevention and control of fire hazards a critical challenge. |
| SAF2- Risks from hydrogen leakage, operational errors, and poor road conditions | Hydrogen is colorless, odorless, and burns with an almost invisible flame, making leak detection extremely challenging using conventional methods [13,48]. Untrained drivers or operators may mishandle cryogenic equipment or overlook early warning signs of leakage, thereby heightening the likelihood of accidents [14,92]. Additionally, traffic congestion, poor road conditions, and route disruptions can impose extra mechanical stress on tanks and valves, potentially compromising containment integrity [11]. Environmental hazards may also occur if insulation materials, coolant fluids, or chemical carriers escape into the surrounding environment [8]. |
| SAF3- High pressure storage risk | $LH_2$ is commonly stored at high pressures, often reaching up to 10 bar [51]. Any failure in storage tanks or valves during loading, unloading, or transit can lead to catastrophic ruptures or explosions [52], posing severe risks to infrastructure, personnel, and the surrounding environment during transport. Additionally, over-pressurization or structural failure of $LH_2$ tanks may lead to catastrophic events such as tank rupture or boiling liquid expanding vapor explosions (BLEVEs), resulting in large blast pressures and severe thermal hazards [13,93,94]. |
| SAF4- Cryogenic temperature hazard | $LH_2$ must be stored at a cryogenic temperature of −253 °C, requiring precise control and specialized equipment [9]. Any mishandling, insulation failure, or equipment malfunction can result in severe cold burns to personnel or structural damage to containers and facilities [5,13]. These hazards significantly increase the complexity and risk of multimodal transport. Furthermore, sudden contact between $LH_2$ and warmer materials can trigger rapid phase transition events, causing violent vaporization and pressure surges that increase operational risk [95,96]. |
| SAF5- Vapor cloud formation | In the event of a leak, hydrogen can rapidly form expansive vapor clouds that, although they disperse quickly, may ignite without warning. This presents a significant hazard, particularly in confined or densely populated terminals where ignitions could lead to explosions or fire [13,15], making effective leak control and ventilation critical. |
| SAF6- Electrostatic discharge risk | Electrostatic discharge poses a significant safety risk during the handling of $LH_2$ in cryogenic tanks. Static charges can build up during loading or unloading, especially under high flow rates or low humidity. Without proper grounding and bonding, these discharges may ignite leaked hydrogen, increasing the risk of fire or explosion during multimodal transport operations [53,54]. |

**Table 4**
Comparison of previous studies and this study.

| Author(s) | Infrastructure challenges (INF) | | | | | Safety risks (SAF) | | | | | | Measuring safety risks in transportation | Study purposes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | INF1 | INF2 | INF3 | INF4 | INF5 | SAF1 | SAF2 | SAF3 | SAF4 | SAF5 | SAF6 | | |
| Chen et al. [55] | √ | × | × | × | × | × | × | × | × | × | × | × | Measuring hydrogen trade readiness at ports |
| Hansen [17] | √ | × | × | × | × | √ | √ | √ | × | √ | × | × | Measuring $LH_2$ behavior with safety concerns |
| Ustolin el al. [46] | √ | √ | √ | × | × | × | √ | √ | × | √ | √ | × | Identifying challenges in $LH_2$ maritime transport |
| Li et al. [21] | × | √ | × | × | × | √ | √ | √ | × | × | √ | × | Reviewing hydrogen storage and transport safety |
| Rigas & Sklavounos [56] | × | √ | × | × | × | √ | × | √ | √ | √ | √ | × | Evaluating hazards in hydrogen storage facilities |
| Mukwanje et al. [6] | × | √ | √ | × | × | × | √ | √ | √ | × | × | × | Study of advancements in composite cryogenic hydrogen tanks |
| Sobola & Dallaev [57] | × | √ | × | × | × | × | × | × | × | × | × | × | Exploring hydrogen embrittlement mechanisms, and risks |
| Okonkwo et al. [58] | × | √ | × | × | × | × | × | × | × | × | × | × | Reviewing hydrogen tank embrittlement mechanisms |
| Chen et al. [59] | × | √ | × | × | × | × | × | √ | × | × | × | × | Embrittlement analysis of aluminum in hydrogen tanks |
| Magliano et al. [11] | × | √ | √ | √ | × | √ | √ | √ | √ | √ | × | × | Reviewing hydrogen tank storage and safety |
| Meda et al. [60] | × | √ | √ | × | × | × | × | √ | √ | √ | √ | × | Analysis of embrittlement-related challenges in hydrogen storage |
| Campari et al. [61] | × | √ | × | × | × | √ | × | √ | √ | × | × | × | Review of hydrogen embrittlement and risk-based inspections |
| Sakib et al. [14] | × | √ | × | √ | √ | √ | √ | √ | √ | √ | √ | × | Study of hydrogen safety across the value chain |
| Andersson & Grönkvist [51] | × | √ | × | × | × | × | × | √ | × | √ | × | × | Analysis of hydrogen large-scale storage |
| Genovese et al. [16] | × | √ | × | √ | √ | √ | √ | √ | √ | × | √ | × | Study of safety measures and equipment performance in HRSs |
| Gusev et al. [62] | × | × | √ | × | × | × | √ | √ | × | √ | × | × | Reliability analysis of hydrogen facilities under emergencies |
| Moradi & Groth [63] | × | × | √ | × | × | × | √ | √ | √ | × | √ | × | Analysis of hydrogen storage, delivery, and risks |
| Chizubem et al. [64] | × | × | × | √ | √ | √ | √ | √ | √ | × | × | × | Study of real-time digital monitoring for hydrogen facility safety |
| Patil et al. [65] | × | × | × | √ | √ | √ | √ | √ | × | × | × | × | Review of Artificial Intelligence innovations in hydrogen safety |
| Karthikeyani et al. [24] | × | × | × | √ | √ | × | √ | √ | × | × | × | × | Revolutionizing fuel cell infrastructure using IoT and hydrogen transport |
| Menon et al. [48] | × | × | × | × | √ | √ | √ | √ | × | × | × | × | Analysis of hydrogen leak detection and safety measures |
| Yang et al. [49] | × | × | × | × | √ | × | √ | √ | × | × | × | × | Detecting hydrogen leakage using distributed temperature sensor |
| Wang et al. [50] | × | × | × | × | × | √ | √ | √ | × | × | × | × | Study of leakage ignition and flame spread |
| Cirrone et al. [5] | × | × | × | × | × | √ | × | √ | √ | × | × | × | Study of hydrogen safety at ambient and cryogenic temperatures |
| Hu et al. [15] | × | × | × | × | × | √ | √ | × | √ | × | × | × | Study of $LH_2$ leakage, diffusion, and explosion control in tunnels |
| Liu et al. [53] | × | × | × | × | × | × | × | √ | √ | × | √ | × | Analysis of electrostatics and risks of $LH_2$ storage |
| Jin et al. [66] | × | × | × | × | × | √ | × | × | × | √ | × | × | Analyzing vapor cloud formation from $LH_2$ spills |
| Liu et al. [67] | × | × | × | × | × | × | × | × | × | √ | × | × | Modeling hydrogen vapor clouds with air humidity effects |
| Imamura et al. [68] | × | × | × | × | × | √ | × | × | × | × | √ | × | Controlling hydrogen ignition risk from electrostatic discharge |
| Sun & Loughnan [69] | × | × | × | × | × | √ | √ | √ | × | √ | × | × | Analysis of vapor cloud explosion from high-pressure hydrogen release |
| Hu et al. [70] | × | × | × | × | × | √ | √ | √ | √ | √ | × | × | Review of hydrogen-air cloud explosions |
| Cekerevac & Cekerevac [92] | √ | √ | √ | √ | × | √ | √ | √ | × | × | × | × | Analyzing hydrogen hazards, risks, and<br>protection |

(*continued on next page*)

**Table 4** (*continued*)

| Author(s) | Infrastructure challenges (INF) | | | | | Safety risks (SAF) | | | | | | Measuring safety risks in transportation | Study purposes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | INF1 | INF2 | INF3 | INF4 | INF5 | SAF1 | SAF2 | SAF3 | SAF4 | SAF5 | SAF6 | | |
| Our study | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | Analyzing $LH_2$ infrastructure challenges and safety risks in multimodal transport |

addressing key research gaps.

## Research methods

We use the ISM method to reveal the interdependencies among the challenges and risks, and the FIS method to assess risk levels. The procedures for both methodologies are shown in Fig. 4. ISM is selected over TISM (Total ISM) and MISM (Modified ISM) because it fits well with our study, additionally due to its methodological simplicity, ease of interpretation, and effectiveness in structuring complex problems within an exploratory framework [71–73]. Furthermore, ISM effectively captures interdependencies without adding unnecessary complexity to the model [27]. Similarly, the FIS method is chosen because it excels at handling uncertainty and imprecision inherent in real-world problems [74]. Unlike deterministic or purely statistical models, FIS accommodates expert judgments expressed as linguistic variables for infrastructure challenges. Its rule-based structure allows incorporation of human expertise into a transparent decision framework [75,76]. Moreover, FIS supports scenario analysis by simply modifying rule bases or operators (e.g., OR vs. AND) [77,78].

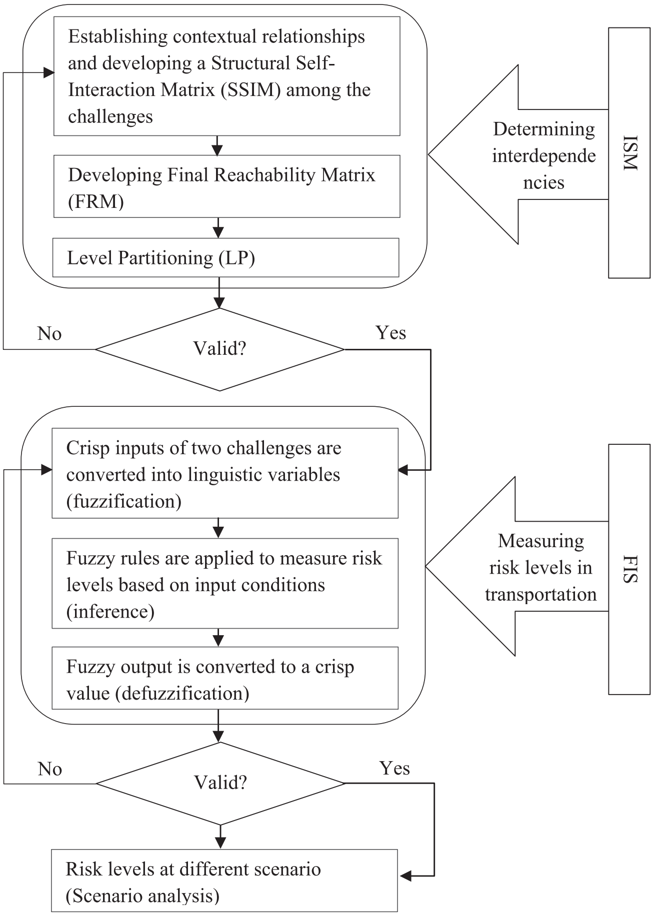

**Fig. 4.** The methodological framework of this study.

### *The ISM*

#### *Developing SSIM*

Table 5 illustrates the interrelationships among the eleven challenges and risks, highlighting how they interact. To establish these interrelationships, evaluations were collected from academic experts, post-doctoral researchers and faculty members at Hamad Bin Khalifa University, Qatar, who specialize in hydrogen-powered vehicles and hydrogen energy. Their evaluations were obtained through small group discussions, during which we successfully gathered ten responses, sufficient for conducting the ISM analysis [26,27]. Since all evaluations were carried out by experts from the same university, the likelihood of evaluation bias is considered minimal.

The SSIM uses some symbols to denote their relationships: **V** indicates that challenge *i* influences challenge *j*, **A** means that *j* influences *i*, **X** shows mutual influence, and **O** represents no direct relationship [27,71]. The matrix provides valuable insights into the dependencies and interactions among those, which is crucial for strategic decision-making and effectively addressing challenges.

#### *Developing FRM*

Table 6 presents the FRM, which indicates direct and transitive links between variables using binary values (1 for influence, 0 for no influence), while asterisks (*) denote inferred relationships derived through transitivity. The 'driving power' column sums up the number of other variables each factor influences, whereas the 'dependence power' row shows how many variables influence a given factor. Notably, INF1 has the highest driving power (11), indicating a strong influence over all other variables, suggesting it is a key determinant in the system. Conversely, SAF1-SAF6 variables exhibit high dependence power (11), highlighting their reliance on other factors.

#### *Performing LP*

Table 7 illustrates the LP derived from the FRM, essential for building the ISM hierarchy. Each element (Mi) is associated with its Reachability Set R(Mi), Antecedent Set A(Ni), and their Intersection Set R(Mi)∩ A (Ni), which determines its hierarchical level. Elements are grouped into levels based on the commonality between their reachability and antecedent sets [71]. Element 1 has both its reachability and antecedent set as {1}, placing it at Level 4, the topmost level. Element 2 is placed at Level 2 due to the intersection of its sets being {2}. Elements 3, 4, and 5 fall under Level 3, as their reachability and antecedent sets intersect at {3, 4, 5}. The remaining elements, 6 through 11, show similar patterns in their reachability and antecedent sets, all intersecting at {6, 7, 8, 9, 10, 11}, placing them at Level 1, the foundational layer of the ISM hierarchy. This LP provides a structural flow from foundational to top-level variables, highlighting the dependencies and relative positioning of the challenges. Lower-level elements (with high driving power) influence the higher-level ones.

### *The FIS modelling*

The FIS provides a computational framework that handles uncertainty and imprecision by mapping input variables through a set of fuzzy rules to produce an output [28,30,79]. It evaluates inputs using membership functions and applies rule-based reasoning to assess outcomes

**Table 5**
The SSIM.

| Variables (challenges) | | $j = 1$ | $j = 2$ | $j = 3$ | $j = 4$ | $j = 5$ | $j = 6$ | $j = 7$ | $j = 8$ | $j = 9$ | $j = 10$ | $j = 11$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | INF1 | INF2 | INF3 | INF4 | INF5 | SAF1 | SAF2 | SAF3 | SAF4 | SAF5 | SAF6 |
| $i = 1$ | INF1 | | V | V | O | V | V | V | V | V | V | V |
| $i = 2$ | INF2 | | | A | O | A | V | V | V | V | V | O |
| $i = 3$ | INF3 | | | | X | X | V | V | V | V | V | O |
| $i = 4$ | INF4 | | | | | O | V | V | V | V | V | V |
| $i = 5$ | INF5 | | | | | | V | V | V | V | V | V |
| $i = 6$ | SAF1 | | | | | | | X | X | X | X | X |
| $i = 7$ | SAF2 | | | | | | | | O | O | X | X |
| $i = 8$ | SAF3 | | | | | | | | | X | X | X |
| $i = 9$ | SAF4 | | | | | | | | | | V | V |
| $i = 10$ | SAF5 | | | | | | | | | | | O |
| $i = 11$ | SAF6 | | | | | | | | | | | |

**Table 6**
The FRM.

| Variables | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | Driving power |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| INF1 | 1 | 1 | 1 | 1* | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 11 |
| INF2 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1* | 7 |
| INF3 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1* | 10 |
| INF4 | 0 | 1* | 1 | 1 | 1* | 1 | 1 | 1 | 1 | 1 | 1 | 10 |
| INF5 | 0 | 1 | 1 | 1* | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 10 |
| SAF1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 6 |
| SAF2 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1* | 1* | 1 | 1 | 6 |
| SAF3 | 0 | 0 | 0 | 0 | 0 | 1 | 1* | 1 | 1 | 1 | 1 | 6 |
| SAF4 | 0 | 0 | 0 | 0 | 0 | 1 | 1* | 1 | 1 | 1 | 1 | 6 |
| SAF5 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1* | 1 | 1* | 6 |
| SAF6 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1* | 1* | 1 | 6 |
| Dependence power | 1 | 5 | 4 | 4 | 4 | 11 | 11 | 11 | 11 | 11 | 11 | |

**Table 7**
The Level Partitioning (LP).

| Elements (Mi) | Reachability Set R(Mi) | Antecedent Set A (Ni) | Intersection Set R (Mi)∩ A(Ni) | Level |
|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 4 |
| 2 | 2 | 1, 2, 3, 4, 5 | 2 | 2 |
| 3 | 3, 4, 5 | 1, 3, 4, 5 | 3, 4, 5 | 3 |
| 4 | 3, 4, 5 | 1, 3, 4, 5 | 3, 4, 5 | 3 |
| 5 | 3, 4, 5 | 1, 3, 4, 5 | 3, 4, 5 | 3 |
| 6 | 6, 7, 8, 9, 10, 11 | 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 | 6, 7, 8, 9, 10, 11 | 1 |
| 7 | 6, 7, 8, 9, 10, 11 | 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 | 6, 7, 8, 9, 10, 11 | 1 |
| 8 | 6, 7, 8, 9, 10, 11 | 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 | 6, 7, 8, 9, 10, 11 | 1 |
| 9 | 6, 7, 8, 9, 10, 11 | 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 | 6, 7, 8, 9, 10, 11 | 1 |
| 10 | 6, 7, 8, 9, 10, 11 | 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 | 6, 7, 8, 9, 10, 11 | 1 |
| 11 | 6, 7, 8, 9, 10, 11 | 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 | 6, 7, 8, 9, 10, 11 | 1 |

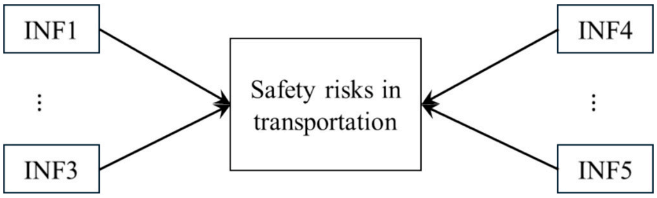

**Fig. 5.** Safety risks resulting from INF1-INF5.

[30], making it well-suited for complex systems such as those involved in the multimodal $LH_2$ transportation network. As illustrated in Fig. 5, INF1–INF5 contribute significantly to increased safety risks during transportation. For demonstration, our study assesses the SAF1 transportation risk resulting from INF1-L1 and INF2-M1 (see definitions in Table 8). Fuzzy values are assigned based on their severity or likelihood, and inference rules are applied to generate a quantified risk level, as shown in Fig. 6. Similarly, the FIS can be used to evaluate the risk level for any pair of sub-challenges. The steps involved in FIS modelling are described below.

### *Fuzzification*

We use a trapezoidal membership function for the fuzzification process, which transforms the crisp numerical evaluations of INF1–L1 into qualitative linguistic terms such as low, medium, and high [30,80]. Trapezoidal functions are chosen for their suitability, interpretability, and simplicity for discrete qualitative assessments. They effectively translate expert judgments into structured fuzzy inputs and outputs [80,81]. Based on discussions with our experts, we adopted a 0–10 scale to score INF1-L1, as shown in Fig. 7. This score represents the expert-assessed severity of the factor. The assigned values are then mapped onto the membership functions illustrated in Fig. 8. These functions assign a degree of membership (ranging from 0 to 1) to each linguistic category based on the input value [28,81]. For example, values between 0 and 4 are associated with low severity, with full membership at 0 and none at 4. Values from 2 to 8 are mapped to medium, peaking at 5 with full membership, while values from 6 to 10 represent high, with full membership at 10. The overlapping triangular membership functions allow a single input to partially belong to more than one category, thus capturing uncertainty and subjective variability in expert judgments. This process is essential for integrating qualitative expert input into quantitative multi-criteria decision-making models [81]. Similarly, to fuzzify INF2-M1, we use the same scale and membership functions as

**Table 8**
Categorizing INF1 and INF2 according to their effects on SAF1.

| Risk levels | Risk in trapezoidal scale | INF1 sub-challenges | | INF2 sub-challenges | |
|---|---|---|---|---|---|
| Low | 0–0–2–4 | INF1-L1 | Transport and storage containers are not designed to meet high safety standards | INF2-L1 | Minor wear and tear possibility under standard conditions |
| | | | | INF2-L2 | Minimal possibility of immediate degradation |
| Medium | 2–4–6–8 | INF1-M1 | Reliance on temporary or modular infrastructure rather than permanent handling systems | INF2-M1 | Fluctuating temperatures and handling conditions accelerate material fatigue |
| | | INF1-M2 | Inadequate interoperability between hydrogen systems across different transport modes | INF2-M2 | Partial degradation during long-distance transport |
| | | INF1-M3 | Regulatory or technical ambiguities causing delays in transshipment | | |
| High | 6–8–10–10 | INF1-H1 | Insufficient hydrogen-ready infrastructure at ports | INF2-H1 | Moderate material degradation under prolonged cryogenic exposure |
| | | INF1-H2 | Lack of adequate cryogenic equipment at transshipment points | INF2-H2 | Good possibility of containment failure during storage or transfer |
| | | INF1-H3 | Incompatibility of current port equipment and vessels with hydrogen applications | | |

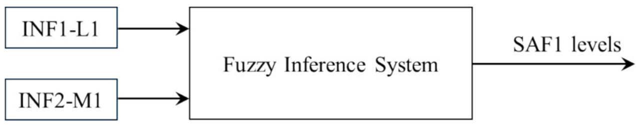

**Fig. 6.** SAF1 assessment for INF1-L1 and INF2-M1.

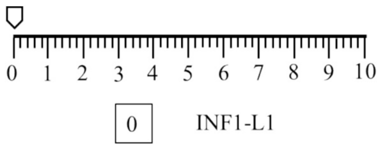

**Fig. 7.** INF1-L1 fuzzification scale.

shown in Figs. 7 and 8, respectively.

Based on expert discussions, we categorize the INF1 and INF2 into low, medium, and high sub-challenges to assess SAF1. This categorization, presented in Table 8, supports SAF1 risk assessment by translating qualitative challenges into corresponding numerical risk representations.

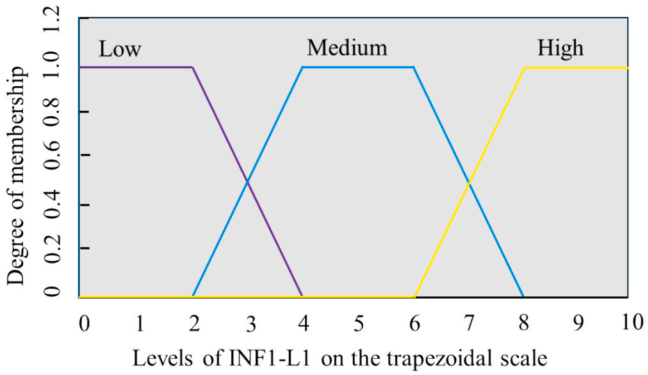

**Fig. 8.** INF1-L1 membership function and degree of membership.

*Inference*

Table 9 presents a set of fuzzy rules using linguistic variables (low, medium, high) for INF1-L1 and INF2-M1, combined using the OR logic operator. The output will be corresponding SAF1 levels to transport $LH_2$ through the corridor, with the rule base showing that a higher risk is typically assigned when either INF1-L1 or INF2-M1 presents a medium or high challenge, as illustrated in Rules 5–7. This reflects the permissive nature of the OR logic, where the presence of a challenge in either input elevates the output risk level. Table 10 shows the binary implementation of the OR operator using the max function. The OR operation is chosen because safety risks can arise if either INF1-L1 or INF2-M1 is present [77]. As shown in Table 10, when either INF1-L1 or INF2-M1 is assigned a value of 1, the OR operation yields a result of 1. The maximization function selects the higher value between INF1-L1 and INF2-M1 [77,78]. The use of this function is illustrated in Table A1 in the Appendix. This binary interpretation supports the FIS by providing a crisp representation of the logic behind the rule combination [82,83], enhancing transparency and computational implementation of the fuzzy model [83,84].

*Defuzzification*

Fig. 9 illustrates the triangular membership functions used for defuzzifying the rules listed in Table 9 [77,82]. The x-axis represents the risk level, expressed as a probability percentage ranging from 0 to 100 %, while the y-axis shows the degree of membership, ranging from 0 to 1.0 [77]. Each triangular corresponds to a specific fuzzy set: the “low” risk level peaks at 25 %, the “medium” at 50 %, and the “high” at 75 %. These overlapping triangles indicate how a particular set can simultaneously belong to multiple sets [85,86]. This visual representation is a key component of the defuzzification process, which translates fuzzy

**Table 9**
Rule set between INF1-L1 and INF2-M1 and their corresponding risk levels.

| Rules | | | | | Logic operator | Risk levels |
|---|---|---|---|---|---|---|
| Rule 1 | Low | INF1-L1 | Low | INF2-M1 | OR | Low |
| Rule 2 | Low | INF1-L1 | Medium | INF2-M1 | OR | Medium |
| Rule 3 | Medium | INF1-L1 | Low | INF2-M1 | OR | Medium |
| Rule 4 | Medium | INF1-L1 | Medium | INF2-M1 | OR | Medium |
| Rule 5 | Medium | INF1-L1 | High | INF2-M1 | OR | High |
| Rule 6 | High | INF1-L1 | Medium | INF2-M1 | OR | High |
| Rule 7 | High | INF1-L1 | High | INF2-M1 | OR | High |

**Table 10**
Binary OR logic: max function applied to rules.

| INF1-L1 | INF2-M1 | OR | Max (INF1-L1, INF2-M1) |
|---|---|---|---|
| 0 | 0 | 0 | 0 |
| 1 | 0 | 1 | 1 |
| 0 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 |

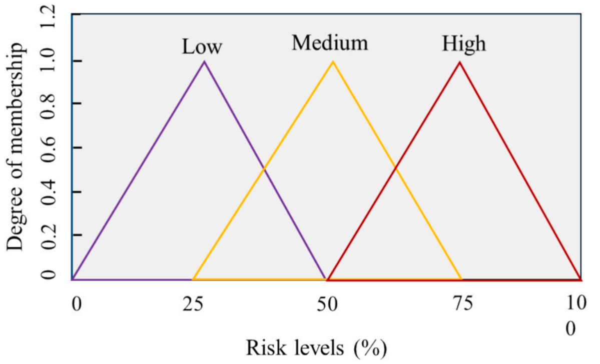

**Fig. 9.** Triangular membership functions for defuzzification.

input values into a single crisp output. An example of translating fuzzy inputs for INF1-L1 and INF2-M1 into a crisp output is presented in the Appendix section.

## Results and discussion

### *ISM-based findings*

### *MICMAC analysis*

**Autonomous variables (quadrant I):** These variables exhibit no dependence and low driving power, indicating they are not influenced by other variables [27,71]. In Fig. 10, Quadrant I represents these variables, which are typically unstable and have minimal impact on the system's overall dynamics. However, in this study, no variables fall into the autonomous category. This suggests that all identified factors possess either significant influence, dependence, or both.

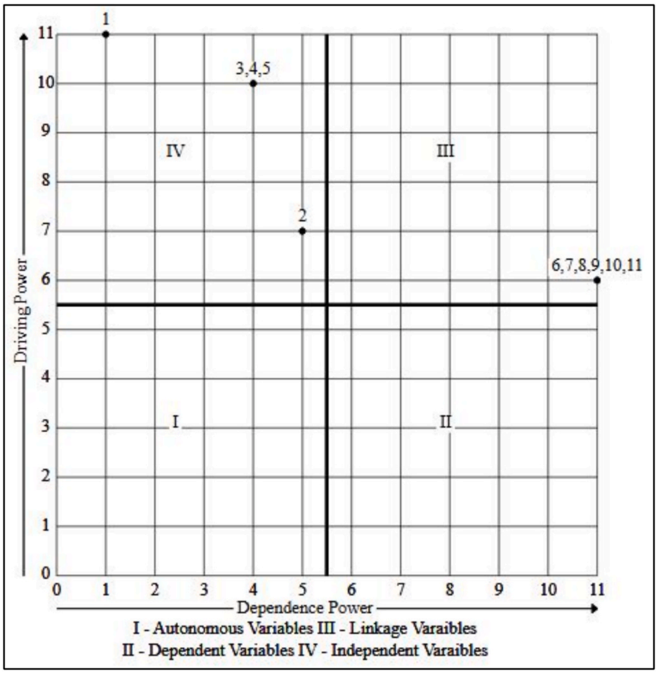

**Fig. 10.** MICMAC-based categorization of variables.

**Dependent variables (quadrant II):** These variables exhibit high dependence power but low driving power, meaning they are strongly influenced by other variables while exerting no influence [27,71]. In Fig. 10, Quadrant II contains these variables, which typically represent outcomes or consequences rather than root causes. The absence of variables in this Quadrant indicates that no challenge/risk is solely influenced by others without exerting influence itself. This suggests a highly interconnected system where all variables either drive or mutually influence each other, emphasizing the complexity of managing hydrogen transportation challenges/risks.

**Linkage variables (quadrant III):** These variables exhibit both high driving power and high dependence, making them highly influential yet vulnerable to changes within the system [27,71]. Positioned in Quadrant III of Fig. 10, these variables play a pivotal role in maintaining system stability and are often key targets for intervention. The presence of six safety risks, SAF1-SAF6, as linkage variables in this Quadrant underscores their dual nature as both highly influential and highly dependent within the $LH_2$ transportation network. These variables are critical because any disturbance in one can significantly impact the others, leading to a cascade of safety risks. The linkage variables are strongly influenced by independent variables.

**Independent variables (quadrant IV):** These variables possess high driving power and low dependence, indicating that they exert strong influence over other variables while remaining largely unaffected by them [27,71]. Positioned in Quadrant IV of Fig. 10, they are considered the most critical for strategic decision-making. The presence of five infrastructure challenges, INF1-INF5, in this Quadrant indicates they serve as foundational elements that significantly influence the entire system but are not themselves easily affected by other variables. Their strategic importance lies in their ability to initiate improvements or disruptions across the hydrogen transport network. Addressing these challenges, such as infrastructure readiness, material durability, and emergency systems, is critical for ensuring system stability and enabling safer, more efficient multimodal hydrogen transportation.

### *The ISM model*

Fig. 11 presents an ISM digraph illustrating the hierarchical structure of contextual relationships among the challenges and risks associated with $LH_2$ transportation along the corridor. The digraph is organized into four levels, showing how challenges and risks are interrelated through both direct (solid lines) and transitive (dashed lines) links.

At Level 1, SAF1-SAF6 represents the most dependent safety risks in the hierarchy. These represent the ultimate risks and are directly linked to the infrastructure challenges at the next lower hierarchical level, but they do not exert any influence on others. INF2, positioned at Level 2, functions as the immediate recipient of these influences. Moving to Level 3, the model highlights three interconnected challenges: INF3, INF4, and INF5. These directly influence material degradation (INF2) and are also mutually dependent, forming a feedback loop that can exacerbate system vulnerabilities. For instance, the lack of digital monitoring can delay emergency responses, while inadequate maintenance can worsen equipment failures. Additionally, the Level 3 challenges exert transitive influence on the safety-related issues at Level 1, indicating deeper, systemic interdependencies across the hierarchy. At the base of the model, Level 4 includes INF1, which represents the foundational challenge to establishing a reliable hydrogen transport network. INF1 influences the upstream challenges both directly and transitively, underscoring how infrastructure readiness shapes top-level safety risks and mid-level operational weaknesses.

Overall, Fig. 11 offers a clear, structured representation of how infrastructure challenges and safety risks are layered and interdependent. It provides insights into prioritizing interventions, suggesting that mitigating safety risks and addressing material degradation are essential first steps toward enabling a resilient and scalable $LH_2$ transport system

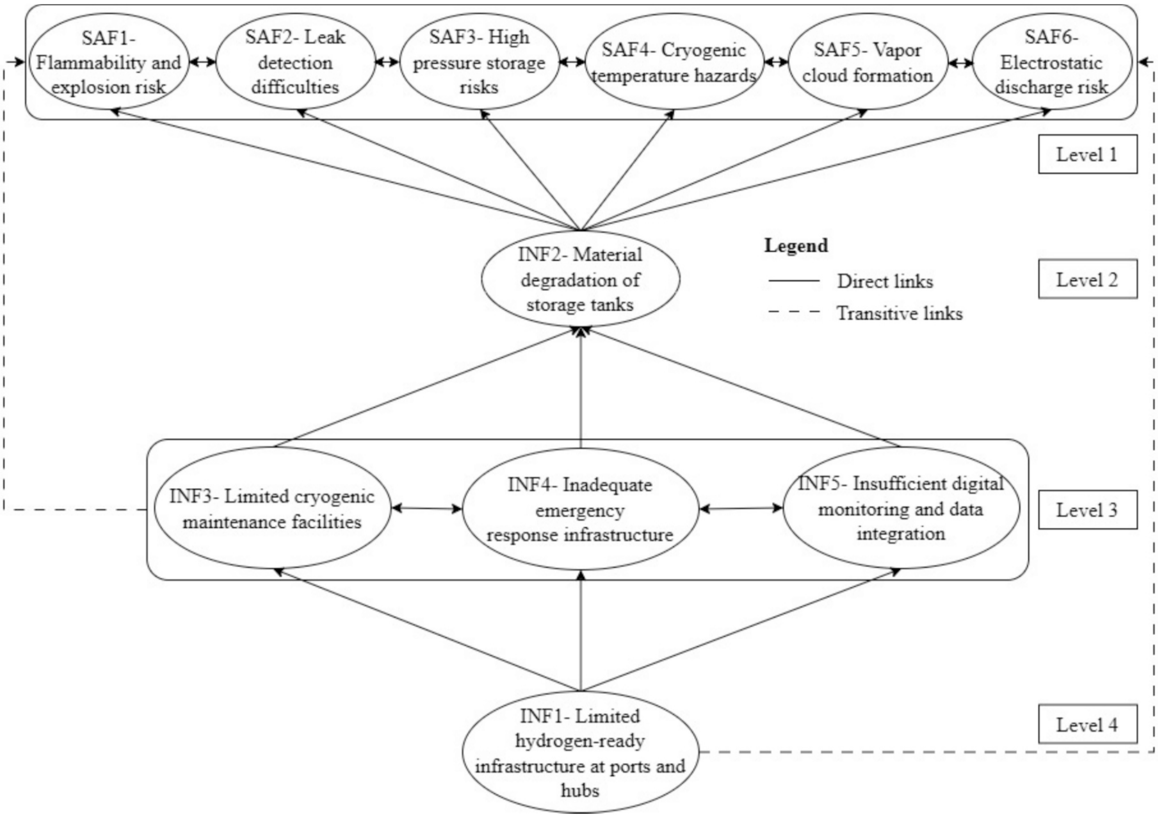

**Fig. 11.** ISM digraph (model) among the infrastructure challenges and safety risks.

across the corridor.

### *FIS-based findings*

This section evaluates how SAF1 levels vary with changes in INF1-L1 and INF2-M1.

#### *SAF1 levels for various input values of INF1-L1 and INF2-M1*

This section analyzes SAF1 levels for both a specific and all trapezoidal membership functions of INF1-L1 and INF2-M1, as detailed in Sections 5.2.2.1 and 5.2.2.2.

***For INF1-L1 = [0, 0, 2, 4] and INF2-M1 = [2, 4, 6, 8].*** Table 11 presents the SAF1 levels based on the low trapezoidal membership function [0, 0, 2, 4] for INF1-L1 and the medium trapezoidal membership function [2, 4, 6, 8] for INF2-M1. Detailed calculations are provided in the Appendix. To systematically evaluate how SAF1 level varies, the values of both inputs are incremented by 0.5 units, covering a wide range of combinations from [2,2] to [4,8]. The table reveals a clear trend of increasing risk as either INF1-L1 or INF2-M1 rises. For instance, the lowest risk level/probability (37.5 %) occurs when both inputs are at their minimum values [2,2]. Risk levels gradually increase, surpassing 50 % when the values reach midpoints (e.g., [3, 3.5] = 52.2) and peaking at 62.5 % when INF1-L1 and INF2-M1 both reach 4 or higher. Notably, a risk level of 56.3 % is observed at [3.5, 3.5], consistent with the defuzzification output discussed in Fig. A3. Additionally, risk values stabilize at their maximum (62.5 %) for several combinations beyond [4,4], particularly where INF2-M1 ≥ 4, indicating a saturation point in the FIS where additional increases in challenge levels do not further elevate risk.

***Both INF1-L1 and INF2-M1 range from [0, 0, 2, 4] to [6, 8, 10, 10].***

**Table 11**
SAF1 levels (%) for INF1-L1 = [0, 0, 2, 4] and INF2-M1 = [2, 4, 6, 8].

| Level of [INF1-L1, INF2-M1] | SAF1 level (%) | Level of [INF1-L1, INF2-M1] | SAF1 level (%) | Level of [INF1-L1, INF2-M1] | SAF1 level (%) | Level of [INF1-L1, INF2-M1] | SAF1 level (%) | Level of [INF1-L1, INF2-M1] | SAF1 level (%) |
|---|---|---|---|---|---|---|---|---|---|
| [2,2] | 37.5 | [2.5, 2] | 43.4 | [3,2] | 47.2 | [3.5, 2] | 49.4 | [4,2] | 50 |
| [2, 2.5] | 43.4 | [2.5, 2.5] | 43.7 | [3, 2.5] | 47.8 | [3.5, 2.5] | 50 | [4, 2.5] | 50.6 |
| [2,3] | 47.2 | [2.5, 3] | 47.8 | [3,3] | 50 | [3.5, 3] | 52.2 | [4,3] | 52.8 |
| [2, 3.5] | 49.4 | [2.5, 3.5] | 50 | [3, 3.5] | 52.2 | [3.5, 3.5] | 56.3 | [4, 3.5] | 56.6 |
| [2,4] | 50 | [2.5, 4] | 50.6 | [3,4] | 52.8 | [3.5, 4] | 56.6 | [4,4] | 62.5 |
| [2, 4.5] | 50 | [2.5, 4.5] | 50.6 | [3, 4.5] | 52.8 | [3.5, 4.5] | 56.6 | [4, 4.5] | 62.5 |
| [2,5] | 50 | [2.5, 5] | 50.6 | [3,5] | 52.8 | [3.5, 5] | 56.6 | [4,5] | 62.5 |
| [2, 5.5] | 50 | [2.5, 5.5] | 50.6 | [3, 5.5] | 52.8 | [3.5, 5.5] | 56.6 | [4, 5.5] | 62.5 |
| [2,6] | 50 | [2.5, 6] | 50.6 | [3,6] | 52.8 | [3.5, 6] | 56.6 | [4,6] | 62.5 |
| [2, 6.5] | 49.4 | [2.5, 6.5] | 50 | [3, 6.5] | 52.2 | [3.5, 6.5] | 56.3 | [4, 6.5] | 62.5 |
| [2,7] | 47.2 | [2.5, 7] | 47.8 | [3,7] | 50 | [3.5, 7] | 56.3 | [4,7] | 62.5 |
| [2, 7.5] | 49.4 | [2.5, 7.5] | 50 | [3, 7.5] | 52.4 | [3.5, 7.5] | 56.3 | [4, 7.5] | 62.5 |
| [2,8] | 50 | [2.5, 8] | 50.7 | [3,8] | 53.1 | [3.5, 8] | 56.9 | [4,8] | 62.5 |

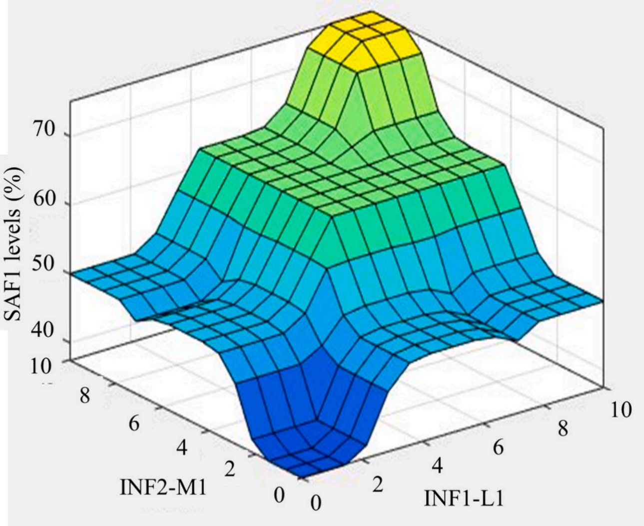

**Fig. 12.** FIS surface plot showing SAF1 levels (%) for INF1-L1 and INF2-M1.

Fig. 12 presents a surface plot generated in MATLAB, based on the rules listed in Table 9, illustrating how variations in the INF1-L1 and INF2-M1 inputs influence SAF1 levels (%). When both inputs fall within the low range [0, 0, 2, 4], SAF1 decreases from 45 % to 0 %, indicating a safer condition. As the inputs increase to the medium range [2, 4, 6, 8], SAF1 rises to approximately 50–65 %, reflecting a moderate risk. At the high range [6, 8, 10, 10], the risk level peaks at around 75 %, marking the riskiest scenario. This trend clearly demonstrates the direct relationship between increasing challenge intensity and elevated safety risk in the FIS model.

*Scenario-based variations in SAF1 levels*

To evaluate how SAF1 levels respond to varying conditions, we consider a modified scenario using AND operators and adjusted rule definitions, as detailed below.

**Scenario:** In this scenario, we use AND operators instead of OR operators in each rule, as shown in Table 9. Additionally, we modify Rule 4 by assigning a high-risk level to the 'medium-medium' input combination, whereas it was previously classified as a medium-risk level.

**Scenario findings:** Fig. 13 shows that a high-risk level (approximately 75 %) is observed only when both input variables (INF1-L1 and INF2-M1) simultaneously reach high values (around 8–10), producing a steeper and narrower peak in the top-right corner of the plot. This contrasts with the original scenario where OR operators allowed for higher risk even when one input was elevated. In this case, if one input remains low while the other is high (e.g., INF1-L1 = 8 and INF2-M1 = 2), the resulting risk stays moderate, around 40–50 %. This pattern reflects the logical filtering effect introduced by the AND operator, which requires both conditions to be met simultaneously to yield a high-risk outcome, resulting in a more stricter risk estimation.

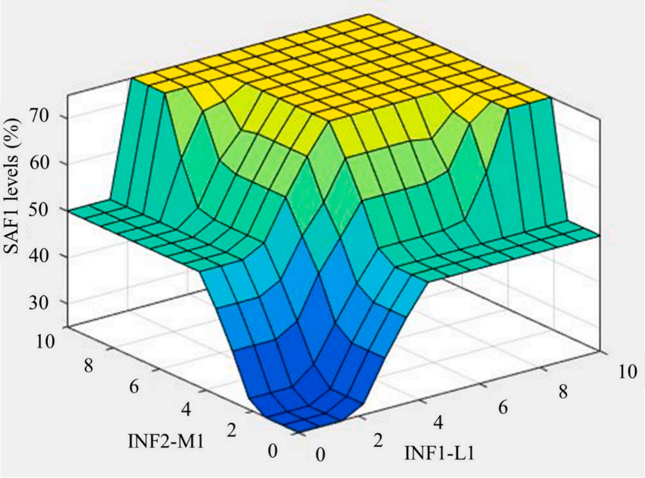

**Fig. 13.** SAF1 (%) in the scenario-based variations.

*Validation of ISM model and FIS findings*

We presented our ISM model and FIS findings to the experts for validation. Regarding the ISM model, one expert suggested that the material degradation of storage tanks (INF2) could be moved to Level 3, implying that Levels 2 and 3 might be aligned. However, the other experts supported the existing structure, noting that Level 3 challenges (INF3–INF5) could influence INF2, justifying their placement at different levels. Concerning the FIS model, a few experts recommended rechecking the fuzzy rules, particularly the use of logical operators during implementation in the MATLAB®. After conducting multiple rechecks, we found the results to be consistent across all evaluations. Based on this, the experts validated our model and advised us to proceed with the findings.

## Conclusion

In this study, we first aggregate the challenges and risks (see Tables 2 and 3), addressing RQ1. Second, we use ISM to reveal a hierarchical structure, distinguishing between foundational, intermediate, and dependent variables. Limited hydrogen-ready infrastructure at ports and hubs emerges as the foundational challenge, exerting broad influence across the system. Intermediate challenges include limited cryogenic maintenance facilities, weak emergency response capabilities, insufficient digital monitoring, and material degradation risks. Safety risks such as flammability risk, vapor cloud formation, electrostatic discharge, leak detection issues, cryogenic temperature hazards, and high-pressure storage risks are found to be highly dependent on the severity of the foundational and intermediate issues. The details of the MICMAC analysis and ISM model are described in Section 5.1, which addresses RQ2. Insights from RQ1 and RQ2 provide a clearer understanding of systemic vulnerabilities in $LH_2$ logistics and can inform targeted strategies to improve infrastructure, safety protocols, and risk management along the corridor. Third, this study examines how varying combinations and intensities of these challenges affect safety risk levels (see Figs. 12 and 13). In response to RQ3, the demonstrative FIS model shows that transportation risk levels are highly sensitive to both the severity of the challenges and their interactions. The results show that when two sub-challenges, transport containers lack design for high safety standards (INF1-L1) and fluctuating conditions accelerate material fatigue (INF2-M1), are at low levels, the overall risk probability remains relatively low, ranging from 0 % to 45 %. However, when the intensity of either challenge increases to a medium range, the risk rises to a moderate level, between 55 % and 65 %. The highest risk, peaking at 70 % to 75 %, occur when both challenges are severe (see details in Section 5.2). These findings highlight the compounded effect of interacting challenges on system vulnerability and underscore the importance of managing not only individual risks but also their combined impact. The scenario-based risk quantification offers practical guidance for prioritizing investments in infrastructure and safety measures to reduce risk across the corridor.

By addressing these challenges, this study contributes to reducing reliance on fossil fuels and lowering carbon emissions in the freight sector. The results also support the development of a safer and more reliable hydrogen transport network, which is essential for scaling up hydrogen as a clean energy carrier across the corridor. Importantly, the identified infrastructural and safety issues, such as material compatibility, high-pressure storage risks, and cryogenic handling requirements, directly relate to established provisions in ISO 21010 (material compatibility in cryogenic vessels), ISO 13985 (liquid hydrogen tanks for land vehicles), NFPA 2 (hydrogen facility and refueling station safety), NFPA 55 (safe handling, transport, and storage of liquid hydrogen), and SAE J2579 (hydrogen vehicle fuel system safety) [13,8,97,98]. By highlighting where vulnerabilities may arise relative to these standards, the findings provide practical direction for aligning emerging $LH_2$ logistics with internationally recognized safety requirements. These contributions are closely aligned with several Sustainable Development Goals (SDGs), including SDG 7 (affordable and clean energy), SDG 9 (industry, innovation, and infrastructure), and SDG 11 (sustainable cities and communities), as discussed by Rahman & Baldacci [2] and Rahman et al. [3]. By enabling progress toward large-scale hydrogen logistics, the study offers actionable insights to help policymakers and industry stakeholders accelerate the transition to low-carbon transport systems. On the theoretical side, the integration of ISM and FIS provides a novel framework for analyzing complex interdependencies and quantifying risks under uncertainty in hydrogen supply chains. The theoretical contributions and practical implications are outlined below.

**Theoretical contributions:** First, this study advances the theoretical understanding of $LH_2$ transportation risk by integrating ISM and FIS into a single framework. This combined approach addresses both structural complexity and uncertainty, which are often overlooked in existing studies on hydrogen logistics. Second, the use of ISM provides a systematic method to identify and map the hierarchical relationships among infrastructural challenges and safety risks. This allows for the classification of challenges as foundational, intermediate, or dependent, offering a new way to conceptualize the layered nature of risks in hydrogen supply chains. Third, FIS modeling introduces a dynamic, scenario-based tool for quantifying how combinations of interrelated challenges influence transportation risk levels under varying conditions. This adds to the literature by moving beyond static risk assessments toward more adaptive and comprehensive models. Finally, the proposed ISM–FIS framework offers a replicable foundation for future research on hydrogen logistics where systemic risks and uncertainties are critical.

**Practical implications:** First, this study provides a structured basis for policymakers and planners to prioritize infrastructure and safety improvements by classifying the challenges. This helps focus attention on the most critical areas, such as hydrogen-ready port infrastructure and emergency response systems. Second, the scenario-based risk assessment using the FIS offers practical guidance on how different combinations and severities of challenges affect overall transportation risk. This allows decision-makers to allocate resources efficiently and plan targeted interventions that address the most influential risks. Third, the integrated ISM–FIS framework serves as a valuable tool for risk-informed planning of future hydrogen corridors/routes, supporting the creation of safer, more resilient hydrogen logistics networks. Fourth, the study's insights can inform the development of safety standards, regulatory frameworks, and investment strategies aimed at minimizing risks while supporting hydrogen adoption. Finally, by addressing these practical considerations, the study contributes to building a low-carbon, sustainable transportation system that supports the broader transition to clean energy.

### *Recommendations for the policymakers and stakeholders*

To successfully scale $LH_2$ transport along the corridor, policymakers should address critical infrastructure, safety, and regulatory needs. The following recommendations provide practical guidance for enabling a safer, more resilient hydrogen logistics network.

- **Prioritize investment in hydrogen-ready port and hub infrastructure:** Policymakers should direct funding toward the development and upgrade of hydrogen-ready infrastructure at key ports, terminals, and hubs along the corridor. This includes building dedicated $LH_2$ storage facilities, cryogenic handling systems, and refueling stations. Strengthening foundational infrastructure will reduce bottlenecks, improve operational safety, and support large-scale hydrogen transport, as supported by Xie et al. [20] and Rolo et al. [87]. Early investment in such infrastructure is important to establish a reliable supply chain that will meet both regional energy needs and export demands to Europe.
- **Enhance emergency response systems and safety protocols:** Governments should work with industry stakeholders to design and implement robust emergency response plans tailored for $LH_2$ transport incidents. This involves training first responders, equipping them with hydrogen-specific tools, and developing coordinated response frameworks across regions. Enhancing emergency preparedness will reduce the severity of potential accidents, protect communities, and build confidence in hydrogen as a safe energy carrier, as demonstrated by Sakib et al. [14] and Yazdi et al. [88].
- **Promote digital monitoring and data integration:** Policymakers should support the adoption of advanced digital technologies to enable real-time monitoring of hydrogen transport operations. Investments in sensor networks, predictive maintenance systems, and integrated data platforms can improve risk detection, incident prevention, and operational efficiency. A standardized digital infrastructure would also facilitate data sharing across stakeholders, ensuring better coordination and faster responses in case of incidents, as supported by Yazdi et al. [88] and Benson and Obasi [89].
- **Develop supportive regulatory frameworks and cross-border coordination mechanisms:** Stakeholders and policymakers should establish clear, harmonized regulatory frameworks, ensuring alignment among Gulf countries, Iraq, and Türkiye. This includes setting technical standards, safety requirements, and environmental guidelines for hydrogen logistics. Additionally, fostering cross-border collaboration through joint task forces or agreements will enable smoother operations, reduce regulatory barriers, and accelerate the corridor's hydrogen transition, as highlighted by Pinto [90] and Yatsenko and Iatsenko [91].

### *Limitations*

This study relies on expert-based assessments which may introduce some subjectivity despite efforts to engage a diverse group of specialists. Future research could strengthen validation by complementing expert input with empirical data from operational hydrogen transport projects. Additionally, the research is limited to the Gulf-Europe corridor, and while the findings offer valuable insights, their direct applicability to other hydrogen routes may be constrained by regional differences in infrastructure, regulations, and geography. Moreover, the FIS model developed in this study includes only two sub-challenges (INF1-L1 and INF2-M1). As a result, it captures only a portion of the overall transportation risk rather than providing a comprehensive risk assessment. Expanding the model to incorporate additional sub-challenges and more complex scenarios could offer a more comprehensive and nuanced risk profile. Furthermore, the study does not fully account for evolving technological advancements, regulatory changes, or market dynamics that could significantly alter hydrogen transportation risks over time. Finally, the study's reliance on static severity scoring may simplify the dynamic nature of risk factors, suggesting a need for more adaptive and real-time assessment tools in future research.

### *Future research directions*

Future studies could incorporate real-world operational data from existing or pilot hydrogen transport corridors to validate and refine the ISM–FIS framework, thereby reducing reliance on expert opinion and enhancing the robustness of risk assessments. In addition, future work should incorporate accident datasets or quantitative, risk-based probability estimates once such data becomes available. This will help strengthen the external validation of the ISM–FIS framework as $LH_2$ infrastructure matures. Extending the FIS analysis to include variables such as regulatory compliance, environmental conditions, and emerging technologies would allow for a more comprehensive and dynamic risk profile for $LH_2$ transportation. Comparative studies across different corridors or regions could further examine how variations in regulatory environments, geography, and infrastructure influence hydrogen transport risks, contributing to the development of globally applicable best practices. Finally, future research could explore the integration of advanced digital tools, such as digital twins, to support real-time, adaptive risk monitoring and decision-making for hydrogen storage and transportation systems.

## Institutional review board statement

The Institutional Review Board of HBKU approved this study under protocol code HBKU-IRB-2025–57 on August 7, 2024.

## Ethics, consent to participate, and consent to publish declarations

Not applicable.

## CRediT authorship contribution statement

**Md. Habibur Rahman:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Roberto Baldacci:** Writing – review & editing, Supervision, Conceptualization.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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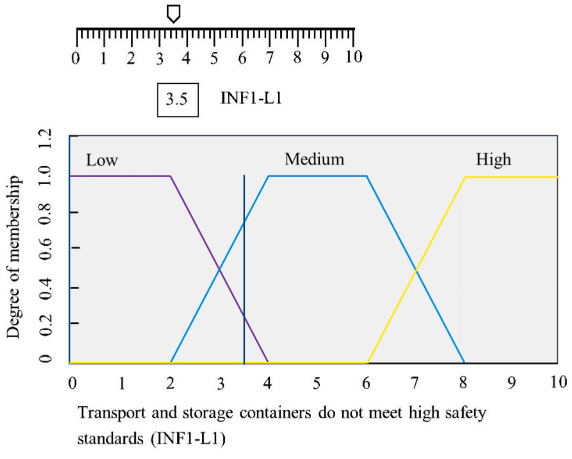
## Appendix

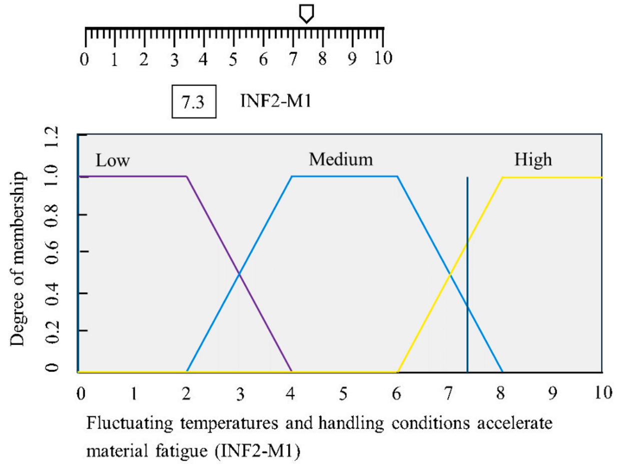
This section describes the FIS methodology used to assess SAF1 levels in $LH_2$ transportation for INF1-L1 = 3.5 and INF2-M1 = 7.3.

**Fuzzification:** To demonstrate how the degrees of membership vary with different values of INF1 and INF2, we present an illustrative example using INF1-L1 = 3.5 and INF2-M1 = 7.3. Figs. A1 and A2 show the degrees of membership for the two fuzzy input variables. Fig. A1 shows the degree of membership for INF1-L1 when its value is 3.5. At this value, it has a low membership of 0.20, a medium membership of 0.80, and no association with the high category (0.00), indicating that INF1-L1 primarily falls within the medium challenge range. Fig. A2 presents the membership degrees for INF2-M1 at a value of 7.3. At this point, the low membership is 0.00, the medium membership is 0.35, and the high membership is 0.65, implying that INF2-M1 exhibits a higher risk level with a notable contribution from both the medium and high categories.



Low = 0.20, medium = 0.80, high = 0

**Fig. A1.** Degree of membership when INF1-L1 = 3.5



Low = 0, medium = 0.35, high = 0.65

**Fig. A2.** Degree of membership when INF2-M1 = 7.3

**Inference:** Table A1 shows fuzzy inference rules that determine risk levels based on two input variables. The rules apply OR logic, using the max operator to select the dominant membership value for each risk category (low, medium, high). For example, Rule 5 yields a high risk of 0.80 based on max(0.80, 0.65), reflecting strong membership in the "high" risk category. Each rule yields a corresponding membership value, and the average column consolidates the result.

**Table A1**
Fuzzy inference rules and corresponding risk levels for INF1-L1 and INF2-M1.

| Rules | Membership functions in rules | Risk levels | Average risk level (%) |
|---|---|---|---|
| Rule 1 | Low = max (0.20, 0) | 0.20 | 56.3 |
| Rule 2 | Medium = max (0.20, 0.35) | 0.35 | |
| Rule 3 | Medium = max (0.80, 0) | 0.80 | |
| Rule 4 | Medium = max (0.80, 0.35) | 0.80 | |
| Rule 5 | High = max (0.80, 0.65) | 0.80 | |
| Rule 6 | High = max (0, 0.35) | 0.35 | |
| Rule 7 | High = max (0, 0.65) | 0.65 | |

**Defuzzification and risk level measure:** Fig. A3 shows the defuzzification process using triangular membership functions, as detailed in Table A1. The figure illustrates how the FIS model interprets the input values INF1-L1 = 3.5 and INF2-M1 = 7.3, as indicated by the red vertical lines intersecting the yellow-shaded membership regions. The corresponding defuzzified output is a calculated risk level of 56.3 %, represented by the red line on the final output graph in blue. This output signifies the estimated safety risk level associated with these specific challenges in multimodal hydrogen transport along the corridor. While the risk level may vary with different input combinations, we find a risk level of 56.3 % for the specific inputs INF1-L1 = 3.5 and INF2-M1 = 7.3.

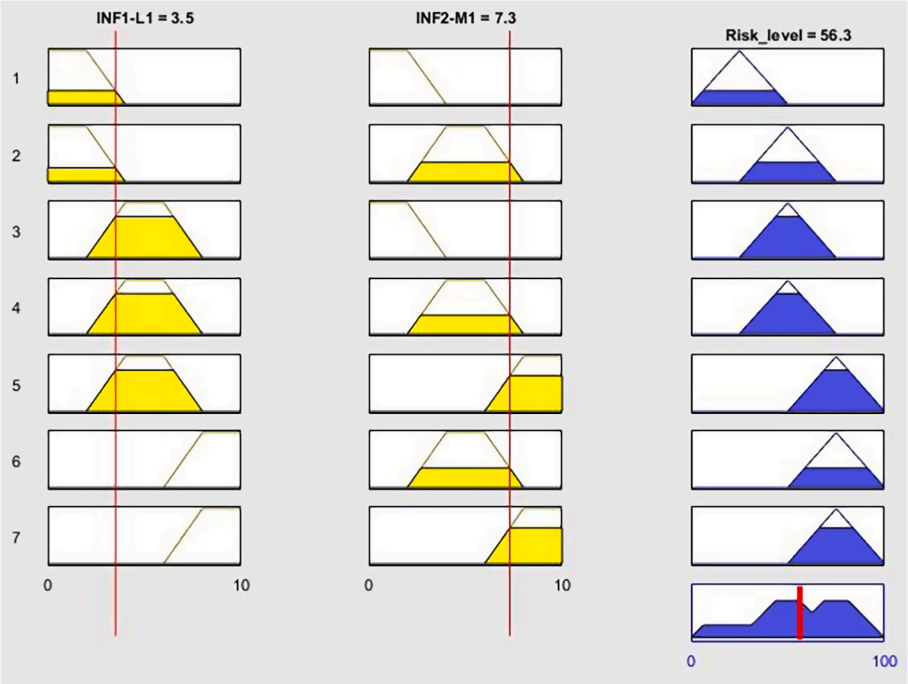


**Fig. A3.** Risk level (56.3 %) in the software output for INF1-L1 = 3.5 and INF2-M1 = 7.3

## Data availability

Data will be made available on request.

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

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