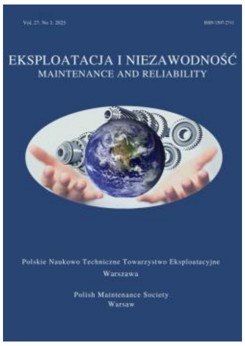

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Mapping FRAM to BN through Accimap for system risk assessment: an application to heavy goods vehicle fire risk in road tunnels

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Highlights

- A structured mapping method from FRAM to BN for risk assessment is proposed.
- Accimap is introduced to enhance the mapping traceability and repeatability.
- Functional hexagons are transformed to Accimaps to describe their internal couplings.
- Accimaps are connected based on upstream-downstream couplings to form a BN.
- The method is demonstrated by a case study of HGV fire in road tunnels.

Abstract

The Functional Resonance Analysis Method (FRAM) is extensively used to qualitatively analyze the risk of socio-technical systems. To quantitatively assess system risk, previous studies have explored various approaches to integrate FRAM with Bayesian Networks (BN). However, the process of mapping FRAM to BN relies heavily on subjective judgments, often lacking traceability and repeatability. In this paper, a structured method for mapping FRAM to BN is proposed through introducing Accimap. Firstly, each FRAM's functional hexagon is transformed into an Accimap, with the six aspects of functions—input, output, preconditions, resources, time, and control—corresponding to Accimap factors. In addition, their internal coupling relationships are obtained by cause and effect investigation in Accimap. Secondly, multiple Accimaps are connected based on the upstream-downstream couplings between functions in FRAM. Through this method, (i) the aspects of FRAM are transformed into Accimap factors and then BN nodes, and (ii) the couplings among the six aspects of functions and across multiple hexagons are converted into BN directed edges. This mapping method effectively mitigates subjective judgments, and analysts can construct the same BN after FRAM is established. Finally, the method is applied in heavy goods vehicle fire accidents in road tunnels to demonstrate its effectiveness.

Keywords
risk assessment, functional resonance analysis method, bayesian network, Accimap, structured mapping method

1. Introduction

Modern socio-technical systems, such as urban transportation system, healthcare system, and power grid system, are inherently very complex due to the dynamic interactions among system elements (e.g. human, machine, and environment). The coupling among these system elements leads to accidents occurring in more unpredictable ways 1. In addition, the consequences of the accidents are sometimes catastrophic. For example, within the tunnel traffic domain, the 2019 Maoliling Road Tunnel Fire in China, caused by a Heavy Goods Vehicle (HGV), resulted in 36 casualties 2. Similarly, the 2018 I-70 Eisenhower tunnel fire and the 2020 Sydney harbor tunnel fire also resulted in significant tunnel damage and property loss 3. Therefore, it is essential to manage the risks of socio-technical systems by a novel theoretical approach.

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Conventional strategy for system risk analysis is breaking system down into various components, including human, machine, and environment, and managing them separately 4. However, such strategy is only suitable for simple system with linear cause-and-effect relations. For complex socio-technical systems, the need for risk analysis has evolved from examining linear cause-and-effect relations to understanding non-linear coupling relations. Therefore, system-based methodologies like Functional Resonance Analysis Method (FRAM) have been developed 5. FRAM is recognized as a significant tool for identifying risks in socio-technical systems 6. It reflects that accidents typically arise not due to catastrophic failures, errors, or violations, but due to the accumulation of variability in everyday performance in unforeseen ways 7. The guiding principles of equivalence between success and failure, approximate adjustments, emergence, and functional resonance within FRAM offer a novel outlook for system risk analysis 89.

Unlike breaking down a system into components, FRAM illustrates a dynamic process or system with various functions, where each function is a sub-entity within the overarching process 10. It defines six aspects for each function—input, output, time, control, preconditions, and resources—to explain the interactions among these functions. FRAM, as a qualitative analysis method, is employed in various domains. In the investigation of the Prestige oil spill accident 11, FRAM was applied to identify the variabilities of events that led to the accident. Within the medical field, FRAM has been employed to analyze deaths or severe injuries occurring during treatment processes due to human factors 12. In addition, Ma et al. 13 and Lee et al. 14 proposed the risk assessment framework based on FRAM, applying it to maritime transportation systems. In industrial processes, several studies have introduced FRAM-based frameworks for the prediction of various system hazards 15. These studies indicate that FRAM excels in capturing the uncertainty and dynamics of complex systems, enabling a more thorough and detailed system analysis.

FRAM stands out as an effective tool for the qualitative analysis of accidents, however, it still has limitations in quantitatively predicting system risks. Previous studies attempt to integrate FRAM with Bayesian Networks (BN) to construct a quantitative model for system risk assessment. The integration of FRAM and BN has emerged as a widely adopted modeling approach, finding applications in diverse domains, including transportation, industrial processes and maritime. In the investigation of fire risks in highway tunnels, Wang et al. 16 introduced a method for mapping FRAM to BN, incorporating lines to denote coupling relationships in FRAM, aiming to establish a link between FRAM and BN. In some studies concerning risk analysis of industrial processes 17181920, FRAM functions as a method for risk analysis and identification. Here, the identified risk factors play roles as nodes in the BN. Specifically, the risk factors identified through FRAM are interlinked, and subsequently, they are directed towards result nodes, establishing the BN of the system. In addition, some studies also attempt to provide a more detailed description of the internal structure of FRAM's hexagons. Li et al. 21 innovatively combined FRAM with Accident Causation Analysis and Taxonomy (ACAT), furnishing an intricate and rigorous depiction of functions through the generation of a closed-loop control system. Following this, Guo et al. 22, in their examination of collision risks in ship navigation processes, attempted to map FRAM into Dynamic Bayesian Network (DBN) through ACAT. Their study regarded ACAT as a technique for identifying inter-level and intra-level risk influencing factors.

Previous studies have made significant strides in exploring the integration of FRAM and BN, while there remains an opportunity for enhancement in the traceability and repeatability of the method. FRAM is a six-dimensional structure, with each function comprising six aspects—I, O, P, R, T, and C; whereas Bayesian networks are two-dimensional structures, where connections between two nodes are established by directed edges. Consequently, direct mapping between the two is challenging. The previous mapping approaches consider FRAM as an effective tool for risk identification, incorporating analysts' subjective judgements to determine coupling relationships among various risk influencing factors. Therefore, the construction of BN relies, to some extent, on the subjective judgment of analysts, which cannot guarantee a complete alignment between the couplings in FRAM and the directed edges in BN. For different analysts, the BN obtained from the same FRAM mapping may not be the same.

This study aims to propose a structured method for mapping

FRAM to BN, intending to formulate a quantitative model for system risk assessment. Unlike traditional FRAM, which uses connections to illustrate coupling relations between functions without delving into how internal aspects influence function output, our proposed method introduces Accimap to establish internal causal relations within FRAM. The Accimap offers a methodology for outlining accidents within the framework of Jens Rasmussen's 23 risk management. This approach originated from recognizing that traditional task analysis methods are inadequate for modeling the complex network of factors underlying accidents 24. In consonance with Rasmussen's paradigm, Accimap is predicated on the foundational tenet that behavior, safety, and accidents manifest as emergent aspects within complex socio-technical systems. This emergence stems from the collective decisions and actions of all stakeholders in the system, encompassing politicians, CEOs, managers, safety officers, and work planners—not solely confined to frontline workers 25. By graphically representing relations among accident chains, event sequences, and system elements, Accimap provides a straightforward and comprehensive analytical framework applicable to diverse fields, such as transportation 262728, maritime 29, and chemical industry 30. The paramount strength of Accimap resides in its capacity to contemplate contributing factors throughout the entire work system, thereby facilitating a comprehension of the interactions and interrelations among these factors 31.

In the proposed mapping method, Accimap serves as a tool for delineating the internal coupling relationships within FRAM's functions. Firstly, functional hexagon's six aspects are transformed into Accimap factors. The internal coupling relationships among these factors are determined by cause and effect investigation in Accimap. Secondly, the transformed Accimap factors can be considered as BN nodes, and their internal coupling relationships can be converted into BN directed edges. Subsequently, by converting the upstream-downstream couplings in FRAM into directed edges that connect multiple Accimaps, a network structure is obtained. Finally, by determining the state classifications, root node probability distributions, and conditional probability table of each node in this network structure, the BN for the system is established. To demonstrate the effectiveness and applicability of this method in real-world scenarios, the case of tunnel fire accidents involving heavy goods vehicles is examined. In enclosed spaces like tunnels, HGV fire is a major factor in causing severe casualties 2. The analysis of HGV fire accidents in road tunnels considers the socio-technical system, encompassing various stakeholders like HGV drivers, freight companies, tunnel operators, fire rescue forces, and others 32. The evolution of accidents is influenced by a multitude of factors, including technical, human, and organizational elements. This case study aims to empirically validate the efficacy of the proposed method.

The main contribution of this paper can be summarized as follows: Accimap is introduced for the first time to propose a structured method for mapping FRAM to BN. FRAM's functional hexagons are transformed into Accimaps, and then multiple Accimaps are connected to map to the BN. This method facilitates a straightforward correspondence between FRAM and BN, and the structure of BN strictly relies on the outcomes of Accimap, resulting in a traceable and repeatable mapping.

The remainder of the paper is organized as follows: Section 2 introduces background knowledge about FRAM, Accimap and BN. Section 3 presents a structured method for mapping FRAM to BN through the integration of FRAM and Accimap. In Section 4, the proposed method is applied to conduct system risk assessment, using the case of HGV fire accidents in road tunnels as an illustration. Section 5 analyzes the results and discusses their implications. Finally, Section 6 provides a conclusion for the paper.

2. Relevant methods

2.1. Functional resonance analysis method

Traditional risk analysis methods mainly focus on linear cause-and-effect relations that lead to accidents. Nonetheless, hazards often evolve outside the confines of linear risk propagation paths, thereby instigating new accidents. Achieving a profound understanding and analysis of system risks necessitates a shift in focus towards learning from success rather than just from failure. FRAM has demonstrably emerged as an effective method, encapsulating the perspective that accidents typically arise not due to catastrophic failure, errors, or violations but due to the accumulation of variability in everyday performance in unforeseen ways 33.

Hollnagel's 34 universal FRAM conceptualizes daily activities as a sequence of interconnected functions. Following the identification of each function, its characteristics are delineated across six aspects: input, output, preconditions, resources, time, and control. This description is visually represented, with each vertex of a hexagon corresponding to one aspect of the function. Input signifies the initiation of the function, while output represents the function's outcome. Time encapsulates temporal constraints affecting the function, and control elucidates how the function is monitored or controlled. Preconditions outline the conditions necessary for a function's execution, and resources denote what the function requires for execution. Figure 1 illustrates the functional hexagon of FRAM.

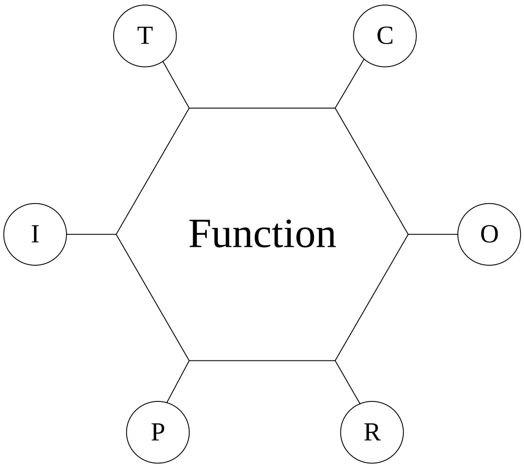

Figure 1. Functional hexagon.

Hollnagel delineates FRAM into four steps. 1) identify functions and their six aspects; 2) identify the variability of each function; 3) identify coupling relations among different functions; 4) manage functional resonance. These four basic steps constitute the complete process of analyzing a system using FRAM.

2.2. Accimap

Accimap is a method used to analyze and depict the causes of complex accidents. It considers factors across multiple levels – from direct actions to organizational decisions and societal context – to identify systemic issues behind accidents 35. This approach emphasizes the interactions between different levels, such as individuals, teams, companies, and governments, and how these interactions may lead to accidents. The goal of Accimap is to provide a comprehensive view of an accident to facilitate more effective risk management and preventative measures 36. It is particularly useful for analyzing accidents in complex environments involving multiple system and human elements.

Accimap serves to aid analysts in discerning and illustrating the complex network of contributory factors leading to an accident. Typically, it encompasses five hierarchical levels: society and market, government and regulatory, company and policy, organizational level, and physical level. According to Branford Kate 37, a series of example reasons for different levels of Accimap are summarized in Table 1. By referring to this table, numerous factors leading to accidents can be categorized and filled into the respective levels accordingly.

The different factors are connected with directed edges, which are determined by cause and effect investigation. Cause and effect investigation in Accimap refers to the process of investigating and analyzing the causal relationships between various factors. In Accimap, these relationships are often represented by directed edges or arrows, where the arrow points to the affected factor. Through cause and effect investigation, analysts can identify the interactions and influences among different factors within a system, aiding in the establishment of system models or conducting risk assessments.

Compared with traditional analysis methods, such as fault tree, decision tree and truth table, Accimap method has great advantages in analyzing system complexity and multi-level causal relationships. Accimap allows for a comprehensive mapping of the interactions between human, technical, and organizational factors within a system, making it particularly effective for analyzing complex socio-technical systems. In such systems, single fault modes or decision paths often fail to capture the full scope of an incident, which requires an understanding of the intricate causal relationships across multiple layers of the system.

In contrast, Fault Tree Analysis (FTA) is proficient at identifying the logical connections of specific failure events but is generally limited to linear analysis, lacking the ability to address the overall system interactions across layers. Decision trees, while useful for visualizing decision processes, are better suited for problems with clear decision paths, and struggle with the multi-dimensional interactions found in complex systems. Truth tables, although effective in modeling logical systems, are insufficient when dealing with the dynamic and non-linear interactions typical of complex systems.

In the Accimap, establishing causal relationships between factors is highly complex and domain-specific, necessitating the input of experts from relevant fields. These experts bring in-depth knowledge that is crucial for accurately reflecting the interactions and influences within the actual system. For instance, technical experts can identify how equipment failures might impact other parts of the system, while human factors specialists can analyze the consequences of operational errors and their effects on overall system safety. By incorporating the expertise of professionals from different domains, Accimap can more accurately depict the causal relationships within complex systems, thereby enhancing the reliability and applicability of the analysis. This expert collaboration not only strengthens the scientific foundation of the model but also provides a solid basis for developing more effective risk management strategies.

Generally, an Accimap can be divided into five levels, as shown in Figure 2. The paramount strength of Accimap resides in its capacity to contemplate contributing factors throughout the entire work system, thereby facilitating a comprehension of the interactions and interrelations among these factors.

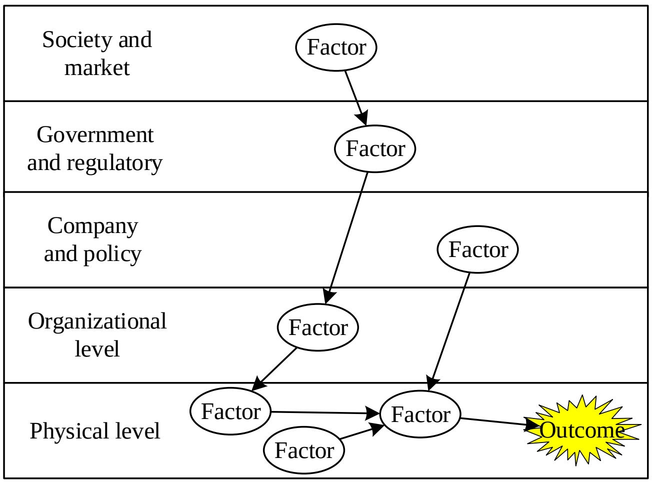

Figure 2. An Accimap template.

Table 1. A series of example reasons for different levels of Accimap 37.

Level definitions	**Categories of causes**		
Society and market	·market forces,·societal values, priorities,·affordability,·historical events,·global politics		
Government and regulatory	**Government:** ·budgeting issues ·inadequate legislation ·inadequate provision of services ·privatization, outsourcing	**Regulatory:** ·regulations, communication of regulations ·certification, permits ·safety standards ·enforcement of regulations ·auditing	
Company and policy	·safety culture and management commitment ·policies and procedures ·resource allocation ·compliance with laws and regulations ·communication and feedback mechanisms		
Organizational level	**Financial issues:** ·organizational budgeting, cost cutting ·resource allocating problems	**Equipment & design:** ·design problems ·equipment problems ·equipment not used as designed	**Defenses:** ·proactive system defenses ·reactive system defenses
	Communication & information: ·information or knowledge flow or organization of information ·communication of instructions, hazard, priorities, objectives, etc.	**Auditing & rule enforcement:** ·implementation and enforcement of rules, regulations and procedures ·internal auditing, inspection	**Organizational culture:** ·incompatible goals ·organizational acceptance or encouragement of short cuts, non-compliance, etc.
	Training: ·training, training equipment and exercises ·training need analysis	**Manuals & procedures:** ·inadequate, ambiguous, conflicting, outdated, absent or difficult to follow procedures, rules, regulations, or manuals	**Human resources:** ·supervision, management, coordination, staff numbers, delegation, accountability ·staff selection procedures or criteria
	Risk management: ·hazard identification or risk assessment ·awareness of risks ·security ·hazard or defects reporting processes for learning from past mistakes		
Physical level	**Physical events, processes & conditions:** ·physical sequence of events ·environment	**Actor activities & conditions:** ·human errors, mistakes, violations, actions, activities, etc. ·false perceptions, misinterpretations ·misunderstandings, loss of situational awareness, etc. ·physical and mental status of actors,·unconsciousness, intoxication	

To construct an Accimap, six common steps are needed. 1) Review the data on the accident; 2) Populate the bottom rows of the Accimap template with immediate physical process; 3) Pick the first immediate physical cause; 4) Identify and record contributory factors for each cause at the appropriate upper levels in the Accimap; 5) Pick the next immediate physical cause and repeat step 4 until all causes are developed; 6) Check and revise the Accimap.

2.3. Bayesian network

The Bayesian network facilitates quantitative risk assessment by examining the probability characteristics associated with event occurrences 38. It is extensively utilized in the realm of accident analysis and system risk assessment. A Bayesian network is represented as a Directed Acyclic Graph (DAG), with each node annotated with quantitative probability information. In a Bayesian network, each node corresponds to a random variable. Relations between nodes are established through directed edges, and when there is an arrow from node X to node Y, X is denoted as the parent node of Y. To quantify the influence of parent nodes on child nodes, a set of parameters is employed.

The formulation of CPTs adheres to the principles of Bayesian network theory. In a Bayesian network, conditional probability plays a crucial role 39. Bayesian's rule, as depicted in Equation (1), is the foundation of probabilistic inference within the system.

$$P(Y|X) = \frac{P(X|Y)P(Y)}{P(X)} \tag{1}$$

Where $P(X)$ and $P(Y)$ respectively represents the probability of event X and Y, and $P(X|Y)$ is the probability of X when Y occurs.

In a Bayesian network, the calculation of the joint probability distribution of nodes is achieved by constructing the overall joint probability of the entire network using conditional probabilities 40, as illustrated in Equation (2).

$$P(Y) = P(Y_1, Y_2, \ldots, Y_n) = \prod_{i=1}^{n} P(Y_i|\, Pa(\,Y_i)) \tag{2}$$

Where, $Pa(\,Y_i)$ is the parent node of Y_i.

Equation (3) demonstrates how, in the presence of new evidence E, Bayesian inference is employed to update the probability estimate of an event.

$$P(Y|E) = \frac{P(E|Y)P(Y)}{P(E)} = \frac{P(E|Y)P(Y)}{\sum_{i=1}^{n} P(E|Y_i)P(Y_i)} \tag{3}$$

Where, $P(Y)$ is the prior probability, E is the new evidence, $P(Y|E)$ is the posterior probability of an event, and $\sum_{i=1}^{n} P(E|Y_i)P(Y_i)$ is the joint probability distribution of the new evidence E.

3. Methodology

The structured method proposed for mapping FRAM to BN serves as an integrative framework, merging FRAM and BN to establish a comprehensive risk assessment model for the system. Figure 3 visually presents the comprehensive methodology framework. The left side, delineated as steps 1 to 4, represents the mapping procedures, while the right side corresponds to the graphical representation of each step.

The structured mapping method is proposed through introducing Accimap as a key tool bridging FRAM and BN, which is manifested in steps 2 and 3. Previous methods for mapping FRAM to BN mainly focus on steps 1 and 4. In other words, they first construct the FRAM of the system, then identify risk influencing factors and analyze their coupling relationships, and finally establish the Bayesian network. The additional steps proposed in this paper address the shortcomings of traditional methods, making the approach structured and repeatable.

In contrast to previous mapping methods, the structured mapping method in this paper comprises four steps. While the grey blocks, representing steps 1.4, 2, and 3, depict the additional steps introduced on top of the previous method. In the initial step of establishing the system's FRAM, 'step 1.4: analyze system-level hazards' was added to the conventional process. Step 2 clarifies internal coupling relationships by transforming FRAM's individual hexagon into a single Accimap. In step 3, multiple Accimaps, according to upstream-downstream couplings in FRAM, are interconnected to form a comprehensive network structure. Finally, step 4 involves constructing a Bayesian network, which includes determining node state classifications, node probability distribution, and conditional probability tables. Detailed steps are explicated in Sections 3.1 to 3.4.

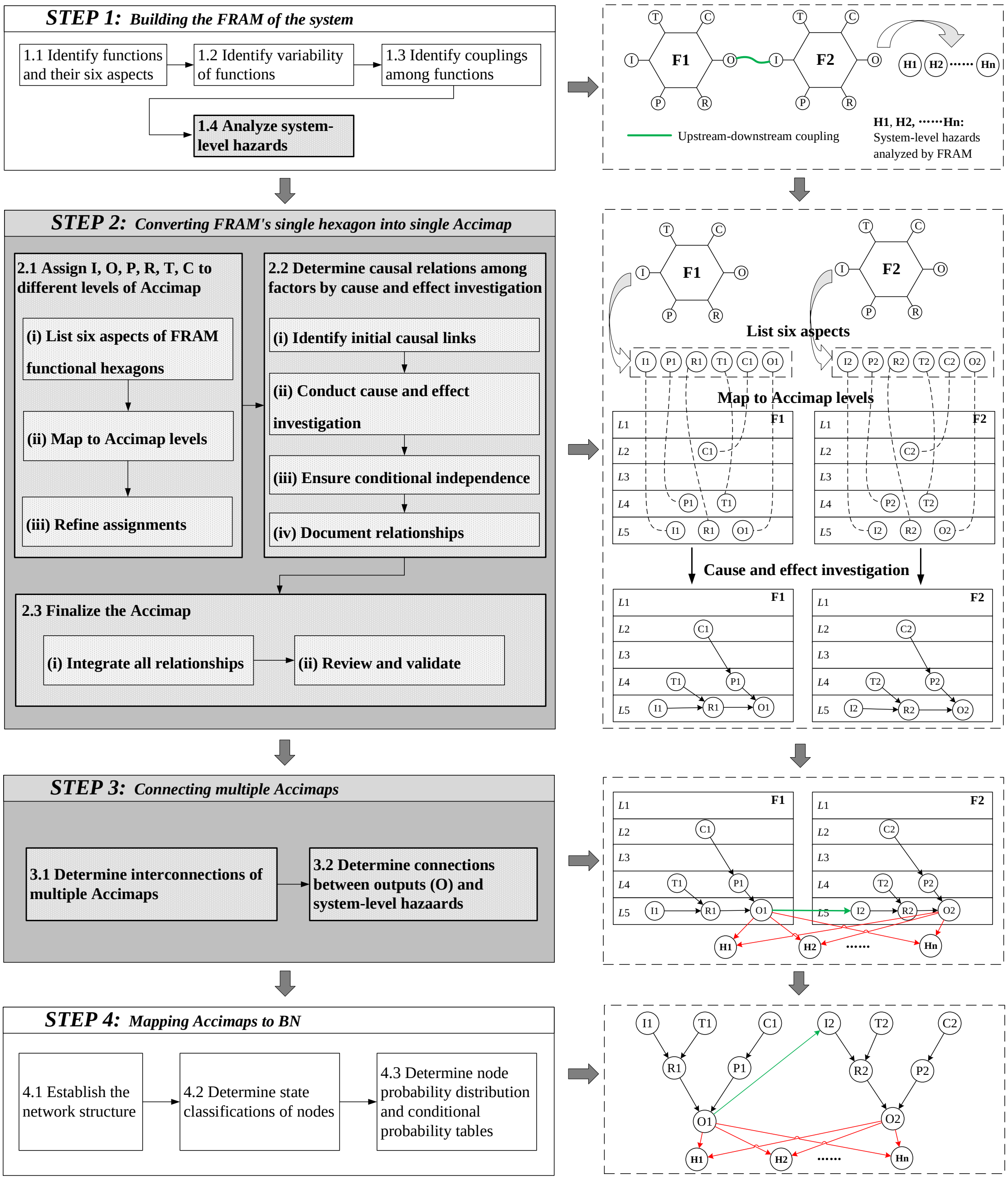

Figure 3. Structured mapping procedures from FRAM to BN.

3.1. Step 1: Building the FRAM of the system

Based on Hollnagel's theory, the construction process of FRAM can be divided into the following three steps: steps 1.1, 1.2, and 1.3. To develop a system risk assessment model, these steps were augmented with step 1.4, aimed at elucidating the impact of system-level hazards. System-level hazards characterize potential threats or harms across the entire system, which is crucial for system risk assessment. The selection of system-level hazards depends on the focus of the analysts.

Step 1.1: Identify functions and their six aspects

Initially, in step 1.1, functions and their six aspects for daily task execution are identified. This step involves decomposing daily operational procedures into multiple functions and determining their six aspects. This step can be executed using tables or other suitable means.

Step 1.2: Identify variability of functions

Step 1.2 is to identify the variability of each function. Three types of functions, including technological functions, human functions, and organizational functions, should be considered. As for the variability of a function, three conditions should be considered, including internal variability, external variability, and upstream-downstream coupling.

Step 1.3: Identify couplings among functions

Step 1.3 entails identifying coupling relations among different functions. The output of upstream functions is influenced by input, preconditions, resources, control, and time, subsequently impacting the variability of downstream functions. This process, termed functional upstream-downstream coupling, involves drawing connecting lines from upstream to downstream functions when functional relations exist.

Step 1.4: Analyze system-level hazards

Beyond these three steps, it is also important to identify system-level hazards by analyzing the variability of functions to facilitate subsequent quantitative assessment of system risk. Therefore, step 1.4 is added to the construction process of FRAM. Researchers analyze system-level hazards based on the hazards that are of concern to them. For example, in the case of a tunnel fire accident, system-level hazards include ‘H1-Casualties’ and ‘H2-Property Losses’. ‘Casualties’ represents the number of people who died or were injured in the accident, while ‘Property Losses’ indicates the specific monetary value of the economic losses incurred.

3.2. Step 2: Converting FRAM’s single hexagon into single Accimap

Hollnagel’s universal FRAM can identify coupling relations between different functions. However, mapping FRAM to BN requires not only the coupling relationships between functions but also the explanation of internal coupling relationships within each function, specifically addressing the influence of I, P, R, T, C on the function’s output.

The existing mapping methods focus on the relationships among risk influencing factors but fail to explain the relationships between I, P, R, T, C and O. Consequently, in this paper, the Accimap is introduced to articulate the internal coupling relations of FRAM’s functions. A FRAM functional hexagon can be converted into an Accimap, establishing causal connections between I, P, R, T, C, and O. The converting process should be divided into two steps.

Step 2.1: Assign I, O, P, R, T, C to different levels of Accimap

(I) List six aspects of FRAM functional hexagons:

Begin by listing the six aspects of FRAM for each function: input, output, preconditions, resources, time, and control. Each aspect will be treated as a vector: $\mathbf{I}=\{I_1, I_2,\ldots, I_{n1}\}$, $\mathbf{P}=\{P_1, P_2,\ldots, P_{n2}\}$, $\mathbf{R}=\{R_1, R_2,\ldots, R_{n3}\}$, $\mathbf{T}=\{T_1, T_2,\ldots, T_{n4}\}$, $\mathbf{C}=\{C_1, C_2,\ldots, C_{n5}\}$, $\mathbf{O}=\{O_1, O_2,\ldots, O_{n6}\}$.

(II) Map to Accimap levels

Then, it is necessary to correspond the I, P, R, T, C and O of the functions with the different levels of Accimap according to certain rules.

As depicted in section 2.2, Branford Kate 37 proposed a series of example reasons for different levels of Accimap in Table 1. Therefore, in this step, based on Hollnagel’s description of the six aspects of functions in FRAM, possible Accimap levels for FRAM’s six aspects are proposed, as shown in Table 2.

Table 2. Possible Accimap levels for the six aspects of FRAM.

	I	O	P	R	T	C
Society and market			√			
Government and regulatory						√
Company and policy				√		√
Organizational level			√	√	√	√
Physical level	√	√	√	√	√	

The input of a function is the entity or function that initiates the function and the entity or function that the function will process or transform, while the output is the result of the function’s operation. For a system, numerous functions are linked together by inputs and outputs, constituting the physical processes of events, which belongs to the "Physical level."

Preconditions are the system conditions or states that must exist before the function is performed. In socio-technical systems, preconditions may include internal organizational conditions, preconditions for the start of physical processes, social expectations, market trends, determining whether a function can be executed. Therefore, preconditions belong to "Society and market," "Organizational level," and "Physical level."

Resources are the entities required for the function to be performed or consumed to produce outputs. This may include internal company resources, policies, employee skills, equipment, materials, and energy needed for physical processes, and more. Hence, resources correspond to "Company and policy," "Organizational level," and "Physical level."

Time involves constraints on the function’s time, related to start time, end time, or duration. The execution time of physical processes, the temporal relationships at the organizational level, and time are closely related. Therefore, it belongs to "Organizational level" and "Physical level."

Control describes how the function is monitored or controlled. Government, company, and organizational factors control the occurrence of events, such as government supervision, regulatory enforcement, internal monitoring within companies, internal management within organizations, and process monitoring. Thus, control belongs to "Government and regulatory," "Company and policy," and "Organizational level."

Based on the nature of each FRAM aspect, map them to one of the five hierarchical levels of Accimap:

Society and Market Level: Typically includes broad external influences such as societal expectations or market trends. Map P here if preconditions relate to these factors.

Government and Regulatory Level: Encompasses external control mechanisms like laws, regulations, and supervision. Map C to this level if control is exercised by governmental bodies.

Company and Policy Level: Includes internal company policies, resources, and controls. Map R, C, and T here if they pertain to internal company factors.

Organizational Level: Includes organizational processes, internal communications, and preconditions. Map I, O, P, R, and T to this level if they relate to internal organizational dynamics.

Physical Level: Represents the physical process or technical elements. Map I, O, P, R, and T to this level if they pertain to the technical operation of the system.

(III) Refine assignments

Refer to existing examples or guidelines, such as those in Branford Kate [37] and Table 2, to ensure accurate mapping of FRAM aspects to Accimap levels.

Step 2.2: Determine causal relations among factors by cause and effect investigation

(I) Identify initial causal links

Using analysts' understanding of the system, start by identifying potential causal relationships between different FRAM aspects that have been assigned to Accimap levels. For example, identify how control at the Government and Regulatory level might influence preconditions at the Organizational level.

(II) Conduct cause and effect investigation

Execute a detailed cause and effect analysis to validate the initial links between factors. This step requires understanding how higher-level factors influence those at lower levels, following Accimap's hierarchical structure. Consulting experts in the relevant domains is crucial to accurately establish these relationships. Experts provide insights into the complex interactions and dependencies specific to their fields, ensuring that the cause and effect links are grounded in practical and theoretical knowledge. For example, if government regulations (C at the Government and regulatory level) influence company policies (P at the Company and policy level), experts can help determine the strength and direction of this relationship, leading to the establishment of a directed edge from C to P. Engaging experts helps in refining the model, ensuring that all significant causal relationships are captured accurately.

(III) Ensure conditional independence

Verify that any nodes not connected by directed edges are conditionally independent. This step ensures that the Accimap model remains logical and adheres to system behavior. Conditional independence is crucial in the subsequent construction of BN.

(IV) Document relationships

Clearly document each identified relationship, noting the rationale behind each causal link. This documentation will be crucial for both validation and future reference.

Step 2.3: Finalize the Accimap

(I) Integrate all relationships

Combine all identified causal relationships into a complete Accimap. Ensure that all FRAM aspects are appropriately represented and that all causal connections are accurately depicted.

(II) Review and validate

Conduct a thorough review of the Accimap to ensure that it accurately represents the system's dynamics. Validation can be achieved by comparing it with known system behavior or consulting with domain experts.

3.3. Step 3: Connecting multiple Accimaps

Following steps 1 and 2, the FRAM of the system and the corresponding Accimap for each functional hexagon were acquired. Thus, in this phase, the integration of multiple Accimaps into a comprehensive network structure is required, involving two critical aspects.

Step 3.1: Determine interconnections between multiple Accimaps

Firstly, the establishment of connections between multiple Accimaps based on the FRAM is essential. Specifically, the upstream-downstream couplings between FRAM's functions align with the directed edges that connect two Accimaps. For example, if in FRAM, the output of F1 is connected to the input of F2, indicating an upstream-downstream coupling between F1 and F2, then in Accimap, a directed edge should be drawn from the output of F1 to the input of F2 to represent their influence relationship. Each coupling in FRAM corresponds directly to a directed line segment in Accimap. The connection between multiple Accimaps are depicted with green lines in Figure 3.

Step 3.2: Determine connections between Outputs (O) and system-level hazards

Subsequently, the relationship between the outputs (O) of each function and system-level hazards need to be analyzed. System-level hazards typically encompass "casualties" and "property losses." According to the FRAM perspective, variations in function outputs lead to unforeseen outcomes, thereby resulting in hazards. Determine the impact relationship between each output (O) and the system-level hazards based on the actual situation of the system. Following the identification of the relationship between function outputs and system-level hazards, this connection is elucidated using an Accimap. The connections function Outputs (O) and system-level hazards are shown with red lines in Figure 3.

3.4 Step 4: Mapping Accimaps to BN

This step involves constructing a Bayesian network for the system based on the interconnected Accimaps obtained in step 3.

Step 4.1: Establish the network structure

Initially, multiple interconnected Accimaps established in step 3 are directly converted into a network structure. The factors in Accimap, including I, O, P, R, T, C, correspond to nodes in the BN, while the directed edges between these factors in Accimap align with connections between nodes in the BN, as illustrated in Figure 3. It is crucial to emphasize that, aside from the nodes and connections identified through FRAM and Accimap, the introduction of new nodes and connections is prohibited, ensuring a structured mapping between FRAM and BN.

Step 4.2: Determine state classifications of nodes

Following the establishment of the BN's network structure, the next step is to determine node state classifications. Node state classifications are contingent on specific circumstances, incorporating descriptors such as "good" and "poor," as well as gradations like "high," "moderate," and "low."

Step 4.3: Determine node probability distribution and conditional probability tables

Finally, it is necessary to determine the probability distribution of all root nodes and establish the Conditional Probability Tables (CPTs) for other nodes. These CPTs can be determined based on expert opinions.

4. Risk assessment application of HGV fire in road tunnels

This section presents the application of the structured mapping method from FRAM to BN for the risk assessment of HGV fire in road tunnels. The mapping steps 1 to 4 in Section 3 correspond to Sections 4.2 to 4.5. Through these steps, the FRAM for HGV fire accidents is established and then mapped to BN through Accimap, leading to the development of a quantitative system risk assessment model.

4.1. Description of a typical road tunnel

Fire accidents involving HGV in road tunnels is a complex socio-technical system 42. Key elements include drivers ensuring the safe operation of vehicles, tunnel administrators monitoring and promptly responding to abnormal situations, and firefighters swiftly extinguishing fires and rescuing trapped individuals. Emergency response vehicles, firefighting equipment, ventilation systems, and monitoring devices are crucial for effective response. Organizational management involves coordinating emergency response teams and receiving support from tunnel management organizations. Legal and regulatory aspects address traffic regulations, safety measures, and compliance oversight by regulatory bodies.

The tunnel to study is a typical road tunnel, characterized by the following details. The tunnel spans approximately 1 km, featuring a cross-sectional area of 70 m^2. It accommodates two-way traffic, with two lanes on each road. The anticipated speed for HGVs within the tunnel is 80 km/h. Standard tunnel facilities comprise a tunnel monitoring system (for fire event surveillance), lighting system, broadcasting system, lane management system, ventilation system, two cross passages, and firefighting facilities spaced at intervals of 50 meters 216.

Figure 4 illustrates the internal structure and equipment layout of the tunnel.

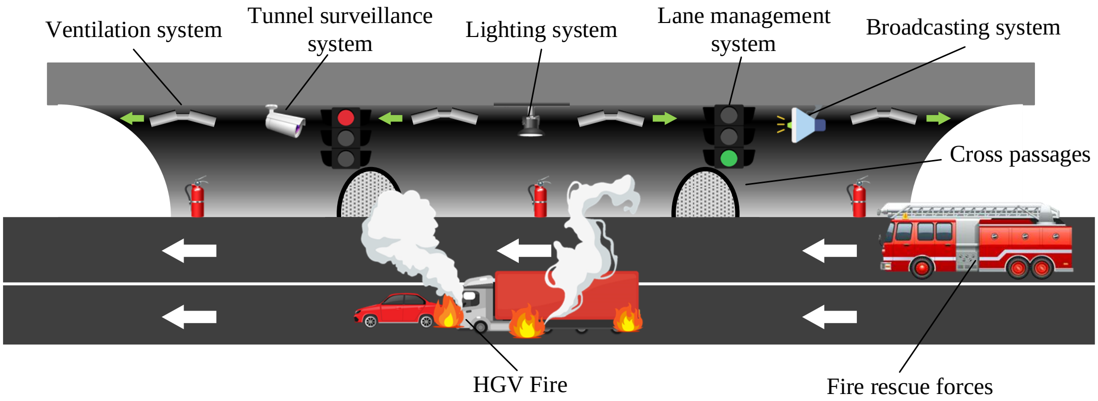

Figure 4. The internal structure and equipment layout of the tunnel.

4.2. Building the FRAM of HGV fire accident (step 1)

4.2.1. Identify functions and their six aspects (step 1.1)

The HGV fire accident can be abstracted into seven functions, which encompass the occurrence of a fire involving an HGV in a road tunnel, as well as the subsequent rescue and evacuation operations following the fire. Detailed descriptions of each function are provided below.

F1(Safety inspection): The safety inspection is crucial for ensuring the safety and efficient operation of HGVs. This process encompasses various aspects, including but not limited to the braking system, tires, lighting and signaling systems, lubrication system, engine system, vehicle chassis and suspension system, cargo loading conditions, fasteners and connections, emergency equipment and tools, as well as necessary documents and permits. Drivers and inspectors are respectively responsible for inspecting the vehicle and cargo to ensure the vehicle is in optimal condition and the cargo is loaded appropriately 43.

F2(The monitoring of drivers by freight companies): In the freight industry, continuous monitoring of drivers is a crucial measure to ensure driving safety and transportation compliance. Freight companies need to closely observe driver behavior, especially actions like speeding and fatigue driving. By employing advanced monitoring technologies, freight companies can track drivers' actions in real-time, identify potential safety hazards, and promptly issue alerts to prompt corrective action by drivers. These measures help mitigate the risk of accidents and ensure compliance with traffic regulations and transportation management requirements, ensuring the safe transport of goods.

F3(Safe driving): Ensuring safe driving is a multifaceted process influenced by factors such as driver behavior, vehicle condition, and road conditions. The goal of safe driving is to ensure the accident-free operation of Heavy Goods Vehicles (HGVs). This requires drivers to maintain a high level of alertness while driving, coupled with regular vehicle maintenance and the adoption of appropriate driving strategies for different road conditions. Comprehensive safety training and continuous driver monitoring contribute to making safe driving a standard practice in truck transportation.

F4(Tunnel surveillance): Tunnel monitoring is achieved through Closed-Circuit Television (CCTV) and an automatic event monitoring system designed to detect fire accidents in the tunnel. This technology allows real-time monitoring and rapid response to potential hazardous situations. CCTV cameras capture the source of fire, and the automatic event monitoring system quickly assesses the risk of a fire accident. In case of potential fire risks, the system triggers automatic fire alarms, enabling swift emergency measures to reduce the impact on the tunnel and driving safety.

F5(Fire emergency response): In responding to emergency situations of tunnel fires, ventilation fans, cross passages, broadcasting systems, lighting systems, and lane management systems play crucial roles in guiding traffic, facilitating personnel evacuation, and exhausting toxic gases. Tunnel managers are responsible for directing and coordinating emergency responses. These measures work in synergy to enhance the effectiveness of emergency handling during fire accidents.

F6(Fire rescue): Upon receiving a fire alarm, firefighting vehicles swiftly enter the tunnel, equipped with firefighting equipment and rescue tools to initiate emergency actions. Firefighters are tasked with extinguishing open flames and conducting personnel rescue. This emergency rescue process requires efficient coordination and a prompt response to minimize damage to the tunnel and casualties caused by the fire.

F7(Daily maintenance of tunnel equipment): To ensure the efficient operation of tunnel equipment and effective response to emergencies, routine maintenance and regular fire drills are crucial. Tunnel equipment such as ventilation systems, cross passages, firefighting equipment, broadcasting systems, and lighting systems need regular inspection and maintenance to ensure their proper functioning during emergency situations 44. Additionally, conducting periodic fire drills is essential.

Table 3. Six aspects of FRAM's function.

Function	I	P	R	T	C	O
F1	-	-	·driver ·inspector	-	·checklist & regulations	·vehicle condition ·loading condition
F2	-	-	·GPS & sensors ·monitoring staff ·software for monitoring platforms	-	·company's penalties	·alerts for drivers
F3	·cargo type	·vehicle safety condition ·cargo safety loading	·driving behaviors ·traffic conditions ·lighting system ·alerts for drivers	-	·tunnel traffic regulations ·driver's safety training	·HGV fire information
F4	·HGV fire information	-	·automatic event monitoring system	-	-	·tunnel manager's response
F5	·tunnel manager's response	-	·ventilate system ·cross passages ·broadcasting system ·lighting system ·lane management system ·tunnel manager	-	·emergency response regulations for tunnel fires	·traffic guide and evacuation
F6	·traffic guide and evacuation	-	·fire rescue forces	-	·tunnel fire rescue plan	·firefighting ·personnel rescue
F7	-	-	-	-	·equipment daily maintenance ·routine fire drills	·equipment conditions ·manager's experience

4.2.2. Identify variability of functions (step 1.2)

The output of a function is influenced by five key aspects: input, preconditions, resources, time, and control, leading to variabilities in function's output. This changed output can be propagated to downstream functions, ultimately resulting in functional resonance to cause an accident. For example, during the Safety inspection (F1), defects in HGVs or risks in goods loading might go unnoticed due to insufficient attention from drivers and inspectors. As the output of F1 acts as a precondition for F3, these output variations are transmitted to F3. Likewise, F2 and F7 transmit variability in output to F3. Consequently, F3 (safe driving) could encounter collisions to cause fire accidents in the tunnel, stemming from inadequate safety inspection, ineffective monitoring, and insufficient driver training. The variability in function output is listed in Table 4.

Table 4. Variability of functions' output.

Function	Output Variability
F1	·Failed to detect HGV defects ·Failure to detect hazards related to the goods
F2	·Failure to detect and correct unsafe driving behavior
F3	·HGV fire
F4	·Failure to trigger fire alarm timely
F5	·The fire spread and personnel were unable to evacuate ·Failure to effectively guide traffic, resulting in congestion
F6	·Tunnel damage and personal injury
F7	·Equipment aging and failure ·Personnel lack of experience

4.2.3. Identify couplings among functions (step 1.3)

According to Table 3, the coupling relationships between functions can be determined. The output of F1 (vehicle condition and loading condition) serves as the precondition for F3. The output of F2 (alerts for drivers) functions as the resource for F3. The output of F3 (vehicle fire information) becomes the input for F4. The output of F4 (fire alarm) serves as the input for F5. The output of F5 (traffic guide and evacuation, and call firefighters) becomes the input for F6. The output of F7 (equipment conditions and manager's experience) serves as the resource for F3, F4, and F5. Therefore, the FRAM of the HGV fire accident is established as Figure 5.

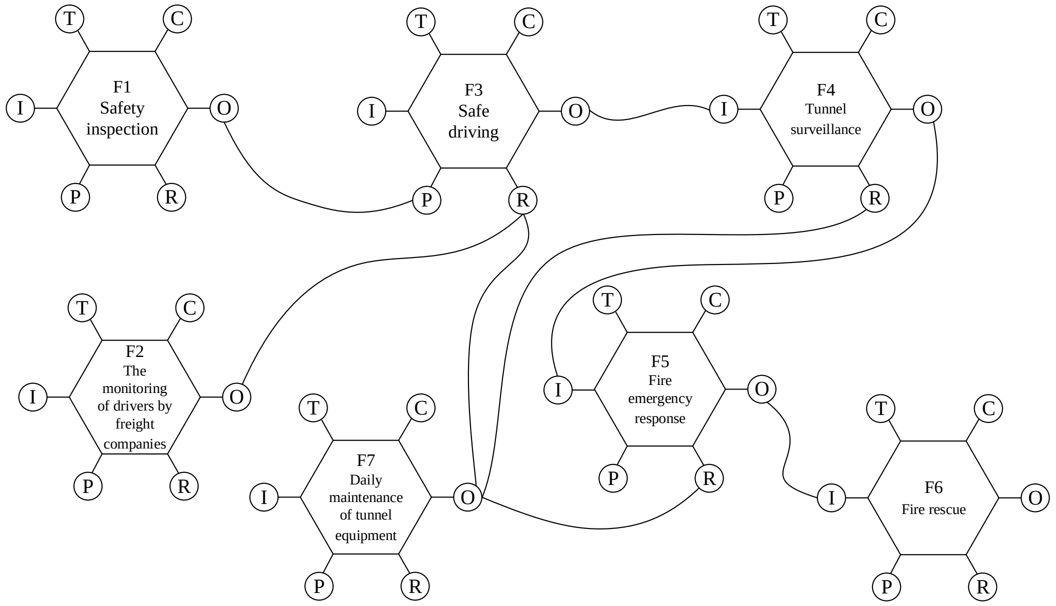

Figure 5. FRAM of HGV fire accident in road tunnels.

4.2.4. Analyze system-level hazards (step 1.4)

The system-level hazards resulting from HGV fires include "H1-Casualties" and "H2-Property Losses," which are collectively influenced by multiple factors. The black curve in the figure represents the upstream-downstream couplings. The variation in the output of functions may lead to system-level hazards.

The output of F3 may change into "HGV fire," and the severity of the fire directly impacts the extent of casualties and property losses. If the fire rapidly spreads and becomes difficult to control, it may lead to larger-scale losses and more severe casualties. Consequently, the couplings "F3(O)-H1" and "F3(O)-H2" are established.

The output of F5 may change into "The fire spread and personnel were unable to evacuate" and "Failure to effectively guide traffic, resulting in congestion." Inadequate or ineffective traffic guidance and personnel evacuation measures during a fire may hinder individuals from timely evacuation, thereby increasing the risk of casualties. Additionally, the chaos and congestion during evacuation may contribute to secondary injuries after the accident. Thus, the coupling "F5(O)-H1" is established.

The output of F6 may change into "Tunnel damage and personal injury." If the effectiveness of fire rescue is subpar, the fire may not be promptly controlled, leading to significant structural damage to the tunnel and increased costs for repair and reconstruction. Furthermore, the spread of the fire may cause harm to other vehicles in the tunnel and their passengers, thereby expanding the scale of casualties. Consequently, the couplings "F6(O)-H1" and "F6(O)-H2" are established.

4.3. Converting functional hexagon F1-F7 into Accimap (step 2)

For each function of FRAM, the six aspects (I, O, P, R, T, C) are placed in different levels of Accimap based on Table 1. and Table 2. The specific results are presented in Figure 6 to Figure 12.

According to causal relations among these factors, connections with directed line segments are established. The internal coupling relations identified by Accimap for each function are visually represented in Figure 6 to Figure 12. The analysis of the internal causality of each function unfolds as follows:

Cause and effect investigation of F1: HGV drivers and inspectors play a crucial role in ensuring the overall safety of the vehicle and its cargo. Their responsibilities extend beyond a mere examination; they meticulously inspect every aspect, from the vehicle’s mechanical condition to the intricacies of cargo loading. This thorough examination involves not only confirming cargo types but also adhering to meticulously crafted checklists and pertinent regulations. The effectiveness of this safety inspection is heavily reliant on the completeness of the inspection checklist and the clarity of management regulations. The more comprehensive and precise these tools are, the better equipped drivers and inspectors are to ensure the optimal state of the vehicle and cargo. Figure 6 is the Accimap of F1.

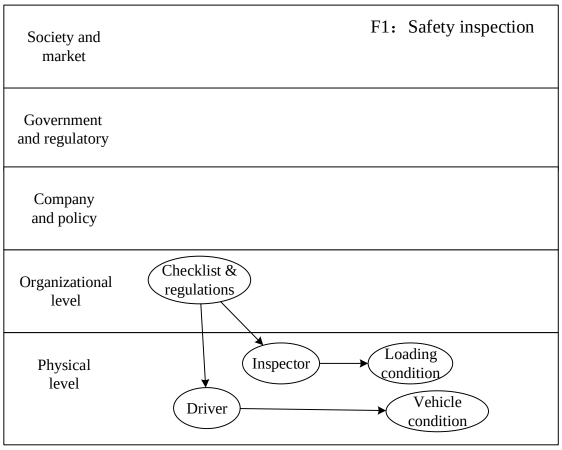

Figure 6. Accimap of F1: Safety Inspection.

Cause and effect investigation of F2: The monitoring of HGV drivers by freight companies involves a sophisticated system utilizing on-board GPS and sensors.

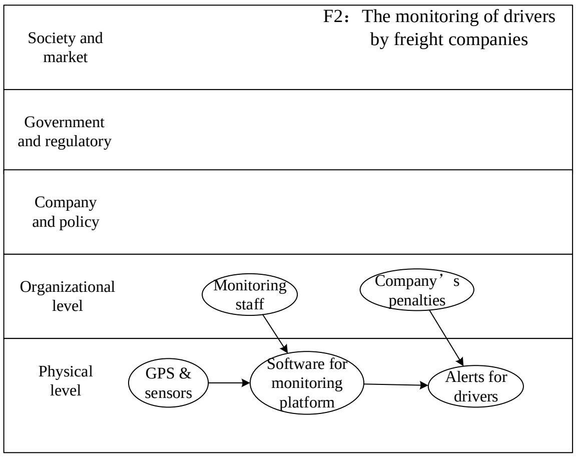

Figure 7. Accimap of F2: The monitoring of drivers by freight companies.

These advanced technologies continuously transmit driving data to a centralized monitoring platform. Here, data analysis software evaluates the safety of drivers’ behavior and issues alerts when necessary. The responsible operators are at the helm of this monitoring system, utilizing their expertise to interpret and act upon the data. The company’s penalties for unsafe driving practices serve as a crucial element, influencing whether drivers strictly adhere to the alerts generated by the platform. Figure 7 is the Accimap of F2.

Cause and effect investigation of F3: Safe driving is a multifaceted responsibility influenced by a myriad of factors.

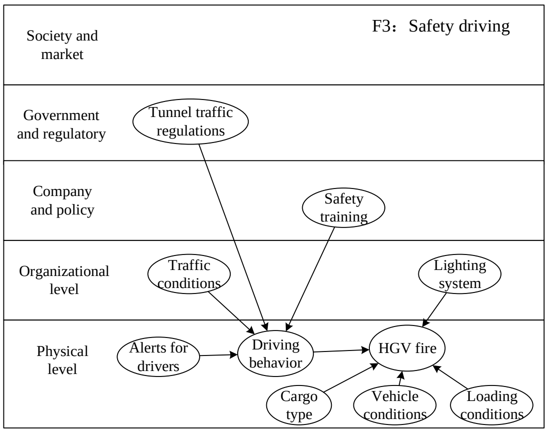

Figure 8. Accimap of F3: Safety driving.

The driver’s behavior is not only shaped by alerts on the monitoring platform but also by external elements such as road conditions, tunnel regulations, and safety training. The cumulative impact of driving behavior, combined with the condition of the vehicle, cargo, and lighting system, directly contributes to the likelihood of HGV fires. Recognizing the significance of factors such as driver fatigue, potential vehicle malfunctions, overloaded cargo, and inadequate lighting becomes paramount in mitigating the probability of HGV collisions and subsequent fires 2. Figure 8 is the Accimap of F3.

Cause and effect investigation of F4: In the event of an HGV fire within the tunnel, a state-of-the-art automatic event detection system springs into action.

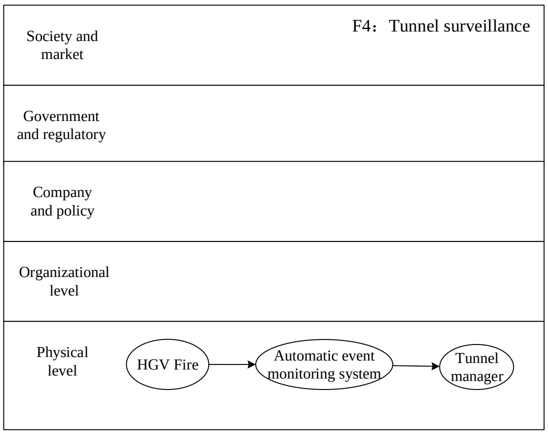

Figure 9. Accimap of F4: Tunnel surveillance.

This system, integral to tunnel surveillance, promptly identifies and reports the accident to the tunnel manager, ensuring swift response and mitigation. Figure 9 is the Accimap of F4.

Cause and effect investigation of F5: The fire emergency response involves a coordinated effort led by the tunnel manager. Promptly upon detecting a fire alarm, the tunnel manager initiates contact with firefighters and activates the lane management system for efficient traffic guidance and personnel evacuation 45. The manager's performance is a reflection of both operational regulations and experiential knowledge. Additionally, the condition of critical elements such as the ventilation system, lighting system, broadcast system, and egress facilities directly influences the efficiency of personnel evacuation. Figure 10 is the Accimap of F5.

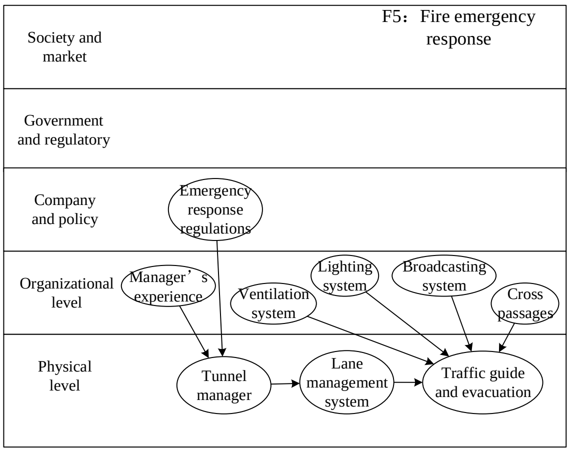

Figure 10. Accimap of F5: Fire emergency response.

Cause and effect investigation of F6: The fire rescue operation kicks into high gear following the receipt of a fire alarm. Firefighting forces mobilize swiftly, entering the tunnel to extinguish the fire and rescue any individuals who may be trapped.

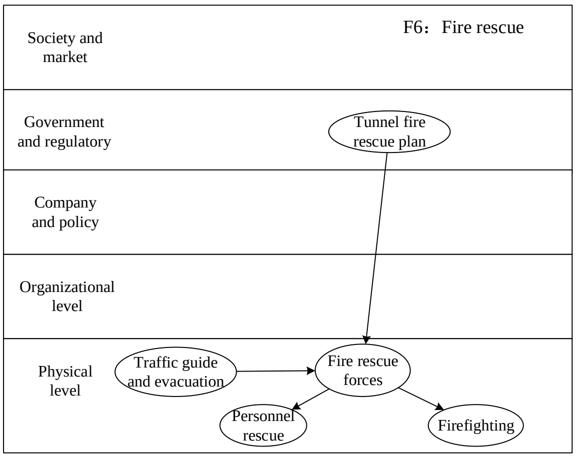

Figure 11. Accimap of F6: Fire rescue.

The efficacy of these operations hinges on the adequacy of the tunnel firefighting and rescue plan, emphasizing the importance of strategic planning and preparedness. Figure 11 is the Accimap of F6.

Cause and effect investigation of F7: The daily maintenance of tunnel equipment goes beyond ensuring functionality; it is a proactive measure to guarantee optimal performance during unforeseen circumstances 46. This includes regular upkeep of lighting, broadcasting, ventilation, and egress facilities within the tunnel. Routine firefighting drills further enhance the skill set of managers, providing them with the requisite experience to proficiently handle tunnel fire accidents. This continuous maintenance and training regimen solidify the tunnel's resilience against potential challenges, contributing to overall safety and operational efficiency. Figure 12 is the Accimap of F7.

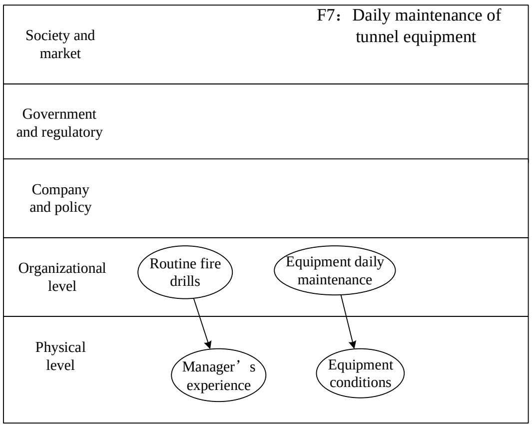

Figure 12. Accimap of F7: Daily maintenance of tunnel equipment.

4.4. Connecting multiple Accimaps of F1-F7 (step 3)

4.4.1. Determine interconnections of Accimaps F1-F7 (step 3.1)

According to Figure 5, the upstream-downstream couplings among functions F1 to F7 can be identified as follows: The output of F1(vehicle condition; goods condition) serves as preconditions for F3, the output of F2(alerts for drivers) acts as a resource for F3, the output of F3(vehicle information) becomes the input for F4, the output of F4(fire alarm) serves as the input for F5, the output of F5(firefighting and evacuation; call firefighters) becomes the input for F6, and the output of F7(conditions of tunnel equipment; manager's experience) acts as resources for F3, F4, and F5. These upstream-downstream couplings are transformed into directed edges to connect multiple Accimaps.

4.4.2. Determine connections between outputs and system-level hazards (step 3.2)

The result nodes of BN are incorporated considering system-level hazards, encompassing nodes “Casualties” and “Property losses.” Nodes “Traffic guidance and evacuation”, “HGV fire”, “Firefighting”, and “Personnel rescue” directly affect the “Casualties” node, whereas “HGV fire” and “Firefighting” exert a direct impact on the “Property loss” node. Consequently, the relationship between the output of the function and two system level hazards “H1-Casualties” and “H2-Property losses” is as follows: F3 (O) - H1, F5 (O) - H1, F6 (O) - H1, F3 (O) - H2, F6 (O) - H2. Based on the analysis of section 4.4.1 and 4.4.2, the interconnected Accimaps can be obtained, as shown in Figure 13.

In this figure, Accimap F1-F7 are interconnected, and function outputs are associated with system-level hazards. The black directed edges in the figure signify the internal causal relationships among functions, specifically, the influence relationships of I, O, P, R, T, C. The green directed edges represent connections between different Accimaps, determined by the upstream-downstream coupling in FRAM. The red directed edges articulate the influence of function outputs on two system-level hazards, ‘Casualties’ and ‘Property losses.’ Through the integration of multiple Accimaps into a unified structure, FRAM is comprehensively mapped into a network structure, forming the groundwork for constructing the Bayesian Network.

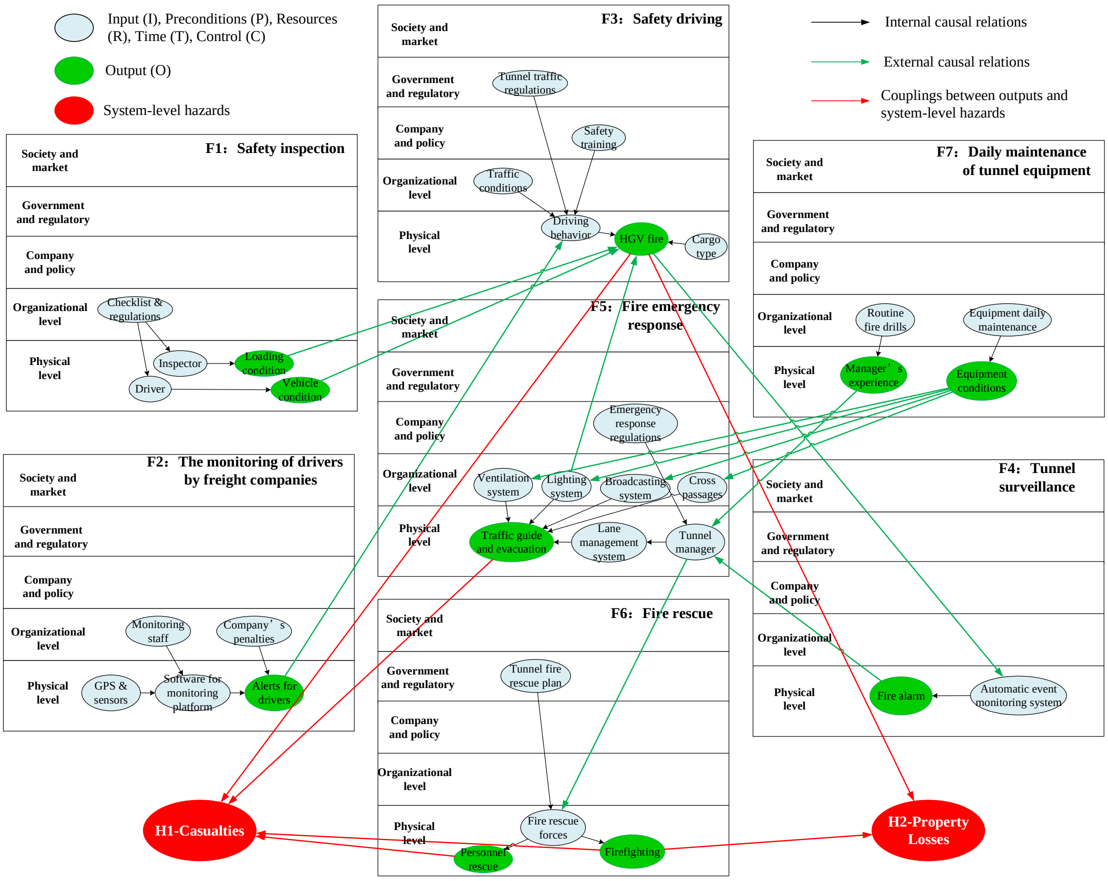

Figure 13. Interconnections of Accimaps F1-F7.

4.5. Mapping Accimaps F1-F7 to BN (step 4)

4.5.1. Establish the network structure of HGV fire accident (step 4.1)

According to the analysis in Section 4.4, Accimaps have been successfully mapped into a network structure. Next, by removing the hierarchical structure of Accimaps in Figure 13, factors and directed edges can be extracted to form the skeleton of the Bayesian network. Specifically, in Figure 13, the factors in Accimap are transformed into BN nodes, while the directed edges between factors directly correspond to the directed edges between BN nodes. Consequently, the BN model of HGV fire accidents can be obtained, as shown in Figure 14.

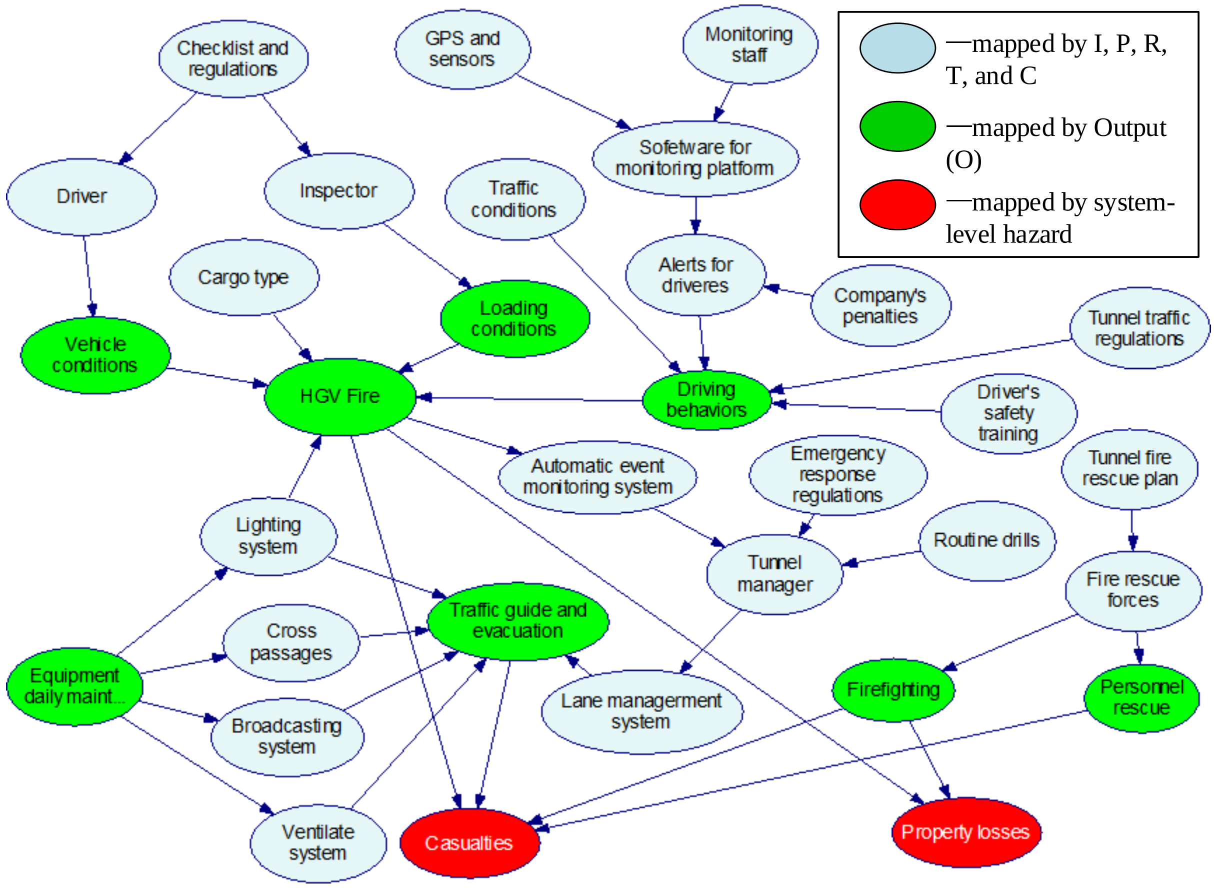

Figure 14. The BN of HGV fire in road tunnels.

4.5.2. Determine state classifications of nodes (step 4.2)

The state classifications for each node in the Bayesian network are elaborated as follows.

(1) Checklist and regulations. Examining HGV and cargo loading involves the effectiveness of checklist and regulations 47. The term "effective" implies that both the inspection checklist and regulations are complete, whereas "ineffective" suggests that these tools are inadequate to facilitate a thorough inspection.

(2) Driver, (3) Inspector. "Effective" indicates that drivers and inspectors have conducted a comprehensive inspection, while "ineffective" signifies that the inspection process is flawed or potential hazards have been overlooked.

(4) Vehicle condition, (5) Loading conditions. "Good" indicates that the vehicle has no potential faults, and the cargo loading is reasonable, while "poor" signifies that the vehicle has potential faults, and the cargo loading is in violation of regulations.

(6) Cargo type. The cargo is classified as either "flammable" or "non-flammable."

(7) Monitoring staff. The staff is responsible for operating the monitoring software. "Effective." indicates that the staff detected unsafe driving behavior and sent alerts, while "ineffective" means that the staff did not identify any unsafe driving behavior by the driver.

(8) Company's penalties. The company imposes penalties on drivers for violations to regulate their driving behavior. Penalty measures are categorized as "strict" and "lenient."

(9) GPS and sensors, (10) Software for monitoring platform. "Effective" means their functions are intact, while "ineffective" indicates a malfunction in their functionality.

(11) Alerts for drivers. The freight company needs to send alerts to drivers to correct their unsafe driving behavior. "Effective" denotes that the driver received a warning, and "ineffective" implies that the driver did not receive a warning.

(12) Traffic conditions. The traffic flow in the tunnel directly influence the driver's behavior. It has three states: high, medium, and low.

(13) Tunnel traffic regulations, (14) driver's safety training. They both have two states: effective and ineffective.

(15) Driving behaviors. Influenced by external

environmental factors such as traffic congestion and time constraints, drivers' behavior may manifest as both reckless and cautious. Therefore, it has two states: safe and unsafe. Unsafe driving behaviors are typically associated with violations such as fatigue driving and speeding.

(16) HGV fire. After a collision accident involving HGV in the tunnel, it is highly prone to trigger a fire 48. Based on the severity of the fire, this node is divided into three states: severe, moderate, and mild.

(17) Automatic event monitoring system, (18) Tunnel manager, (19) Lane management system. They identify and manage accidents in the tunnel 49. These three nodes have two states each: effective and ineffective. "Effective" indicates that the automatic event monitoring system and lane management system functions are operational, and the tunnel manager's emergency response is correct. The meaning of "ineffective" is the opposite.

(20) Traffic guide and evacuation. After a fire occurs in the tunnel, traffic guidance and personnel evacuation are crucial as they directly relate to the casualties caused by the fire 50. This node is divided into two states: good and poor.

(21) Lighting system, (22) Cross passages, (23) Broadcasting system, (24) Ventilate system. These tunnel facilities are used for emergency response to fires 51, and their status is divided into two categories: normal and malfunction.

(25) Emergency response regulations for tunnel fires, (26) Tunnel fire rescue plan. The tunnel fire emergency response regulations and rescue plans are used to guide the handling and rescue of fires. "Effective" indicates that they are reasonable, while "ineffective" indicates that they are outdated.

(27) Manager's experience. In the event of a fire, the experience of the manager has a significant impact on his/her actions and is divided into two states: "experienced" and "inexperienced."

(28) Fire rescue forces. The firefighting and rescue of trapped individuals in the tunnel both require the assistance of firefighter. This node has three states: good, moderate, and poor.

(29) Firefighting, (30) Personnel rescue. "Effective" indicates that the firefighters promptly extinguished the fire and rescued trapped individuals, while "ineffective" signifies that the fire continued to spread, and individuals remained threatened by the fire.

(31) Equipment daily maintenance, (32) Routine fire drills. Daily equipment maintenance and fire drills are crucial to ensuring the reliability of equipment and personnel in the event of a fire 52. Both of these nodes have two states: effective and ineffective.

(33) Casualties. Casualties represent a primary metric for assessing the severity of an accident. Following the pertinent regulations of the Chinese government, this node can be categorized into three states: "Minor" denotes "less than 10 deaths or fewer than 50 injuries," "Moderate" encompasses "11 deaths to more than 30 deaths or 51 injuries to more than 100 injuries," and "Severe" includes "30 deaths or more or 100 injuries or more."

(34) Property losses. Property losses constitute another significant metric for assessing the severity of an accident. Following the relevant regulations of the Chinese government, "Minor" denotes property losses of CNY 50 million or less (approximately USD 7 million), "Moderate" encompasses property losses between CNY 50 million and CNY 100 million, and "Severe" includes property losses of CNY 100 million or more 16.

4.5.3. Determine node probability distribution and conditional probability tables (step 4.3)

Determining the node probability distribution and Conditional Probability Table (CPT) is a crucial step in applying the Bayesian network method to address practical issues. Generally, methods for determining node probability distribution and CPTs include parameter learning and expert elicitation. Due to the limited historical records and relevant data on HGV tunnel fires, it is not feasible to employ parameter learning. Therefore, in the current research, an expert scoring approach is adopted to determine them. Previous studies have confirmed the effectiveness of incorporating expert experience and knowledge to determine the node probability distribution and CPT in BN models 53.

In this paper, four experts from the relevant industry were invited to participate in the survey. The probability distribution of the root nodes is determined based on expert opinions. Consideration was given to the experts' professional titles and work experience to determine their weights, as outlined in Table 5.

Table 5. Weight of experts' judgement.

No.	Experts' experience	Weight
1	Researchers or engineers with senior professional titles and above 15 years working experience in tunnel safety field	1.0
2	Researchers or engineers with associate senior professional titles and above 10 years working experience in tunnel safety field	0.9
3	Above 8 years working experience in tunnel safety field	0.8
4	Above 5 years working experience in tunnel safety field	0.7

The computation process for the node's CPT is expressed by Equation (4).

$$p_j^i = \sum_{r=1}^{4} \omega_{ijr} \,/\, \sum_{i=1}^{n} \sum_{r=1}^{4} \omega_{ijr} \qquad (4)$$

Where, p_j^i denotes the probability of risk factor j being in state i. The variable n signifies the number of states for the risk factors, while j represents the total number of risk factors. Additionally, ω_{ijr} represents the weight coefficient assigned by expert r when assessing the occurrence likelihood of state i for risk factor j.

For instance, in the "safety inspection", the child node "vehicle condition" is under the influence of the parent node "driver." Consequently, experts are required to determine "Yes" or "No" for the child node's "Effective" and "Ineffective" for each combination of states associated with the parent node. The expert opinions are computed using Equation (4), yielding the CPT for the child node, as outlined in Table 5. Similarly, the CPTs for other nodes can also be determined.

Table 5. Example CPT of "Vehicle Condition".

Driver	Vehicle condition "Good"				Vehicle condition "Poor"				Vehicle Condition	
	1	2	3	4	1	2	3	4	Good	Poor
Effective	Y	Y	Y	N	N	N	N	Y	0.79	0.21
Ineffective	N	N	Y	N	Y	Y	N	Y	0.24	0.76

5. Results and discussion

5.1. Risk assessment of HGV fire in road tunnels

According to the structured mapping method outlined in Section 4, a Bayesian network was constructed to assess the risk of an HGV fire in a road tunnel, as depicted in Figure 15. Two result nodes, namely casualties, and property losses, were selected for detailed analysis.

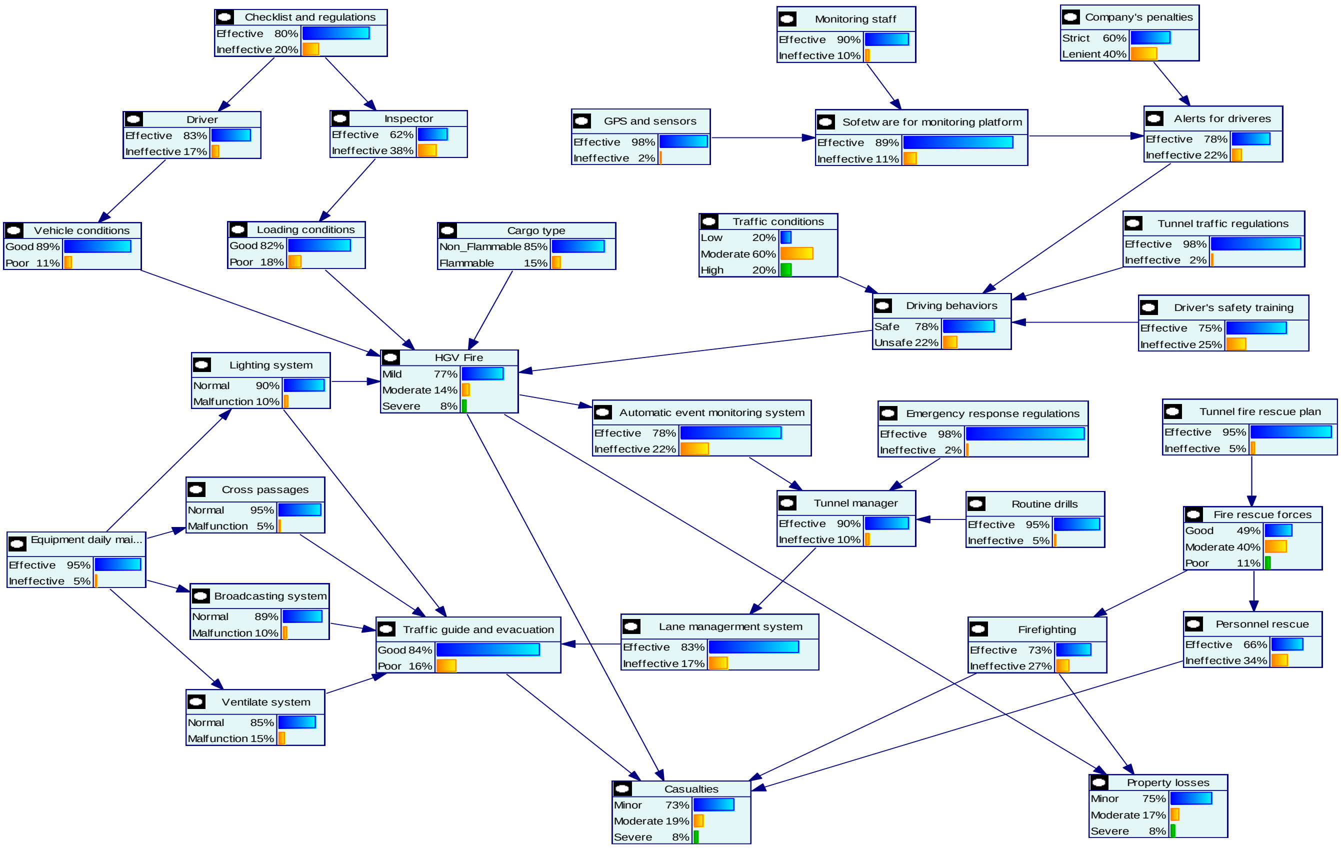

Figure 15. Probability distribution of BN nodes.

The probability distribution of casualties is minor-73%, moderate-19%, severe-8%, while for property losses, it is minor-75%, moderate-17%, severe-8%. These results suggest that, given the assumed model conditions, the likelihood of minor casualties and minor property losses is higher, while the probability of severe casualties and severe property losses is relatively lower. In most scenarios, the impact of a fire accident appears manageable; however, there is still a proportion of situations that could result in severe consequences. Section 5.2 will delve into the factors influencing fire accident outcomes and potential preventive measures.

5.2. Sensitivity analysis and improvement measures

Sensitivity analysis of BN 54 involves assessing changes in model parameters or node variables within a Bayesian network to comprehend their impact on the model's output. Its primary objective is to identify key variables, namely, those that exert the most significant influence on system behavior. In Bayesian networks, sensitivity analysis aims to evaluate how variations in each node variable or model parameter influence subsequent nodes or the overall system output probabilities. This analysis enhances the understanding of system complexity, aiding decision-makers in risk identification, decision optimization, and model reliability improvement. Additionally, sensitivity analysis can validate model assumptions, assess the impact of input data, and optimize the structure of BN.

GeNIe software was utilized to compute the BN. The target nodes, "Property Losses" and "Casualties," were selected, and the sensitivity for each node was computed. A higher sensitivity value indicates a greater influence on the target node 55. Consequently, the tornado diagram of two result node, namely "Casualties" and "Property Losses", are generated as Figure 16 and Figure 17. The sensitivity of top 10 nodes are shown in Table 6.

5.2.1. Sensitivity ranking of nodes

In Table 6, the ranking of node sensitivity reveals that, regarding "Property Losses," the five nodes exerting the most significant impact are "HGV fire," "Firefighting," "Cargo type," "Vehicle condition," "Fire rescue forces," and "Loading condition." In the case of "Casualties," the top five nodes with the most pronounced impact are "Firefighting," "Fire rescue forces," "Personnel rescue," "Traffic guide and evacuation," and "HGV fire." It is apparent that "HGV fire," "Firefighting," and "Fire rescue forces" wield substantial influence on both outcome nodes.

Table 6. Sensitivity of node "Property Losses" and "Casualties".

Property Losses		**Casualties**	
Node	Sensitivity	Node	Sensitivity
HGV fire	0.145	Firefighting	0.092
Firefighting	0.055	Fire rescue forces	0.073
Cargo type	0.031	Personnel rescue	0.067
Vehicle condition	0.031	Traffic guide and evacuation	0.035
Fire rescue forces	0.027	HGV fire	0.020
Loading condition	0.019	Tunnel fire rescue plan	0.019
Lighting system	0.008	Lane management system	0.011
Tunnel fire rescue plan	0.007	Lighting system	0.010
Driving behaviors	0.006	Cross passages	0.007
Inspector	0.005	Cargo type	0.005

When considering "property losses," a major source of property loss is the fire caused by a heavy-duty truck. The scale, rate of spread, and impact on the surrounding environment of the fire will directly determine the extent of the loss. Effective firefighting and rescue operations are equally crucial in rapidly controlling the fire and reducing property losses from the accident. Additionally, different types of cargo may lead to fires of varying severity, increasing the likelihood of property damage. The condition of the truck, including whether there is leakage or mechanical failure, also affects the occurrence and spread of the fire. Finally, having an ample and professional firefighting and rescue force is more likely to rapidly control the fire in the early stages, minimizing property losses.

As for "casualties," firefighting and rescue are among the most critical factors. Swift and efficient firefighting and rescue actions are crucial for minimizing casualties, including controlling the fire and evacuating individuals. Having sufficient firefighting and rescue forces is also key to ensuring timely rescue and medical services, reducing casualties. Organized and efficient personnel rescue operations similarly ensure that trapped individuals can quickly and safely evacuate the scene, minimizing casualties. Well-planned traffic guidance and evacuation strategies help prevent traffic accidents and chaos, ensuring that individuals can safely leave the accident site. Lastly, the scale and burning characteristics of a fire caused by a heavy-duty truck directly impact casualties. Therefore, effective fire control is crucial for reducing casualties.

5.2.2. Multi-node sensitivity combination analysis

In the tornado diagram depicting “Casualties=minor” (Figure 16), the four conditions: “Firefighting=effective, Personnel rescue=effective, Traffic guide and evacuation=effective, HGV fire=mild” exhibit the most significant positive impact on “Casualties=minor.” This indicates that improving these four conditions as much as possible is essential for better controlling the number of casualties resulting from accidents. Additionally, “Fire rescue forces=good” has a notable impact on both “Firefighting=effective” and “Personnel rescue=effective,” suggesting that ensuring effective accident response requires robust firefighting and rescue forces, imposing higher demands on the government to maintain a strong firefighting capability.

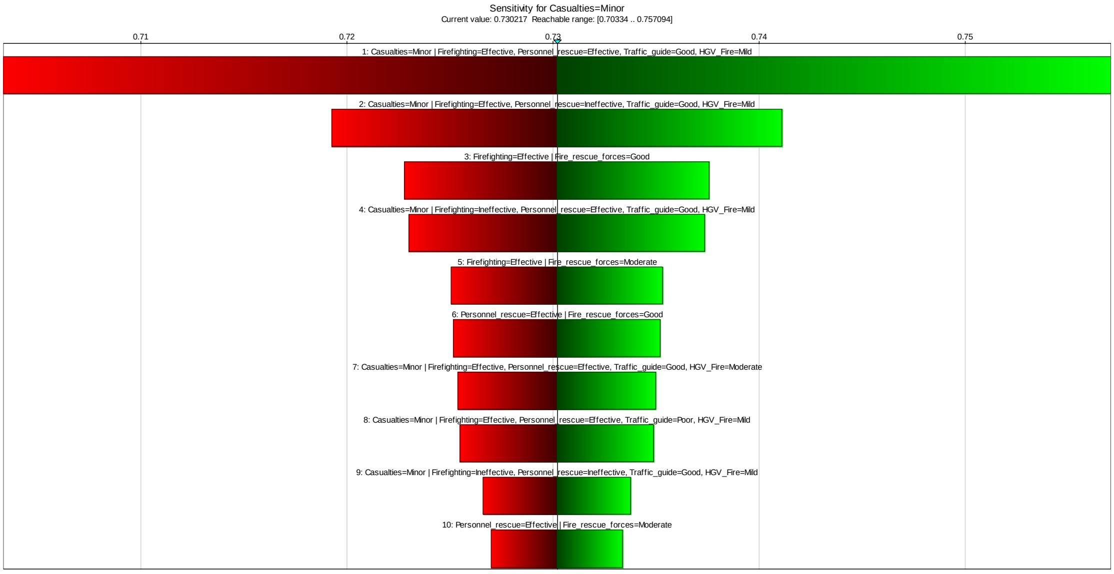

Figure 16. Tornado diagram when “Casualties” is minor.

In the tornado diagram illustrating “Property Losses=minor” (Figure 17), the two conditions, “HGV fire=mild, Firefighting=effective,” have the greatest positive impact on “Property Losses=minor.” This implies that efforts should be made to contain the spread of fires and enhance firefighting efficiency to minimize property losses resulting from accidents. Furthermore, conditions such as “Vehicle conditions=good, Cargo type=non-flammable, Loading conditions=good, Driving behaviors=safe, Lighting system=normal” exhibit significant positive impacts on “HGV fire=mild.” This suggests that to reduce the severity of fires, improvements must be made in terms of vehicle conditions, cargo types, driver behaviors, and lighting.

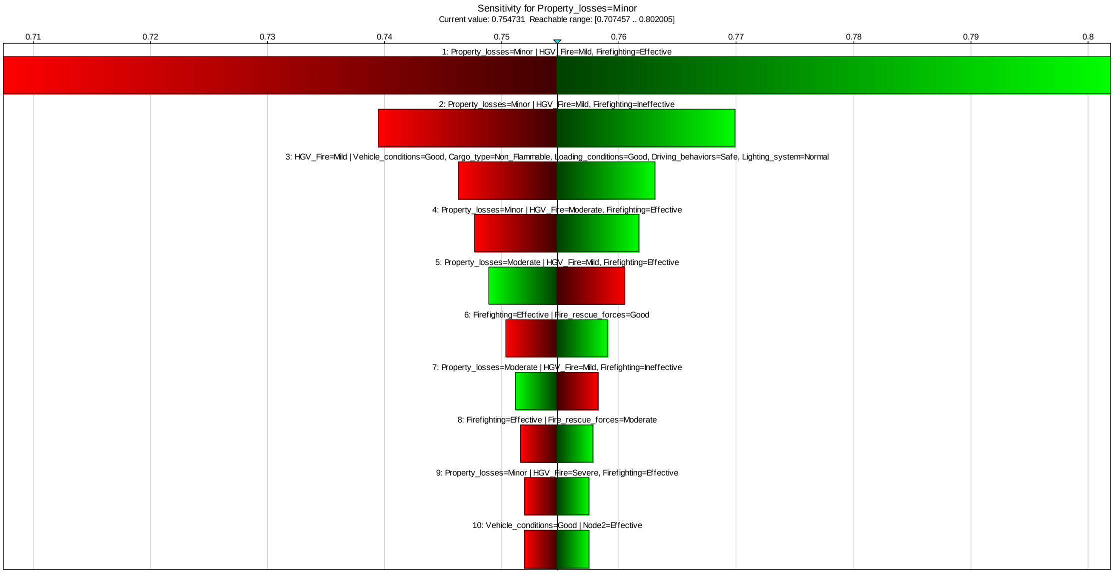

Figure 17. Tornado diagram when “Property Losses” is minor.

5.2.3. Managing functional resonance

Tracing the origins of these nodes in FRAM uncovers that "Cargo type" and "Vehicle condition" are outputs of F1 (Safety inspection), "HGV fire" is the output of F3 (safety driving), and "Traffic guide and evacuation" is the output of F5 (fire emergency response). "Tunnel fire rescue plan," "Fire rescue forces," and "Personnel rescue" are associated with F6 (fire rescue). It is evident that the outputs of F1, F3, F5, and F6 have the most substantial impact on accident outcomes, serving as the primary sources of functional resonance. Therefore, specific improvement measures need to be proposed for these functions to prevent the occurrence of accidents.

In response to these functions with significant impact on accident consequences, several improvement measures are proposed to manage the functional resonance.

(1) To ensure the safe operation of HGVs, safety inspections are important. Freight companies should enhance management regulations to incentivize drivers and inspectors to diligently perform safety checks. Additionally, refining the inspection checklist to encompass all safety-related issues is crucial. For HGVs transporting flammable goods, equipping them with more effective onboard firefighting equipment is essential to handle fire accidents.

(2) Ensuring driver safety and preventing accidents necessitates freight companies to recruit experienced drivers. Designing well-structured and scientifically planned tasks can help avoid traffic violations, such as speeding and fatigue driving, stemming from an excessive pursuit of profits. Furthermore, monitoring platforms should consistently send alerts to drivers, ensuring they adhere to safe driving practices.

(3) In the event of a tunnel fire, the emergency response of tunnel management relies on related equipment and administrators. Therefore, ensuring the high reliability of equipment, including lighting, broadcasting, ventilation, and escape routes, is crucial. Reinforcing regular firefighting drills for personnel is also essential to enhance emergency response capabilities.

(4) Tunnel fire rescue primarily depends on firefighters. The analysis demonstrates that a comprehensive firefighting and rescue plan significantly enhances the effectiveness of firefighting and rescue operations. Therefore, designing a rational plan tailored to the actual conditions of the tunnel is crucial to guide firefighting and rescue operations.

The findings highlight key factors—such as "Cargo type," "Vehicle condition," and the effectiveness of "Fire rescue"—that significantly influence accident outcomes in HGV fires in road tunnels. These insights can improve safety standards and risk management practices by encouraging stricter safety inspections, promoting the use of more effective firefighting equipment in HGVs, and enhancing driver training programs to reduce traffic violations. Furthermore, improving emergency response systems, including better maintenance of critical equipment and conducting regular drills, can lead to more reliable firefighting and rescue operations. Overall, these targeted measures can help prevent accidents and mitigate the consequences of tunnel fires, ultimately informing and enhancing industry-wide safety standards.

5.3. Discussions

This paper proposes a structured mapping method to integrate FRAM and BN for quantitative risk assessment of socio-technical systems. In recent years, various methods have been developed to enhance the process of mapping the FRAM to BN for system risk assessment. These methods primarily attempt to map FRAM to BN from two different directions.

The first direction is to first transform FRAM into an intermediate model, and then map the intermediate model to BN. In Guo et al.'s 22 study, researchers focused on risk assessment in ship pilotage operations, attempting to map FRAM to BN using this approach to establish a risk assessment model. In their research, the intermediate models used were the inter-level function model and intra-level function model. The second direction is to directly map FRAM to BN, ensuring a one-to-one correspondence between the elements of FRAM and BN. In Wang et al.'s 16 study, they attempted to modify the structure of FRAM to achieve a direct mapping from FRAM to BN. In their article, a new kind of link was added to FRAM, aiming to explain the source of functional resonance. Based on this modified FRAM structure, the authors proposed some executable steps to directly map FRAM to BN.

In the proposed study, the first type of mapping method from FRAM to BN is adopted, which involves mapping through an intermediate model—Accimap. Compared to existing mapping methods, our proposed method enhances the traceability and repeatability of the mapping procedures, thus mitigating subjective judgements of analysts during constructing BN.

5.3.1. Advantages of the proposed FRAM to BN mapping method

The proposed method uses Accimap to achieve the mapping of FRAM to BN. Comparing with other peer methods, such as RCA56, HFACS57, and Bow-Tie Analysis58，Accimap distinguishes itself through its holistic, systems-based perspective, mapping multi-layered causal relationships across all system levels—from immediate causes to broader systemic influences. In the case study of the HGV tunnel fire, the accident involved various types of factors, such as the vehicle checklist, driver's driving behavior, company policies, and tunnel operation management. These factors span different levels, including physical factors that directly caused the accident and higher-level organizational management factors that indirectly influenced its occurrence. Accimap is particularly effective in such socio-technical systems, where accidents often result from interactions across multiple layers. By visualizing these interdependencies, Accimap helps identify systemic weaknesses that might be missed by methods focused on specific components, guiding interventions toward root issues rather than symptoms. Its use in this paper ensures a structured and traceable integration of FRAM with BN, enhancing the mapping's rigor while reducing subjective bias, ultimately supporting more reliable risk assessments.

The proposed method's ability to provide a clear, traceable, and repeatable analysis of socio-technical systems also makes it a powerful tool for refining safety standards and enhancing risk management practices. By mapping FRAM to BN, the method allows for a detailed, quantitative assessment of how various functions within the system, such as safety inspections, driving behavior, emergency response, and rescue operations, contribute to potential accident scenarios. The FRAM-BN mapping method highlights key functions and their outputs that directly impact accident outcomes, enabling the identification of high-risk areas where safety standards need reinforcement. For example, in the case of the HGV tunnel fire, pre-departure safety checks, company monitoring of drivers, and routine fire drills in the tunnel are critical factors that indirectly influence the incident. The proposed method comprehensively identifies these factors, promoting the update of industry safety standards and ensuring that essential safety measures are embedded within tunnel management systems. Additionally, the method's ability to trace functional resonance—where failures in one area can trigger cascading failures in others—provides tunnel operators with a clearer understanding of risk dynamics. This insight supports more effective risk management by prioritizing functions with the greatest influence on accident severity. For instance, key risk mitigation strategies could include enhanced driver training, better task scheduling, and improved maintenance of fire emergency equipment.

The proposed method also has important applications in other areas. In healthcare, it helps identify key interactions that impact patient outcomes, leading to the development of more effective safety protocols and risk mitigation strategies. In aerospace, it supports the design of more resilient systems by mapping interactions between subsystems, improving pilot training, and refining emergency response strategies, thereby reducing the likelihood of accidents.

5.3.2. Limitations of the proposed method

While the structured mapping method proposed in this paper successfully achieves the mapping from FRAM to BN using Accimap to establish a model for socio-technical systems, there are some limitations that need to be acknowledged.

Firstly, although the method effectively facilitates the mapping from FRAM to BN, there are challenges in accurately quantifying the BN nodes. In this study, the BN quantification is primarily based on previous literature and expert opinions. However, this approach may not always guarantee precise quantification. Future research should focus on developing more accurate methods for determining the initial probability distributions and conditional probability tables of BN nodes, particularly in the context of the complex uncertainties inherent in socio-technical systems.

Secondly, while Accimap is utilized in this method to structure the analysis, and it provides certain rules for analysis, the identification of causal relationships within Accimap still slightly relies on expert judgment. This reliance introduces a degree of subjectivity, which can impact the objectivity of the analysis. Future studies should explore ways to enhance the objectivity of causal relationship analysis in Accimap, potentially by integrating data-driven methods or developing more explicit criteria for causal inference to reduce the dependence on expert opinions.

These limitations highlight areas for further improvement and refinement of the proposed method, and addressing them in future work will contribute to enhancing the robustness and applicability of the method in socio-technical systems.

5.3.3. Broader application of the proposed method

The structured FRAM-BN mapping method proposed in this paper has substantial applicability across various socio-technical systems, particularly in healthcare and aerospace domains. In healthcare systems, this method can be used to model the complex interactions between human factors, technological elements, and organizational processes that contribute to patient safety. For instance, in surgical procedures, where multiple functions such as pre-operative preparation, anesthesia, surgery, and post-operative care are interdependent, the FRAM-BN approach can identify critical points where failures might propagate, allowing for both predictive risk assessments and retrospective analyses of adverse events. This method provides a comprehensive understanding of how different factors contribute to surgical outcomes, enabling more effective interventions to improve patient safety.

In the aerospace sector, the FRAM-BN method is equally valuable in assessing the safety and performance of complex systems, such as during flight operations or maintenance procedures. For example, in the analysis of aircraft maintenance processes, the FRAM-BN method can map out the intricate interactions between maintenance personnel, equipment, procedures, and organizational policies. By identifying potential vulnerabilities and their propagation paths, this approach helps prevent maintenance errors that could lead to flight safety issues. Additionally, the method's ability to quantify risks and model various scenarios allows for better decision-making and risk management, ensuring that both human and technical factors are adequately addressed.

6. Conclusions

This study proposes a structured mapping method from FRAM to BN for system risk assessment. The key contribution of this paper is the introduction of Accimap as a novel approach to create a structured method for mapping FRAM to BN, thereby improving the method's traceability and repeatability. In this process, the functional hexagons of FRAM are converted into individual Accimaps, which are then interconnected and mapped to the BN. This approach ensures a clear and systematic correspondence between FRAM and BN, with the BN's structure directly determined by the results of Accimap.

This method was applied to assess risk of HGV fire in road tunnels, demonstrating its effectiveness. The analysis unveiled probabilities of "Casualties" as Minor-73%, Moderate-19%, Severe-8%, and "Property Losses" as Minor-75%, Moderate-17%, Severe-8%. Sensitivity analysis identified the output (O) of F1, F3, F5, and F6 as significantly impacting the consequences of accidents. In response to these findings, several improvement measures are proposed to manage the functional resonance.

The structured FRAM-BN mapping method developed in this study represents a significant contribution to both the theoretical and practical domains of risk assessment. Future research may focus on the creation of automated modeling tools that can enable the proposed system to function as an online, real-time decision support platform. By automating the mapping process from FRAM to BN and integrating real-time data inputs, the system could provide dynamic, continuous risk assessments. This advancement would allow decision-makers to respond to emerging risks and operational changes more effectively, making the system valuable not only for offline analysis but also for real-time safety management and preventive decision-making in various industries.

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