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Review

Disaster Risk Assessment for Railways: Challenges and a Sustainable Promising Solution Based on BIM+GIS

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Abstract: Natural hazards constantly threaten the sustainable construction and operation of railway engineering facilities, making railway disaster risk assessment an essential approach to disaster prevention. Despite numerous studies that have focused on railway risk assessment, few have quantified specific damages, such as economic losses and human casualties. Meanwhile, the mechanism of impact damage from various disasters on railway facilities and the propagation of functional failure in railway systems have not been thoroughly summarized and addressed. Thus, it is essential to conduct effective quantitative risk assessments (QRAs) to facilitate the sustainable design, construction, and operation of rail infrastructure. This paper aimed to review and discuss the systematic development of risk assessment in railway engineering facilities. Firstly, we highlighted the importance of disaster QRA for railway facilities. Next, numerous limitations of QRA methods were concluded after conducting a comprehensive review of the risk assessment research applied to railway facilities, such as bridges, tunnels, and roadbeds. Furthermore, true QRA (TQRA) application in railway engineering has faced several significant challenges. Therefore, we proposed a promising TQRA strategy for railway engineering facilities based on the integration of building information modeling (BIM) and geographic information systems (GIS). The proposed BIM+GIS technology is expected to provide sustainable future directions for railway engineering QRA procedures.

Keywords: railway; natural disasters; quantitative risk assessment; building information modeling; geographic information system

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1. Introduction

Railway traffic incidents related to disasters can disrupt traffic operations and cause irreparable damage and casualties [1]. Natural disasters, including landslides, rockfalls, and floods, have caused serious physical and functional damage to railway structures, even resulting in the paralysis of the entire railway system. The occurrence of a landslide located in Xining City, Qinghai Province, China, on 15 September 2022 resulted in damage to two viaduct piers belonging to the Lanzhou–Xinjiang Railway, leading to the cessation of its operation [2]. Similarly, the flood triggered by Storm Daniel in Thessaly, Greece, in September 2023 encompassed an area of 720 square kilometers, causing significant damage to the country's railway infrastructure and resulting in the unfortunate loss of 17 lives [3]. As climate change accelerates, the intensity and probability of disaster hazards will increase in the future, leading to greater risks to critical railway engineering infrastructures [4,5]. Aside from disasters caused by extreme weather, frequent checks of railway track health are required to keep trains moving safely and reliably. Cracks, loose nuts and bolts, scorched wheels, and other variables induced by human error on the tracks as a result of delayed maintenance and testing represent severe hazards and threats to railway safety [6]. Human error was responsible for 85% of railway accidents in India between 2000 and 2016 [7]. According to European statistics, at least 75% of fatal railway incidents between 1990 and 2013 were caused by human error [8]. Therefore, a detailed risk assessment is urgently needed to improve the safety of and reduce the maintenance costs of railway construction. Such an assessment can provide scientific support for risk prevention and emergency plans.

However, the majority of risk assessment methods rely on a qualitative assessment approach, which usually requires experienced experts to judge items, such as the analytic hierarchy process (AHP) method [9] and index weight method [10]. Even some studies that claim to use quantitative risk assessment (QRA) methods [11–13] fail to quantify specific economic losses or casualties, particularly for railway engineering with complex facilities and exposure to multi-hazard risks. Previous risk assessment methodologies utilized in railway engineering are very well-established tools based on probabilistic risk analysis, such as fault tree analysis [14], the analytic hierarchy process, and Monte Carlo simulation [15,16]. These studies have shown that risk reduction measures should be implemented to decrease the potential of disasters occurring, and minimize losses if the risks associated with the railway system are significant. However, these methods often do not account for information's uncertainty. Thus, QRA for railway engineering frequently encounters situations in which risk data are incomplete or highly uncertain [17]. Statistical methods have been used to evaluate risk assessment by weighting disaster-related factors. These statistical data and information are fundamental to the evaluation of risk assessment in railway systems, but not all of the data are available for analysis, and information on significant failure instances may be missing. Railway engineering involves many physical or material indicators that interact in complex ways, making it difficult to establish the connection between these indicators using generalized algorithms [18].

The problem stems from three main factors. Firstly, railway infrastructures are classified into various facilities, such as tunnels, bridges, and roadbeds [19], each containing a wide range of detailed components with varying attributes based on geometry and material properties. Detailed quantitative evaluation using established QRA methods requires accurate knowledge of the shape and property characteristics of all the components of the railway facilities, a resource-intensive process not frequently adopted by previous QRA methods. Secondly, the impact damage of disasters on railway engineering infrastructure is a highly complicated changing process of interaction between the engineering components and disasters [20,21]. This involves a complex disaster dynamics process [22] as well as an understanding of the impact damage [23,24] to the physical/mechanical properties of railway facilities, which remain unclear. Thirdly, due to the complexity and interdependence of railway systems, it is particularly important to evaluate the damage and failure sequence of components of a track–bridge system for railways under disasters [25,26]. Hence, estimating how the functional disruption of an individual component or facility will propagate to other parts of railway engineering is difficult.

Moreover, the QRA for engineering demands accurate knowledge of the shape and material properties of facilities, which requires an information repository with completed and detailed characteristics. A correct and effective QRA should also take into account factors such as the type and scale of disasters, and the interdependence of the engineering facilities. However, it is challenging to ensure that the traditional QRA approach can collect data on changes in engineering facility parameter indicators while considering the complex interactions between disasters and the disaster-bearing bodies of the engineering facilities. Additionally, accounting for the functional damage transfer effects of the railway construction itself further complicates the QRA process. Accident scenario analysis is a widely used method of risk assessment [27]. Risk assessment for railway systems based on accident scenarios was established via the collection of numerous accident reports and the organization of multiple workshops with railway safety specialists [28]. More specifically, the accident scenario method of safety analysis is built on two models: a general accident scenario presentation model and an accident scenario implicit reasoning model.

They are used to explain the static–dynamic status of accident situations, as well as the categorization, assessment, and production of scenarios, respectively [29]. However, the interpretation of static characteristics and dynamic modeling of accident scenarios is mostly reliant on approaches such as accident information gathering and categorization [30,31]. If the dynamic process of an accident can be reproduced in a visual simulation based on 3D models, the accuracy of the risk evaluation results will increase dramatically. Therefore, there is an urgent need for novel digital information technology to plan and manage large volumes of information data and different evaluation algorithms to estimate disaster risk assessment for railway engineering.

In recent years, building information modeling (BIM) has become a popular tool for infrastructure construction projects due to its digital and automated capabilities [32–35]. European countries have planned to implement BIM technology for railway systems [36]. Meanwhile, BIM technology's benefits in decision support, planning, and operation have been summarized. The secondary development capability of BIM allows for customized technical components to be obtained, which helps railway projects visualize potential design, construction, or operational concerns in a simulation environment [37]. For BIM, the whole life cycle is for a single refined model, but the risk assessment cannot be isolated from the effect of the surrounding macro-geographic environment. This necessitates the integration of geographic information systems (GIS) with BIM to provide geographic querying, spatial analysis, and dynamic simulation capabilities. Some researchers have focused on the integration of GIS and BIM for risk assessment and the management of flood damage to buildings [38] and subways [39]. BIM+GIS technology also has been adapted to visualize various types of information and monitor the dynamic security risk in deep excavation [40] and metro excavation engineering [41]. A QRA approach for residential buildings based on BIM+GIS technology has been proposed to produce risk maps and predict specific disaster losses [42]. Despite BIM+GIS having been applied to risk management in many domains, there remains a paucity of previous research on refined disaster QRA for the complex structures and facilities of railway engineering.

This paper provides a comprehensive review of the issues related to disaster QRA for the railway engineering system. In Section 2, we introduce the primary methods of risk assessment and emphasize the importance of QRA for railway engineering. Section 3 provides an overview of the risk assessment for railway bridges, tunnels, and roadbeds, highlighting the limitations and gaps in QRA for railway systems. Section 4 describes and evaluates the challenges experienced in applying disaster QRA to railway systems. Section 5 discusses the potential applications of BIM, GIS, and other new technologies in different aspects of railway engineering systems. Finally, in Section 6, we summarize the limitations of conventional QRA procedures and identify gaps, proposing innovative alternative solutions.

2. Importance of Quantitative Disaster Risk Assessment for Railway

Sustainability may be summed up as the capacity to continue at a specific pace or degree of performance [43]. To maintain this specific performance, it is essential to minimize the risk of disasters to which a project is vulnerable since regular operations would be disrupted if a disaster destroyed it. Especially for a huge system project like railway engineering, the influence of the surrounding environmental elements is critical to the sustainable development of the railway system. Risk assessment aims to determine the system's security assurance level by identifying and calculating risk assets, threats, and vulnerabilities, and developing effective and reliable risk prevention and mitigation [44,45]. The approaches to risk assessment can be categorized as qualitative and quantitative methods [46]. Qualitative approaches generally refer to site analysis, indexes of factors based on expert knowledge, and a risk score rating system [47–49]. While this is a simple and straightforward approach to risk assessment, it cannot be applied to performing a thorough economic analysis [50]. However, the estimated economic losses and human casualties provide the most direct basis for successful catastrophe risk mitigation measures [51]. Hence, more realistic QRA methods are required. A common quantitative disaster risk assessment is to determine the probability of a disaster occurring. The damage to individuals and property caused by the disaster is determined based on this probability while considering the characteristics of the disaster-bearing body itself. A similar QRA is necessary for railway incidents caused by human error to estimate the probability of human error so that actions may be taken to minimize the risk of errors occurring within the system, hence enhancing the overall safety criteria [52]. The accurate losses estimated by QRA will promote the disaster mitigation and prevention work undertaken by government departments.

Risk management in a railway system is challenging due to its large span of influence, the variability of engineering facility characteristics, and a complex natural environment. Bridges, tunnels, and roadbed sections are the three major categories of railroad facilities. In mountainous/hilly areas, the proportion of bridges and tunnels is higher than in plain areas. Due to the special topography, bridges and tunnels have complex engineering structures and a huge number of foundation components. The engineering structure components differ in their physical characteristics, functional properties, and shape, which also puts the components at different levels of risk. Qualitative risk assessment methodologies cannot account for the complex structural features of large engineering infrastructures such as railway systems, especially for the quantified risk of key structural components. Consequently, QRA methodologies suited to the characteristics of railway systems consisting of many complex structural components are needed. Quantitative geohazard risk assessment criteria can provide risk avoidance guidelines for railway systems from a sustainable safety perspective [53].

3. Deficiencies of Quantitative Disaster Risk Assessment for Railway

The United Nations Department of Humanitarian Affairs (UNDHA) has proposed that risk is the expected loss, including loss of life, injury to humans, damage to property, and interruption of economic events, because of a specific threat in a specific area over a specific period [54]. This concept refines the sources and states of loss and reflects the interaction of the bearing body with the hazard. The classic risk assessment framework $R = H \times V \times E$ was proposed [55], in which R is risk, H is hazard, V is vulnerability, and E is exposure. The hazard represents the probability that any given area will be affected by disruptive activities over some time. Exposure is a property of the hazard-bearing body, and vulnerability depends on the relationship between the characteristics of the hazard and the bearing body. The majority of risk assessment methods have adopted this framework.

3.1. Overview of Disaster Risk Assessment for Railways

Railway engineering has a long engineering scope and complex infrastructure. It is considered that a disaster risk assessment for a complete railway project is overly complex, cumbersome, and time-consuming. Because a lot of the work assessed pertains to items of the same type, a consistent division of the railway infrastructure into item categories, including bridges, tunnels, and roadbeds, has been utilized to arrange a review of risk assessment. In addition, natural disasters influence diverse engineering facilities in the railway system to varying degrees and in various ways (Figure 1). All railway infrastructure including bridges, tunnels, roadbeds, embankments, etc. are influenced by extreme weather events, such as extreme high or low temperature, windstorms, snow, rainfall, and floods [56]. Extreme rainfall events also tend to raise the pore water pressure on steep slopes, raising the possibility of those geology hazards. Extremely high temperatures in summer can lead to the buckling and thermal stretching of railway tracks [57].

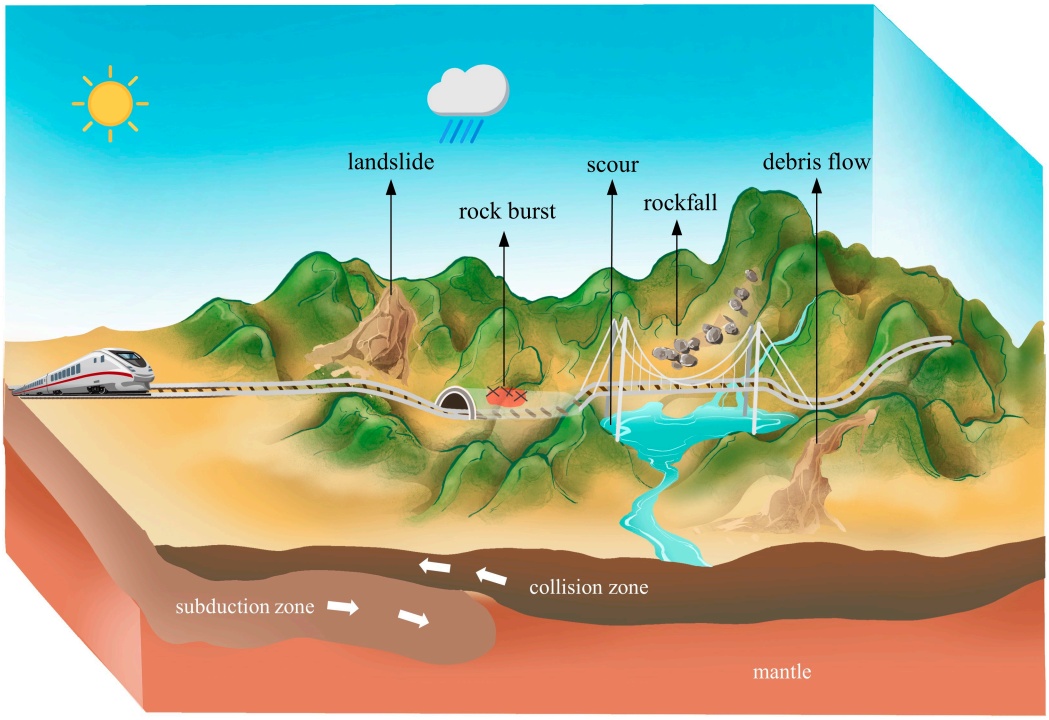


Figure 1. The impact of multiple disasters on railway engineering.

To present a comprehensive review of disaster risk studies on the subject of railroad engineering, a systematic search and selection approach for reviewed publications were utilized. The literature data selected for this study were collected from the Web of Science (Core Collection) database and Google Scholar. Search strings including "disaster", "risk assessment", and "railway" were chosen as "topic" items for the search activity, with documents of type "article" selected and the time period ranging from 2002 to 2022. The search keywords were combined using the Booleans operator "AND" to ensure that they followed the format required by the search engines. The articles' content was screened for relevance to the disaster risk assessment of railways, producing 120 research articles. According to the search results, the number of articles has grown significantly since 2016. Most of the articles about the disaster risk assessment of railways were published between 2018 and 2022 (Figure 2a).

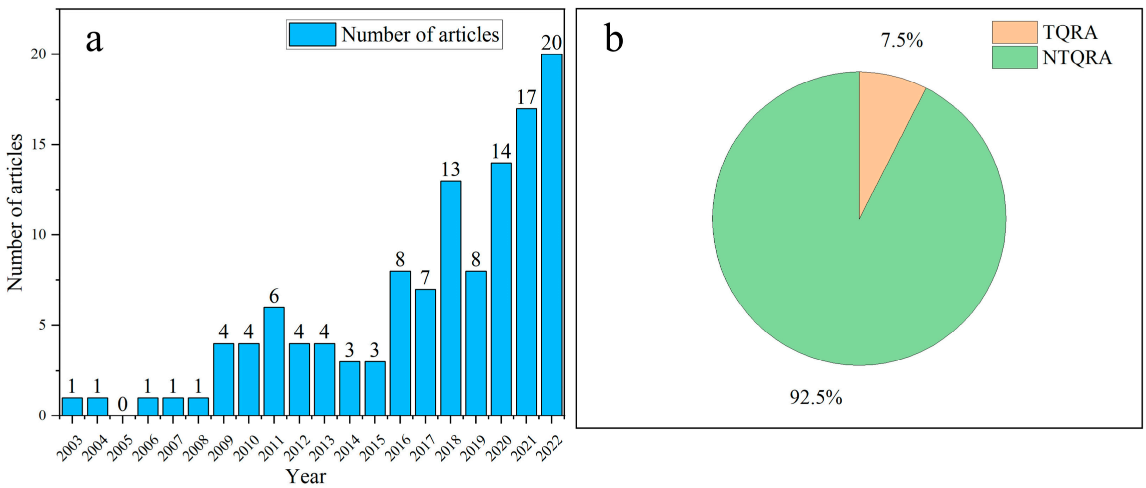


Figure 2. Literature statistics of QRA for railway engineering: (**a**) distribution of articles by year of publication; (**b**) ratio of research articles conducted using true quantitative risk assessment methods.

3.1.1. Disaster Risk Assessment for Railway Bridges

Bridges are threatened by multiple hazards during their operation period, which may cause damage to bridge structures. Most bridges are built to cross rivers or streams, and the piers are in direct contact with the water flow. So, over the last few decades, a substantial number of studies have concentrated on flood or scour risk assessments. However, only a few studies have implemented quantitative risk assessment.

Bridge failures due to flooding or debris flow are most usually caused by extreme rainfall [57]. A return period of flooding and precipitation is often adopted to express the probability and severity of flood hazards occurring. Based on the data from 1846 to 2004, the average failure caused by disasters in the UK and Ireland was a 160-year return period, while a 200–250-year return period applied to most of the failures caused by floods [58]. It is considered that scouring undermining the bridge abutments and piers is the typical cause of flood-induced bridge failures [59]. The AHP method is an indicator-based approach often used in risk assessment, while fuzzy AHP was utilized to calculate the weights of risks, which could rank the risk indicators [60]. The risk indicators are analyzed via expert opinion based on their impact, their occurrence, and the damage of disasters. This new method proved to be more practical and efficient for bridge risk assessment than the traditional AHP method. The effect of scouring on bridges is a long time-dependent process. Therefore, the risk assessment of bridges should be based on time-dependent reliability estimates of structures [61]. Due to the complexity of the physical interaction process between piers and water flow, a limited number of research works have been conducted on the evaluation of the vulnerability of bridges to scouring or flooding [62].

Meanwhile, some quantitative approaches are also used to assess risks for bridges. In Britain, 100 bridge failures caused by scouring have been investigated to construct fragility curves, which could quantify the failure risk based on the intensity of a flood occurrence [63]. A risk assessment approach ought to account for the probability of these multiple hazards occurring during the life cycle of infrastructure. An empirical–statistical model (i.e., UBCDFLOW) was adopted to analyze the size and travel distances of debris flows, as well as their damaging effect on railway bridges based on the bridge blockage ratio of debris flow [64]. In recent years, numerical approaches have also been adopted to investigate the vulnerability of bridges. In addition, more advanced and comprehensive numerical models are needed to consider the complex three-dimensional characteristics of bridges [65–68].

3.1.2. Disaster Risk Assessment for Railway Tunnels

Tunnels are generally built to traverse mountains. This causes tunnel excavation to be threatened by multiple geology hazards, including collapse, rock bursts, and portal landslides. The limited space in tunnels will lead to huge economic losses and casualties when disasters occur in the construction and operation period, such as water inrush, poisonous gas leaks, and fire.

Tunneling risks can be assessed using both qualitative and quantitative approaches. Most of the previous research has been dominated by non-quantitative methods, such as qualitative and semi-quantitative methods. Based on the data collected on disaster incidents in tunnels in China from 2002 to 2018, the major geohazard in mountain tunnel construction is collapse, with the highest percentage of 62.89% [69]. Some newly developed strategies, such as full life cycle construction management and in-site monitoring technologies, may lead to a significant reduction in geohazards. Equally, 3D geological modeling has wide application for geological environment assessment in engineering. Since the geological conditions and risk assessment have various requirements at the different construction stages of tunnels, the demands of tunnel engineering applications cannot be satisfied using single-scale geological modeling methods. A novel geology modeling approach with multi-scale characteristics based on a Hermite radial basis function (HRBF) and Monte-Carlo algorithm has been proposed [70]. This modeling methodology produced a reasonable risk assessment on the different scales of the actual tunnel engineering requirements. Enhancing the effectiveness of dynamic updates, refinements, and plugins to geologic and engineering construction models will be a significant concern for engineering risk assessment in the future. Obtaining historical and real-time data and trends on future changes in the engineering facilities and the surrounding environment is the key to engineering risk assessment. This will require field monitoring and numerical simulations to collect the key data and the prediction of the tunnel's health state in the future.

Numerical model simulations are effective methods for investigating and simulating processes that would otherwise be impossible or unachievable in real engineering constructions. Disasters that occur on the tunnel portal slope, including landslides, rockfall, and debris flow, which are affected by the slope's instability, may be caused by tunnel excavation. The reasons for landslides were investigated while excavating a mountain tunnel via the interaction of the upper soft and lower hard stratum [71]. An adaptive encryption upper-bound theorem for finite elements according to the strength reduction method, coupled with field monitoring and investigations, was utilized for tunnel landslide risk assessment. Deep underground engineering excavation can cause rock bursts, which is one of the most common disasters in tunnel construction. A parsimonious attribute evaluation model was developed based on the entropy weight ideal point method and stress field inversion [72]. The unique engineering characteristics of the Sichuan–Tibet railway tunnels were analyzed and six critical scientific issues were defined [73].

There is also research focused on the QRA method for risks in tunnels. As part of the development of fire safety design, a methodology has been proposed for the quantitative assessment of personnel safety risks in railway tunnels [74]. Three coupled models (e.g., smoke spread, evacuation, and consequence model) have been utilized to determine the consequences of risk. The Fractional Incapacitation Dose (FID) value determines the possible number of fatalities in case of a fire disaster in a railway tunnel, while the social risk is represented by a Frequency/Number of Casualties curve (FN curve).

3.1.3. Disaster Risk Assessment for Railway Roadbeds

The engineering characteristics of railway roadbeds (the subgrade of the whole railway is considered as a line) vary between railway bridges and tunnels, including due to long routes, the environment along the railway line, and the strong heterogeneity of environmental dominant factors in different regions.

Much of the previous research focuses on the geological hazard susceptibility of a region or a site using a non-quantitative method, while few works of literature pay attention to the geological hazard susceptibility along a line engineering project [75]. The analytic hierarchy process (AHP), which is a traditional method of making multiple criteria decisions using qualitative as well as quantitative criteria, has been widely used in research on the risk assessment of geological disasters. Some studies combined the AHP with other methodologies to boost the performance of their models. An integrated triangular fuzzy number (TFN) and AHP were proposed to perform geohazard assessment [76]. The results demonstrated that an integrated approach is more effective than the traditional AHP method in detecting high-risk regions. However, the method based on the AHP also retains the basic characteristics of the quantitative and qualitative elements. The probability of landslides was an important part of geological disaster risk assessment. The railway hazard was interpreted as the probability of specific quantities of landslides occurring, or other geological disasters, which belong to a specified range volume occurring within a section along the railway [77]. Landslides were classified into three classes and the overall number of landslides predicted per km of the railway for different return periods, which was multiplied by the probability of which magnitude class the landslides would belong to. The frequency–volume statistics were utilized to estimate the probability of the landslide magnitude. The risk for a certain return time was represented as the number of landslides of a specific magnitude class per km of railway.

An assessment of risk requires knowledge of certain factors on which statistical data are rare, key to the process of subjective probability. Such approaches are restricted by the uncertainty associated with the probabilities elicited. A quantitative risk assessment method considering the uncertainty of a railway was proposed [78], including the risk to the life of train workers working along some critical sections with a high frequency of instability. The uncertainties were compensated for using upper and lower bounds. Then, an analysis of the estimated risks was conducted using a Monte Carlo simulation methodology.

In addition to the ordinary parts of the railway trackbed, the level crossing area is also a railway-disaster-prone area [7,79]. The majority of the accident-influencing factors discovered in previous research were related to the physical characteristics of the rail level crossing itself, its operating state, and the user behavior, while few interactions between the components have been identified [80]. For example, in assessing the vulnerability of level crossings, indications including the maximum allowable speed of trains, the density of railway and road traffic, the extent of level crossings, and the visibility of train driver's cabs were considered. The safety of Lithuanian railway level crossings was evaluated and analyzed using a logistic regression approach, with a model to estimate risk at level crossings demonstrating 86% validity [81]. In order to estimate the risk, a general method for causal statistical risk assessment based on Hierarchical Causal Bayesian Networks was developed to evaluate the numerous factors that could result in accidents and identify the elements that have the greatest effect on level crossing accidents [82].

3.2. Lack of Quantitative Disaster Risk Assessment for Railways

The above literature demonstrates that many studies have been conducted that present risk assessment methods for the railway system. However, while the validity of these studies in the risk assessment of railway systems has been established, most of them are mainly concerned with non-quantitative methods. Additionally, the majority of studies with non-quantitative risk assessment used mixed methods, which are mainly referred to as analysis based on data from field investigation [71,83] and the AHP method [60,76].

Even though all of these papers are about the disaster risk assessment of railways, those that use true quantitative risk assessment (TQRA) as their primary strategy are still in the minority (Figure 2b). The ultimate goal of these TQRA-based studies is to analyze and predict particular disaster losses, such as economic losses and human casualties. On the contrary, for those studies that employ a not true quantitative risk assessment (NTQRA) strategy using quantitative research methodologies, the final analysis cannot provide specific loss prediction data (Table 1).

Table 1. Review of QRA research focusing on railway bridges, tunnels, and roadbeds.

Category	Reference	Methodology/Theory Applied	Theme: Contribution/Major Findings	TQRA	Limitations
bridge	2011 Decò [61]	Associates the consequences of a structural failure or malfunction with the probability of bridge failure.	Assessed time-dependent failure probabilities, hazard functions, and probability density functions of the time to failure.	no	Not applicable (N.A.)
	2013 Benn [28]	Considers the combination of the design life of the bridge, the return period, and the acceptability degree of risk.	Proposed scouring flood assessment and protection design based on 200-year return period flood events in the UK.	no	N.A.
	2016 Andric' [60]	Combines the Fuzzy Analytic Hierarchy Process (FAHP) with fuzzy knowledge representation and fuzzy logic techniques into a single integrated framework of disaster risk assessment.	Proposed a practical and efficient method for a quick and reliable multi-hazard risk analysis and assessment of bridges.	no	N.A.
	2019 Lamb [63]	Quantifies the failure possibility of bridges based on vulnerability curves and flood event levels.	Provided a dataset of 50 flood events in Britain and obtains the risk of flushing failure based on the global system and associated economic costs.	yes	1. Variations in construction and servicing criteria in the global system are ignored; 2. The risk of scouring on a global scale cannot represent individual bridges.
	2021 Fernandes [84]	Consideration of time-dependent degradation effects (structures) in bridge risk assessment.	Calculated the time-dependent risk on a bridge and estimated the direct/indirect implications for the various damage degree states.	yes	The pier's highest displacement stands for the displacement of the whole bridge, which does not consider the varied characteristics of components in bridges.
tunnel	2016 Van Weyenberge [74]	Bow-tie model, smoke spread, evacuation, and consequence model.	Calculated the probability of death caused by fires in tunnels using specified lethal parameters to quantify the risk of fires in tunnels.	yes	To establish the original fire frequency for trains, fire frequency data are obtained from governmental agencies. The frequency data may be not applicable to local tunnels.
	2018 Xiong [70]	A proposed multi-scale three-dimensional geological model for tunnel engineering at different construction stages in risk assessment.	Different scale models are applied to the Yuelongmen tunnel with the Hermite radial basis function on a regional scale and dense drilling and geological prediction data on a project scale.	no	N.A.
	2020 Wang X [69]	The collected dataset includes all the geohazard occurrences observed in the tunnel system between 2002 and 2018.	The main geological hazard in mountainous tunnel constructions is collapse, and it occurs frequently in loess and karst terrain areas.	no	N.A.
	2021 Zhang [71]	Field investigations and tests, theorem of adaptive upper bounds for finite components based on an intensity-discounting approach.	Continuous rainfall occurrence and portal landslides caused mostly by loose soil, bedding planes, and shifted topography. Recommended anti-slide piles, backfilling, and slope-brushing protective measures effectively improved the stability of the slope.	no	N.A.

Table 1. *Cont.*

Category	Reference	Methodology/Theory Applied	Theme: Contribution/Major Findings	TQRA	Limitations
tunnel	2022 Zhang [73]	Established a multidisciplinary research framework to guide the Sichuan–Tibet Railway tunnels' construction.	Proposed six key scientific issues in the Sichuan–Tibet railway tunnel construction, presented based on a related multi-layer study of key tunnel engineering challenges.	no	N.A.
	2021 Zhou [72]	Created an assessment model that includes characteristic reduction. The entropy weight ideal point approach was then used to calculate the weights of the major assessment criteria and the offset distance.	Presents an effective approach to predicting rock bursts in hard rock and deep-lying long tunnels.	no	N.A.
	2022 Rahmada [85]	Summed up and classified the indicators of vulnerability, susceptibility, and resilience with geophysical and geotechnical investigation and using the formula $R = (H \times V)/C$ for the final risk score.	Analyzed the disaster susceptibility, vulnerability, capacity, and risk of the case study tunnel. Recommended measures for the study tunnel.	no	N.A.
roadbed	2011 Jaiswal [77]	The hazard for a specific return period was determined using the entire amount of individual landslides per kilometer of the (rail) road and the probability that the landslides belonged to a given magnitude class.	Focused per kilometer of rail, estimated the possibility of the landslide magnitude depending on the frequency percent associated with distinct scales of rainfall events.	no	N.A.
	2016 Macciotta [78]	A quantitative risk assessment (QRA) event tree related to slope instabilities was used to quantify the possibility of disasters.	Upper and lower bounds were elicited to cope with the uncertainties associated with QRA in the railway.	yes	The QRA just focused on the frequency and probability of disasters occurring. There was no detailed study of the damage (e.g., impact energy) caused by disasters to roadbeds and trains.
	2020 Wang W D [75]	Matter-element extension model, gray correlation model, and support vector machine.	A new index approach to evaluate geological hazards was proposed, taking into account the influence of the railway.	no	N.A.
	2021 Su [83]	Drilling and monitoring approaches, as well as geophysical methods for the causative factors and characteristics of the landslide and the localization of the landslide; an integration of the transient electromagnetic technique and electrical resistivity tomography was used.	Investigated the characteristics and fundamental causes of landslides along the Jiheng Railway in China, and presented a risk evaluation for potential landslide events.	no	N.A.
	2021 Zheng [76]	A combination of methods for integrating triangular fuzzy numbers (TFNs) and the analytic hierarchy process (AHP) into geographic information systems (GIS).	Within the previous 10 years, it has become possible to precisely forecast the distribution of geohazard risks in the study region. The TFN–AHP method is more efficient in identifying high-risk areas compared with the original AHP.	no	N.A.

3.3. Limitations of Quantitative Disaster Risk Assessment for Railways

The current QRA methods concentrate on the losses of a whole engineering project, which are unable to meet the demands of refined risk assessment for modern engineering. The major reason is that there is a lack of refined-scale new technology of digitization, intelligence, and informatization to satisfy the risk assessment requirements of the architecture, engineering, and construction (AEC) industry. In addition, although TQRA methods were adopted in some research, limitations still exist, such as:

(1) The physical and functional characteristics of railway facility components vary. As a result, changes in the indicators of various components do not indicate variation in the tendency of entire engineering facilities.
(2) There are no detailed studies about the damage (e.g., impact energy) caused by disasters to railway facilities, especially complex structural components. The dissipation of impact energy and the resulting variations in component damage are still unclear.
(3) The risk assessment just simply addresses one component (e.g., a part of the railway roadbed) of the railroad system's infrastructure, neglecting the influence of disaster risks to this component on the overall system (e.g., the whole railway line). That is, the object of the risk assessment is thought to be isolated, and the connection between components and the whole system is ignored.

4. Challenges in Quantitative Disaster Risk Assessment for Railways

The TQRA is obtained by evaluating the probability of a disaster occurring as well as the specific losses suffered by the disaster-bearing entity, including economic losses and human casualties. The main reason for limitations has been attributed to a lack of advanced fine modeling approaches to express the diverse characteristics of components in engineering facilities, an investigation of the relationship between engineering facility structures and environmental conditions, and a system that includes the entire facility as well as the surrounding environment. Figure 3 shows the main study methodologies and challenges for QRA in railway systems.

4.1. Refined Structural Modeling of Railway Facilities

Due to their complicated structures, engineering facilities with linear properties, such as railway bridges, tunnels, and roadbeds, are difficult to represent using simple 3D shapes. So, employing refined modeling representation is particularly crucial in the context of railway project planning, since these structures not only have a very large extent (hundreds of kilometers) but also the structural components must be designed in the scope of only a few cm in length to provide the required connections and avoid spatial conflicts [86]. Various constructions, including tunnels, bridges, tracks, stations, and electricity infrastructure, are included in the classification of railway infrastructures. Railway bridges and tunnels not only have their own engineering characteristics but also lay tracks and determine other railway infrastructure. This makes railway bridge and tunnel modeling approaches more challenging than conventional highway bridges and tunnels.

Each component of different structures is exposed to different risks owing to its unique physical and functional purpose. For instance, in the different parts of suspension bridges, the main disaster risks faced by bridge piers are scouring and the impact of debris flow [63]. Meanwhile, the suspension ropes are exposed to the disaster risk of complex wind fields [87]. The degree of damage to the risk-bearing body in the occurrence of a hazard is indicated by its vulnerability, which is an essential component of QRA. The disaster risk assessment for critical components of railway facilities can benefit from the representation of refined 3D models at the component scale. However, many studies on risk evaluations of railway bridges and tunnels rely on simplified 3D models, which will decrease the computation cost of QRA, but a huge amount of crucial information is lost as a result. These simplified 3D models cannot express the detailed features of the actual bridges, tunnels, and other complex structural engineering facilities. Refined features are also critical in assessing the vulnerability of the facilities themselves. Therefore, the development of a refined structural modeling methodology is urgently necessary, especially for railway infrastructures that are faced with multi-hazard risks.

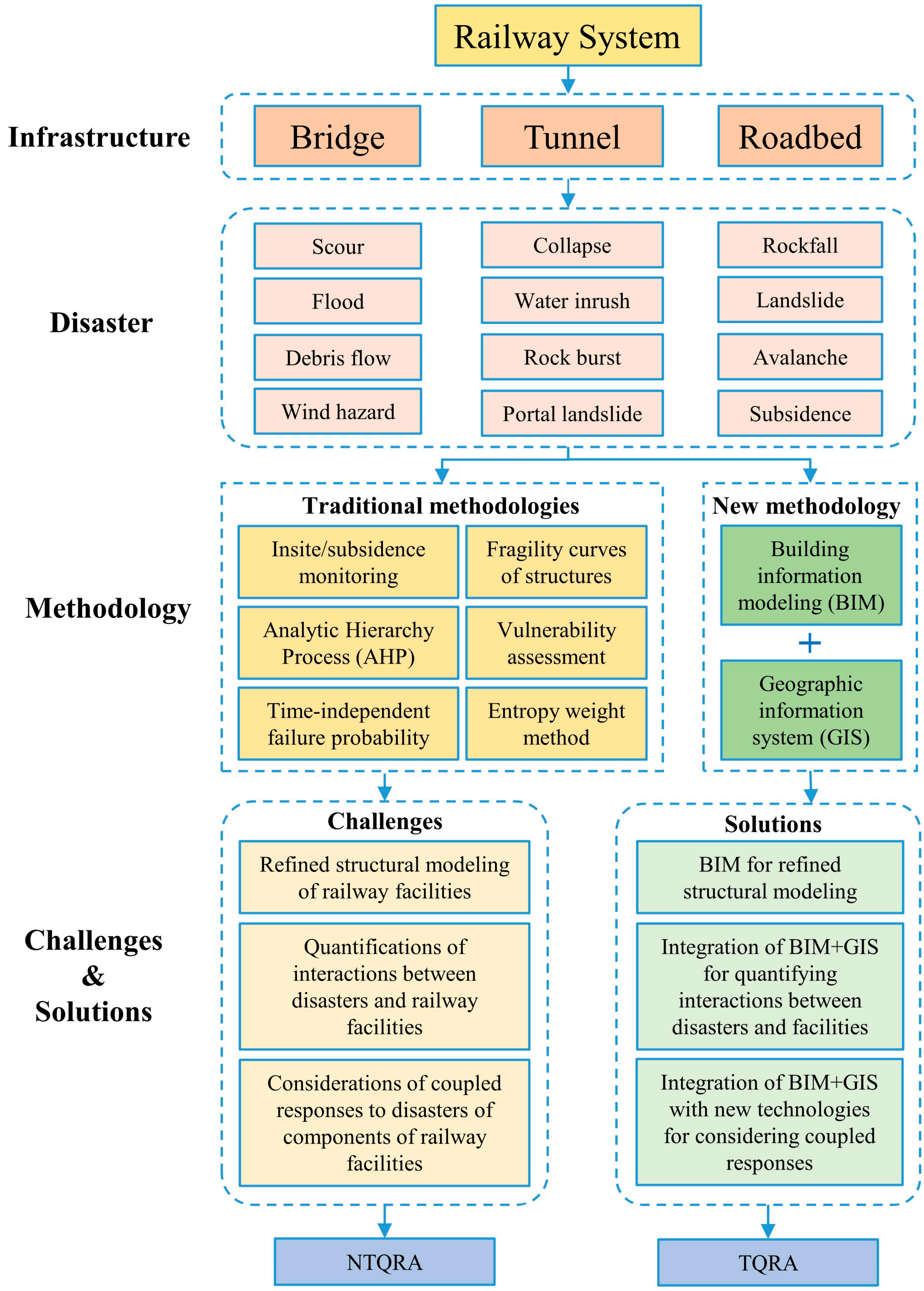


Figure 3. Flowchart of this research about QRA for railway engineering.

4.2. Quantifications of Interactions between Disasters and Railway Facilities

To achieve a more accurate quantitative susceptibility assessment, both the material characteristics of the risk-bearing body and the physical processes of disasters must be incorporated into the susceptibility calculation. For railway facilities, the catastrophe damage is mostly caused by the interaction process between the disaster and the engineering structure. These interactions include the impact of geological hazards on engineering facilities [88–90], the scouring effect of floods on bridge piers, the destructive processes of rock burst and water inrush in tunnels, the diffusion processes of fire and smoke, etc.

The direct contact between geological hazards and railroad facilities, in particular, is determined by the characteristics of both the risks and disaster-bearing bodies. Variations in one or more indicators of physical or other functional characteristics are commonly used to indicate the interaction process of a disaster with a disaster-bearing body. For railway bridges and tunnels, many parameters indicate that the status of facilities varies because of complicated engineering structures and complex geologic and geomorphic environments. During this process, a high degree of uncertainty persists in the interactions, which makes it difficult to quantify disaster risks using traditional research methods.

Currently, the research undertaken on exploring the steps and detailed process of interactions between disasters and facilities, calculating the changes in physical and mechanical parameters for railway engineering structure components, and methods for simulating and quantifying the impact of disruptions caused by disasters does not satisfy the requirements for risk prevention and engineering control for railway engineering.

4.3. Considerations of Coupled Responses to Disasters of Components of Railway Facilities

Large-scale engineering as we know it in the modern world is more and more dependent on a complex network of essential infrastructure systems. Recent disasters have demonstrated that the most hazardous vulnerability is hidden in the interdependencies across various infrastructures [91]. Damage in one system may cause failure in another, resulting in a disruptive cycle of cascading and increasing failures. Disaster-risk-induced consequences can quickly spread through heterogeneous infrastructure systems due to explicit and implicit interdependencies as infrastructure systems become more sophisticated and complex [92].

Railway engineering facilities are complex systems for which it is typically hard to deduce global active trends from the examination of individual components, particularly in the face of failures and disasters. Components of railway bridges and tunnels do not share the same likelihood of potential damage when exposed to disasters [93]. On the other hand, components within the same railway infrastructure system may contribute differently in terms of ensuring an appropriate operational performance, because various components differ in their functional features. However, most studies assess risk for only one component of a system or a simplified model of complex engineering facilities, while little attention has been devoted to the linkage and interdependency between railway facilities. It is therefore preferable to enhance vulnerability evaluation by simultaneously executing integrated analysis of various infrastructure systems or heterogeneous components of one facility system rather than focusing solely on a boundary-enclosed infrastructure system or an isolated component of one facility system. This will reveal the monolithic behavior at the system-of-systems level when disasters occur.

Currently, the vast majority of research undertaken on risk assessment of railways and other linear engineering only concentrates on regional or entire railway system risk assessment, which does not meet the needs of refined quantitative risk assessment for the railway infrastructure throughout its whole engineering life cycle. Therefore, realizing breakthroughs in quantitative risk assessment and refined-structure probing technology for railway infrastructures is urgently needed.

5. A Promising Solution Based on BIM+GIS

BIM and GIS are tools for digitally representing architectural and environmental entities. BIM is concerned with the micro-scale representation of architectural details, whereas GIS is focused on the macro-scale investigation of environmental elements. BIM+GIS may create a comprehensive representation of the built environment that includes both the building's regional environmental aspects and information on its particular characteristics [94]. Based on their functional properties, BIM+GIS can be a significant tool for risk assessment of disaster-affected construction facilities.

5.1. Potential of BIM in Refined Structural Modeling

BIM is defined in various circumstances and from different perspectives [95]. Early definitions stated that BIM was just a 3D representation of a facility, was inaccurate, and failed to convey the full potential of digital, object-based, interoperable building information modeling procedures and technologies, as well as current communication methods. According to a widely recognized definition offered by the US National Building Information Modeling Standard (NBIMS-US™, formerly buildingSMART alliance), BIM is "a digital representation of physical and functional characteristics of a facility. BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition." [96].

For the convenience of modeling operations, BIM software (e.g., Autodesk Revit 2020) and systems with BIM capabilities frequently provide a significant number of preset parametric object classes and families. Users can also customize when the needed parameterized items do not exist in a certain BIM platform [97], which greatly improves the efficiency of the parametric modeling process for engineering infrastructure. One of the benefits of BIM is the refined 3D visualization model. However, the core of BIM is to provide a complete and detailed building engineering information base for virtual three-dimensional models of buildings or infrastructures using digital technology. This database consists of geometry information, physical parameter attributes, and building component state information (e.g., space and motion behavior). In this context, "building" is a verb that refers to the whole life cycle of a facility, including its conception, design, construction, functional life, renovation, adaptive uses, and recycling/disposal stages. A high-precision 3D model in BIM can depict railway building facilities (e.g., bridges, tunnels, etc.) from the inside to the outside and query the related attributes. The integration of dynamic and static information into the whole process of railway construction by the BIM model, as well as multi-level information aggregation, can realize multi-dimensional information sharing and the transmission of railway construction progress.

GIS is a computer system that collects, stores, manages, analyzes, describes, and applies the whole of or part of the Earth's surface and the data information related to spatial geographic distribution. GIS can perform geographical spatial analysis for large regions based on the spatial analysis of patterns and relationships, which is the core function of GIS. However, GIS cannot express and analyze the refined and comprehensive characteristics of details of buildings or infrastructures. The emergence of BIM solved the deficiency of traditional GIS in the field of engineering. Different from GIS, the basic goal of BIM is to generate a comprehensive and accurate database of building specifications for virtual three-dimensional models of buildings or infrastructures using digital technology. The Levels of Detail/Development (LODs) of BIM and GIS have significant differences (Table 2). BIM's expression of 3D architectural design and geometric semantics can run through the whole life cycle management of railway engineering. Figure 4 shows a high-precision 3D BIM model that can express the railway building facilities (such as bridges, tunnels, and roadbeds) from the inside to the outside and query the related attributes.

Unlike GIS, BIM takes the information data of the whole life cycle of the project as the model basis. The data record the attribute information of each infrastructure component of the engineering project in detail. Meanwhile, they also express the geometric information of the component in a refined three-dimensional model display. Therefore, BIM+GIS can make up for the shortcomings of GIS, such as the incomplete presentation of single-model details. At the same time, GIS can also make up for the defects of BIM that information on the association between the project and the surrounding macro geographical environment is not in-depth enough, and spatial analysis between the internal component models of the project is not sufficient.

Table 2. The difference of LODs between BIM and GIS.

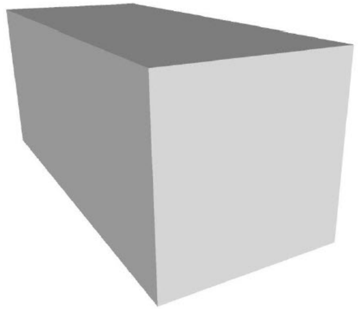
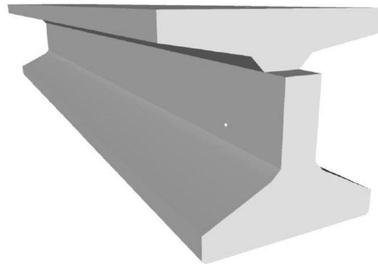
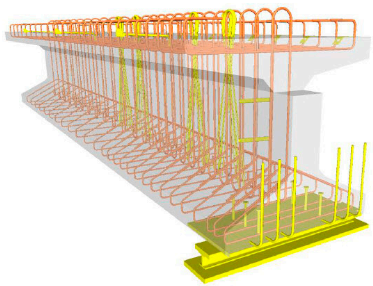
	LOD	Description	Examples
BIM	LOD100	Elements are not geometric representations. Model elements or symbols that indicate the presence of a component but do not specify its shape, scale, or specific position.	Railway bridges precast structural I girder
	LOD200	Approximate geometry of structural concrete elements.	
	LOD300	Increases the specific element's size, shape, and location.	
	LOD350	Increases the shape, size, height, location, quantity, and orientation information of the connecting elements (anchor rods, strands, reinforcement bars, etc.).	

Table 2. *Cont.*

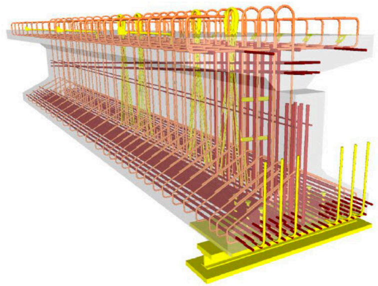
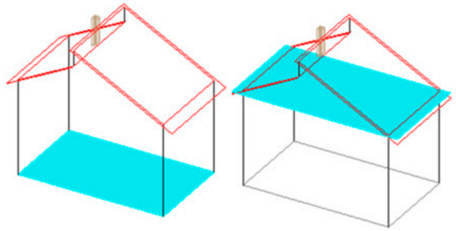
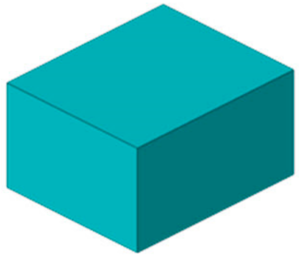
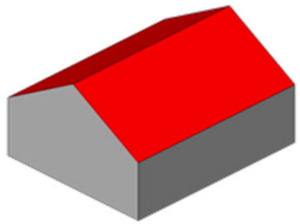
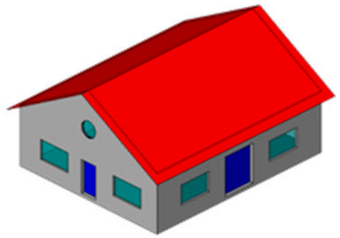
	LOD	Description	Examples
BIM	LOD400	Increases the shape, size, height, location, quantity, and orientation detailed information of element attachments (anchor rods, strands, reinforcement bars, etc.).	
GIS	LOD0	Building floor plans, which are LOD0 representations of building interiors.	
	LOD1	The inaccurate outside shell of a building.	

Table 2. *Cont.*

	LOD	Description	Examples
GIS	LOD2	Building shell without details such as windows and doors.	
	LOD3	Building shell with detailed elements.	

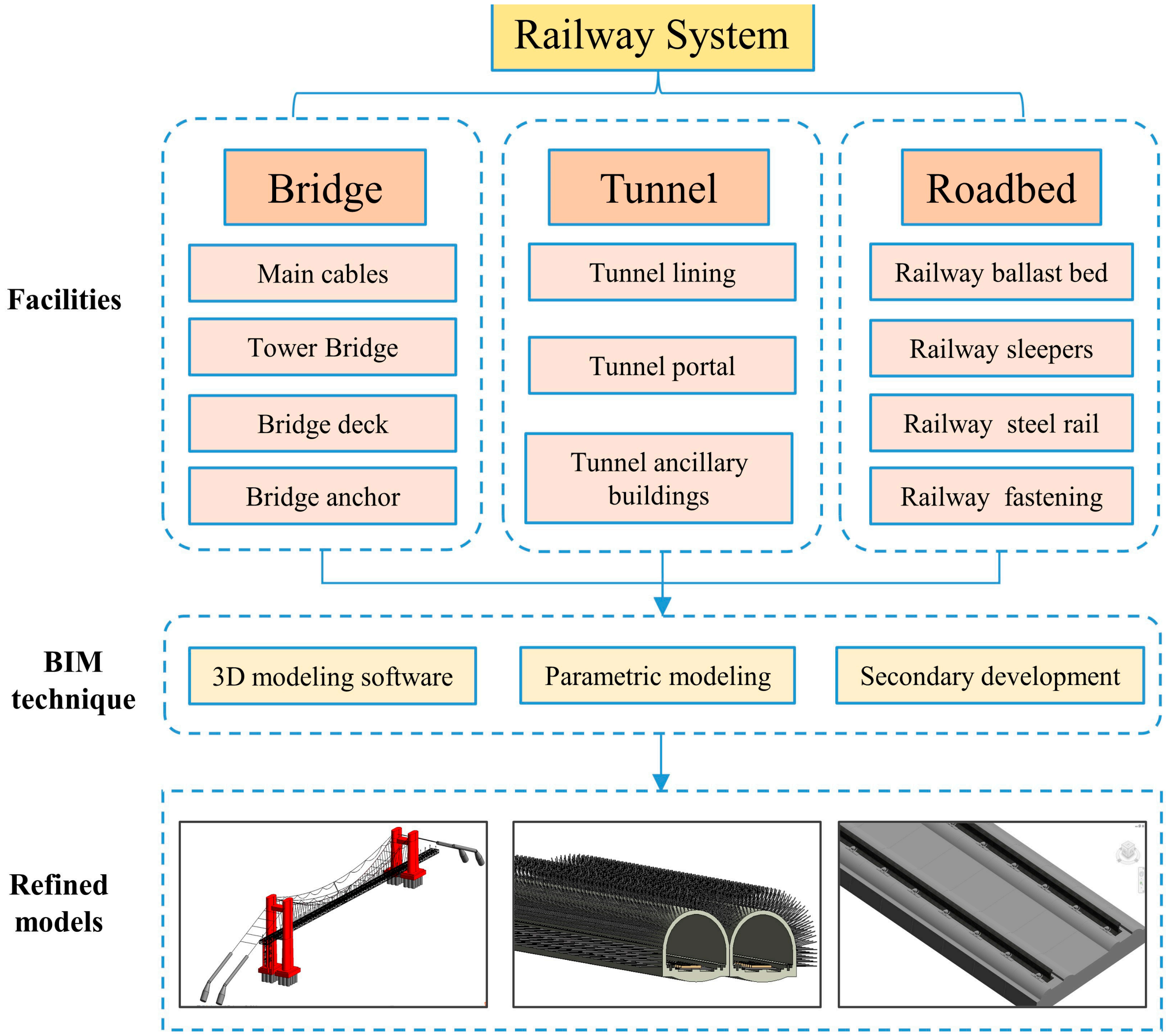


Figure 4. Process flow of refined BIM modeling for railway facilities.

5.2. Integration of BIM+GIS for Quantifying Interactions between Disasters and Facilities

GIS involves surface information as well as data information related to the spatial distribution of geographic elements. Within the area of macro geography, GIS can provide several useful geographic queries and analytical services. GIS has become an essential tool for natural disaster analysis and simulation due to its strong investigation of natural environmental elements in large regions. Figure 5 shows that GIS can effectively simulate the movement process and effect scope of geological hazards. GIS modeling was utilized coupled with a 3D rockfall process to assess the spatial frequency distribution, bounce height, and kinetic energy of falling rocks [98]. Landslide Analyst (LA) was developed as a GIS-based landslide dynamics simulation model that employs a combined rigid body motion theory and fluid theory strategy to account for block size heterogeneity. This model can accurately and efficiently calculate the landslide area, velocity, and block size distribution [99]. A statistical debris flow simulation model (Debris Flow Analyst model) was proposed, in which the intrinsic stochasticity in debris flow movement is represented using stochastic differential equations (SDEs) [100]. In comparison to a conventional approach, the proposed numerical method integrated an uncertainty assessment mechanism into the GIS platform via multiple simulations. However, GIS cannot correctly and precisely represent the geometry and attribute information of the architectural components. The integration of BIM data allows GIS to achieve refined management of interior and outdoor integration.

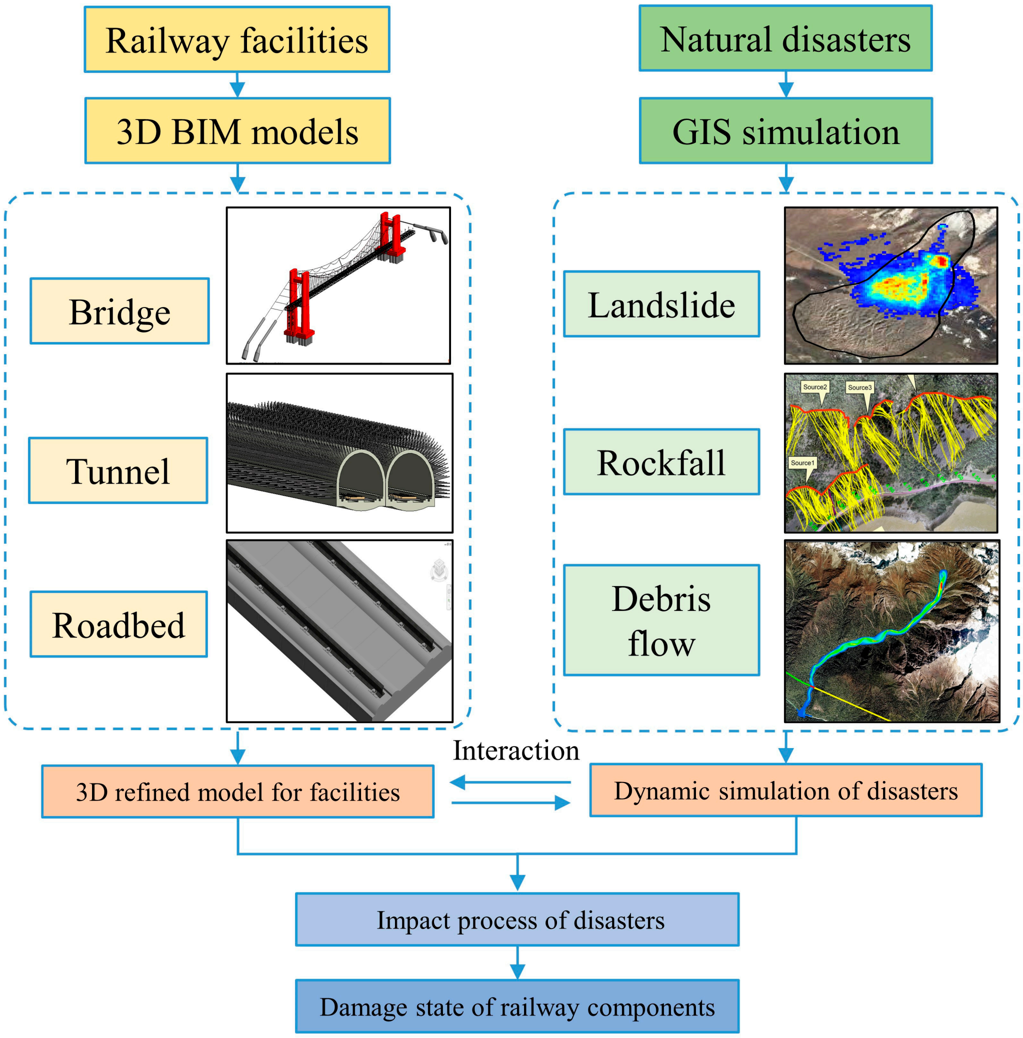


Figure 5. Integration of BIM+GIS for analyzing the interaction between railway facilities and disasters.

Table 3 lists the different concerns in the field of engineering facility modeling, while Figure 5 shows the characteristics of BIM and GIS. The integration of GIS and BIM can make up for the shortcomings of GIS, such as the incomplete presentation of single-model details. At the same time, it will compensate for shortcomings of BIM such as the effect of the surrounding macro geographical environment not being considered.

There have been some research attempts to utilize BIM+GIS-related technologies to assess the risk encountered by infrastructure during construction, operation, and maintenance. An integrated 3D BIM–geology interaction system was proposed that can account for the environmental impacts of new infrastructure construction [101]. The fundamental engineering characteristics (e.g., building geometry and properties) were extracted from the BIM framework. The georeferenced 3D shallow subsurface model was developed using Digital Elevation Model (DEM) data, which are important in GIS. BIM and 3DGIS technologies were applied to site monitoring and risk management of deep excavation [40]. A BIM–3DGIS framework was utilized to establish and display 3D models of the supporting structures and surrounding environments in deep excavation. The BIM–GIS framework has also interacted with a web risk management platform to support risk protection decision-making. An integration of BIM and GIS techniques was utilized to mitigate the hazards of metro system flooding [39]. A spreading algorithm was proposed and applied to GIS to obtain the geographical distribution of the depth and range of flooding. Meanwhile, BIM was used to design and establish refined models of metro stations, which will create a visual representation of a subterranean region. The BIM+GIS framework was integrated with the AHP method to quantify the flood risks in the metro system. An integrated framework coupling comprehensive 3D building models (BIM) with 3D visualization of flood damage to buildings (GIS) based on their different flood behavior has been proposed [38]. This framework could assess damage details quantitatively by utilizing costs as well as information about where and why the damage occurred with an analysis of flood damage to the structures and components.

Table 3. The difference between BIM and GIS in the field of engineering facilities.

Function	BIM	GIS
3D display	Refined 3D model of buildings.	3D expression of geospatial information.
Coordinate system	The coordinate system is centered on the buildings without the concept of geographic or projected coordinate systems.	GIS can locate the 3D model in the real geographical environment with the geographic or projected coordinate systems.
Spatial relationship	BIM provides geometry and semantic information on facility components and the logical spatial relationships that exist between each component.	The location or spatial information data's collection, storage, and management are the main components of GIS. GIS cannot represent the geometrical and semantic information of each building's element.
Spatial analysis	The length, area, and volume measurement and clash detection of building components.	Buffer analysis and other geospatial analysis for both raster and vector data.
Construction spatial planning	Mostly used in building indoor planning analysis.	Mostly used in planning and geospatial analysis for outdoor areas.

5.3. Integration of BIM+GIS with New Technology for Considering Coupled Responses of Railway Components to Disasters

The main focus of QRA is on the induced effects of infrastructure system component failure [102]. The effects include not just physically damaged parts but also other components that are no longer functioning effectively as a result of the impact of damaged parts. Spatially localized failures (SLFs) are described as the failures of a group of infrastructure components spread across a spatially limited region as a result of damage suffered, while other components outside the zone do not fail directly as a result [103]. Traditional risk assessments frequently fail to take into account the relationships between engineering facility components. Each risk assessment consumes a lot of computational resources. The structural components of engineering facilities are susceptible to varied risks, while the interactions between the various structural components differ. This requires the development of a new technological system capable of automatically obtaining information on the properties of each component following changes in the surrounding environment, such as changes in material properties, physical functions, and new risks to each component after a disaster occurs. New technologies can be applied to the management system of BIM+GIS for coupled responses of railway components to disasters (Figure 6). Based on sensing, recognition, and communication technologies, the Internet of Things (IoT) was regarded as an ideal emerging technology to collect information on numerous indicators in the natural environment or infrastructure system [104]. This real-time collection of information on the operating status of components can not only reflect the extent of damage caused by natural disasters, but also determine which components need to be overhauled in short order, effectively reducing the negative consequences caused by human error. BIM combined with real-time monitoring data from IoT sensors is a powerful framework to make construction and operation more efficient. BIM, GIS, and many kinds of IoT devices can be useful tools in emergency response for disaster risk management [105].

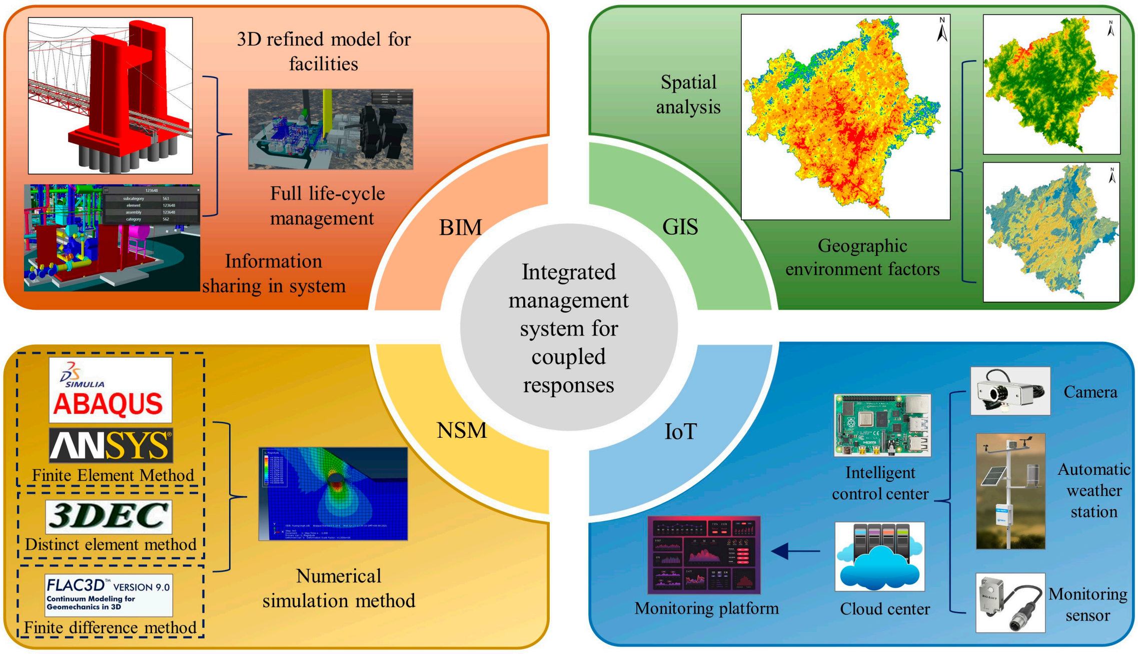


Figure 6. Interaction of BIM+GIS with new technologies for coupled responses of railway components to disasters.

In consideration of the interdependencies between networked infrastructure systems, a BIM, GIS, and domain-specific computational engine (DCE) integrated approach was proposed to assess the vulnerability of infrastructures [106]. This BIM–GIS–DEC framework was validated using the case of a building transportation net in an urban flood. The building information was extracted from the BIM model, and the domain-specific function of infrastructures during a disaster was simulated using DCEs. At the same time, the risk effects caused by interdependencies may be recorded and visualized on a GIS platform. These three technical tools work together to characterize both the vulnerabilities caused directly by a hazard occurring in one system and the downstream repercussions propagating from other interconnected systems. Even though BIM provides outstanding 3D visual modeling, it lacks a structural computation capacity for the engineering domain [107]. Based on computer technology, numerical simulation methods (NSMs) can produce simulation analysis results that satisfy the engineering requirements. One of the trendiest concerns right now is how to supplement and enhance BIM with other technologies to meet diverse professional domains [108,109]. The combination of BIM's high-precision modeling capabilities, GIS's ability to evaluate environmental factors, and numerical simulation's powerful computation capability for complex structures will be incredibly helpful in engineering disaster risk analysis and management. A methodology applied to road engineering for an integrated 3D BIM model with numerical simulation for structural analysis was proposed [110]. It reinforced BIM with a structural computation capacity using the interface of ABAQUS, which offers substantial technical assistance and effectiveness for spatial design.

6. Conclusions

This paper reviewed different disaster risk assessments adopted in railway engineering construction, owing to the complicated physical and functional characteristics of its facilities, multiple hazards surrounding their construction, and interdependencies between infrastructure and components. Moreover, the summarization of risk assessments focusing on railway bridges, tunnels, and roadbeds is a crucial factor that should be considered when estimating QRA based on new technologies. The investigation into risk assessment approaches for railway infrastructure reveals that previous research methodologies, such as AHP, fuzzy set theory, and so on, provided subjective conclusions due to their reliance on expert assessment. Furthermore, because most QRA applications do not focus on the evaluation of economic losses or casualties, the QRA results are unable to provide accurate and sustainable disaster risk prevention strategies throughout railway construction development, operation, and maintenance. Based on an overview of disaster risk assessment for major railway facilities (e.g., bridges, tunnels, and roadbeds), this paper highlights the limitations of previous studies and presents three significant challenges for the practical application of TQRA, which are (1) the refined structural modeling of railway facilities, (2) the quantifications of interactions between disasters and railway facilities, and (3) the considerations of coupled responses to disasters of components of railway facilities. These issues severely limit the implementation of TQRA in railway construction and make achieving a refined and accurate disaster risk assessment for railway facilities problematic. Therefore, it is urgent to establish a highly effective and refined QRA approach based on new technology, which will reduce the damage of hazards and allow scientific research on disaster prevention measures.

The QRA proposed in this research, which is based on BIM+GIS technology, can increase the accuracy of railway system risk assessment. This study elaborates on the benefits of BIM+GIS technology in QRA for railway engineering from three perspectives: a refined digital 3D model, interactive simulation of railway facilities and disasters, and compatibility with other relevant new technologies. The QRA results are generated from objective criteria such as changes in the surrounding environment of engineering facilities and their functioning state. From a sustainable design perspective, this approach increases railway projects' capacity to safeguard against natural disasters.

Despite BIM+GIS technology being the current technological development trend for the AEC industry, certain issues should still be addressed. The present cost of digital 3D modeling visualization is expensive, including the precise data required for modeling, labor cost, software and hardware equipment expenditures required for modeling, and so on. In the future, lightweight and practical modeling approaches may be developed. Dynamic monitoring on the status of the surrounding environment and the inside system may be dependent on the IoT. Computer numerical simulation techniques may be employed in analytical computations for complicated structural facilities. Nevertheless, BIM+GIS technology presently lacks a unified interface technique and rules with these new technologies. Future work will concentrate on improving BIM+GIS compatibility with other innovative technologies.

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Abbreviations

AEC	Architecture, Engineering, and Construction
AHP	Analytic Hierarchy Process
BIM	Building Information Modeling
DCEs	Domain-Specific Computational Engines
DEM	Digital Elevation Model
FAHP	Fuzzy Analytic Hierarchy Process
FID	Fractional Incapacitation Dose
FN curve	Frequency/Number of Casualties Curve
GIS	Geographic Information System
HRBF	Hermite Radial Basis Function
IOT	Internet of Things
LA	Landslide Analyst
LOD	Level of Detail/Development
NBIMS-US	US National Building Information Modeling Standard
NSM	Numerical Simulation Method
NTQRA	Not True Quantitative Risk Assessment
QRA	Quantitative Risk Assessments
SDEs	Stochastic Differential Equations
SLFs	Spatially Localized Failures
TFN	Triangular Fuzzy Number
TQRA	True Quantitative Risk Assessment
UNDHA	United Nations Department of Humanitarian Affairs

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