Dynamic Network Analysis of the Risks of Mega Infrastructure Projects from a Sustainable Development Perspective

Li, Y.; Xiang, Pengcheng; You, Kairui; Guo, Jin

DOI
10.3390/buildings12040434

Publication date
2022

Document Version
Final published version

Published in
Buildings

Citation (APA)
Li, Y., Xiang, P., You, K., & Guo, J. (2022). Dynamic Network Analysis of the Risks of Mega Infrastructure Projects from a Sustainable Development Perspective. *Buildings*, *12*(4), Article 434. https://doi.org/10.3390/buildings12040434

buildings

Article

Dynamic Network Analysis of the Risks of Mega Infrastructure Projects from a Sustainable Development Perspective

Yuanli Li [1,2,*], Pengcheng Xiang [1,3,4], Kairui You [1] and Jin Guo [1]

[1] School of Management Science and Real Estate, Chongqing University, Chongqing 400044, China; pcxiang@cqu.edu.cn (P.X.); youkairui@cqu.edu.cn (K.Y.); guojeen@cqu.edu.cn (J.G.)
[2] Faculty of Architecture and The Built Environment, Delft University of Technology, 2628BL Delft, The Netherlands
[3] International Research Center Sustainable Built Environment, Chongqing University, Chongqing 400045, China
[4] Construction Economics and Management Research Center, Chongqing University, Chongqing 400045, China
* Correspondence: y.li-37@tudelft.nl

Abstract: Mega infrastructure projects (MIPs) are exposed to numerous interdependent risks of various natures which pose difficulties in risk management. Thus far, the research on the risk interactions of MIPs has been focused on developing static risk networks within a single category of risks, at certain stages of the project. It is essential to understand the risk interactions at various stages of MIPs to identify the key risks and key risk relationships that jeopardise their success. This is especially relevant nowadays, as MIPs are expected to be delivered sustainably. Therefore, to analyse the dynamic risk interaction of MIPs, initially, through literature analysis and expert interviews, combined with the four dimensions of sustainable development and the four stages of MIPs, 98 risk factors of MIPs were identified. Subsequently, semi-structured interviews were conducted to determine risk relationships and weights. Risk networks were developed for each stage of MIPs, and improved social network analysis was applied to these risk networks. Finally, the key risks and key risk relationships in each stage of MIPs were identified by analysing the changes of multi-level network indicators. This aided in determining risk control strategies. The results demonstrate that the key risks and key risk relationships are different for each stage of MIPs. Furthermore, the risks of different dimensions of sustainable development have different relationships at different stages. This research is the first to identify the risk relationships involved in MIPs by taking into consideration the whole project life cycle and its sustainable development. This research provides theoretical support for the risk management of MIPs, and strategic suggestions for controlling the risks at each stage of the project.

Keywords: mega infrastructure projects; sustainable development; risk interaction; dynamic network analysis; life cycle

check for updates

Citation: Li, Y.; Xiang, P.; You, K.; Guo, J. Dynamic Network Analysis of the Risks of Mega Infrastructure Projects from a Sustainable Development Perspective. *Buildings* **2022**, *12*, 434. https://doi.org/10.3390/buildings12040434

Academic Editor: Syed M. Ahmed

Received: 18 February 2022
Accepted: 30 March 2022
Published: 1 April 2022

1. Introduction

Mega infrastructure projects (MIPs) refer to large-scale public engineering projects with funds exceeding USD 1 billion, usually commissioned by the government and delivered by capable private contractors and suppliers, which provide basic public services for social production and residents' lives [1]. MIPs are usually in the transportation, water conservation, telecommunication, power generation, and other such sectors that significantly affect national politics, economy, national security, public health, environmental protection, and society [2]. In contrast with small or medium-sized infrastructure projects, MIPs have a larger investment scale, longer implementation period, complex uncertain factors, and numerous stakeholders [3]. MIPs involve many potential risks, which are multidimensional and interrelated [4]. Risk interaction may lead to abnormal risk propagation, due to which the occurrence probability and negative impacts of risks are amplified, significantly jeopardizing the project objectives [5]. Failure to adequately analyse these complex relationships results in poor risk assessments, ineffective risk mitigation initiatives and strategies [6]. Therefore, it is important to explore the interaction of risks to ensure the successful risk management of MIPs.

Many scholars agree that considering risk interactions is crucial when studying risk management for MIPs, and have carried out a series of relevant studies [4,7,8]. For example, Chang et al. determined the interrelationship between political risk factors for international high-speed rail projects, to enable international contractors to better understand the political risks of projects [9]. Lu and Zhang identified the key safety risk factors during the construction stage of subways and drew relationships between the subway construction safety risk factors, which are conducive to reasonable risk management by the government and managers [10]. Chen et al. examined the diversity and interdependence of construction schedule risks and generated more reliable risk identification and risk inferences [11]. Etemadinia and Tavakolan analysed the risks and risks relationships in the design stage of construction projects and identified the key risks that have a greater impact on project goals [12]. While research on risk interactions has received some attention, most studies have focused on the development of static risk networks that only consider certain phases of MIPs and a single category of risk factors.

However, few studies have examined the dynamics of risk interactions over the life cycle of MIP, and considered risk interactions among different categories. The risks of MIPs dynamically evolve throughout the project life cycle, with not only changes in the risk factors at each stage, but also in the means and intensity of interactions between risks [13]. When the risk interaction changes drastically, the accuracy of the static risk network analysis decreases, underestimating the importance of some nodes. This is because in a static network, important nodes at a certain time seem to be less important [14]. Furthermore, the effectiveness of risk control strategies proposed for key risks is greatly reduced. Therefore, it is necessary to transform the aggregated static risk network into a dynamic analysis of the risk network in different stages to determine the key risks.

Moreover, MIPs involve a variety of risks, including not only cost, schedule, and quality risks, but also social, economic and environmental risks associated with the project [1]. Hence, it is imperative that sustainable development is addressed as a core issue in MIPs risk management. To achieve sustainable project delivery, economic losses, environmental issues, and social disputes cannot be handled separately [15]. For example, large-scale hydropower infrastructure projects reduce energy consumption and bring huge economic benefits. However, some of these projects have caused serious environmental degradation and ecological disasters. This has intensified confrontations between the public, enterprises, and the government. Tao et al. argue that the interrelationship between different risk categories increases the complexity of the risk system [16]. Hence, it is necessary and challenging to integrate multiple dimensions of sustainable development to conduct MIPs risk interaction research.

This study aims to analyse the dynamic changes of risk interaction from different dimensions of sustainable development and different stages of the life cycle of MIPs. It expands the research perspective of MIPs risk interaction and makes up for the lack of consideration given to the dynamic characteristics and complexity of risks in the literature. This study uses the improved social network analysis (SNA) to calculate and analyse the dynamic changes in the multi-level network indicators for the established multi-stage risk network, and determine the key risks and risk relationships at each stage. This can help stakeholders develop risk response strategies to significantly reduce the complexity of risk networks to prevent or minimize adverse impacts and create more stable and sustainable projects.

Following this analysis in Section 1, the remainder of this paper is organised as follows: a brief overview of the relevant literature is presented in Section 2, and Section 3 describes the research process, lists the risks, and proposes an improved SNA approach. The results of the dynamic network analysis are presented in Section 4. The proposed risk management strategies and the risk network simulation are presented in Section 5, and the conclusion with future research suggestions in Section 6.

2. Literature Review

2.1. Risks of MIPs

The Project Management Institution defines risk as an uncertain event or condition, and the occurrence of risks will have a positive or negative effect on project goals [17]. Most of the existing studies on MIPs' risks constrain the project objectives to cost, schedule, and quality [18]. Thamhain believes that it is necessary to manage MIPs to exceed a simple analysis of costs and schedules and try to understand the real cause of any uncertainty [19]. Sustainable development makes project risk management abandon the traditional goals (cost, schedule, and quality), and it is particularly crucial for construction projects [20]. Some scholars have studied the risks of MIPs from a sustainable development perspective, but most of the research only considered a single dimension of sustainable development. Yuan et al. used a questionnaire survey to determine the social risks of the transportation public–private partnership project, and proposed corresponding risk control measures to cope with negative social effects [21]. Malik et al. collected data from 156 different construction companies to study the link between environmental issues and project performance to reduce environmental risks [22]. There is no overall analysis of risks in all sustainable development dimensions.

In practice, balancing the three pillars of sustainable development is necessary [21]. Some studies assessing the sustainability performance of infrastructure have proposed other dimensions, such as transformational change and political system dimension [23], or integrated managerial infrastructure sustainability [24]. Some international organisations published regional infrastructure sustainability rating systems and considered additional dimensions, including the 'IS Rating' program initiated by the Infrastructure Sustainability Council of Australia [25], the Envision system organised by the Institute for Sustainable Infrastructure [26], and the institutional dimension proposed by the Inter-American Development Bank [27]. However, the importance of balancing the iron triangle of sustainable development has been underestimated in risk management research on MIPs [28]. Li et al. emphasised that coordinating the relationship between stakeholders and unifying their motives, goals, attitudes, and actions can avoid unnecessary disputes, thereby synergistically promoting the sustainability of the project in three aspects [29]. Therefore, when conducting risk management research on the sustainable development of MIPs, it is crucial to include the coordination dimension to examine the potential risks that may lead to an imbalance in the three pillars.

This article draws on Li et al. definition of MIPs' risks from a sustainable development perspective [29]. That is, the risks of MIPs are factors that have a negative effect on the achievement of the goals of economic sustainability, social sustainability, environmental sustainability, and the coordination sustainability of projects.

2.2. Analysis of MIPs' Risk Relationship

Over the past decade, different methods of analysing risk relationships for MIPs have been proposed and investigated, such as the Monte Carlo simulation [11], analytic network process [30], structural equation modelling [9], interpretative structural modelling [12], fuzzy analytic network process [31], fuzzy interpretive structural modelling [32], Bayesian belief network [33], and SNA [5]. Compared with the above methods, SNA is more suitable for representing the risk relationship network. It can check and determine risk interrelationships, visualise the structure of risk relationships, and use the network characteristics of nodes and links to quantify the risks and the risk relationship [34].

Although SNA has been widely used to study the risk relationship of MIPs [5,35,36], limitations still exist. An increasing number of SNA applications have calculated indicators based on link weight, but there are few studies that consider both the link weight and number. Most scholars have realised that the relationship between risks may be different in strength, so they assign different weights to links in the risk network [35]. However, for some network indicators such as degree and betweenness centrality, a calculation using only the weight or number of links cannot accurately reflect the true importance of the risk or the risk relationships [37]. Therefore, SNA indicators can be improved by determining the weighted value of the total weight of, and the number of, risk links.

In summary, through a literature review, it was found that the trend of papers within the subject area has shifted from traditional risk studies to risk studies integrating sustainable development goals, and finally, to risk relationship studies. Nevertheless, there are still some limitations that hinder risk prediction. According to the improved SNA, this study solves the complex dynamics of MIP risks and provides new opportunities for the risk management of MIPs.

3. Methods and Data

3.1. Research Process

The purpose of this study is to conduct a dynamic, quantitative, and visual understanding of the risk interrelationships at different stages of MIPs, and to formulate a reasonable and effective risk response strategy for the project. The research framework includes four steps: (1) risk identification of MIPs at each stage through a literature review and semi-structured interviews; (2) risk interaction relationship quantification and risk network establishment through a literature review and expert interviews; (3) risk network analysis in the life cycle of MIPs through improved SNA; and (4) formulation of risk mitigation strategies. The research framework is illustrated in Figure 1.

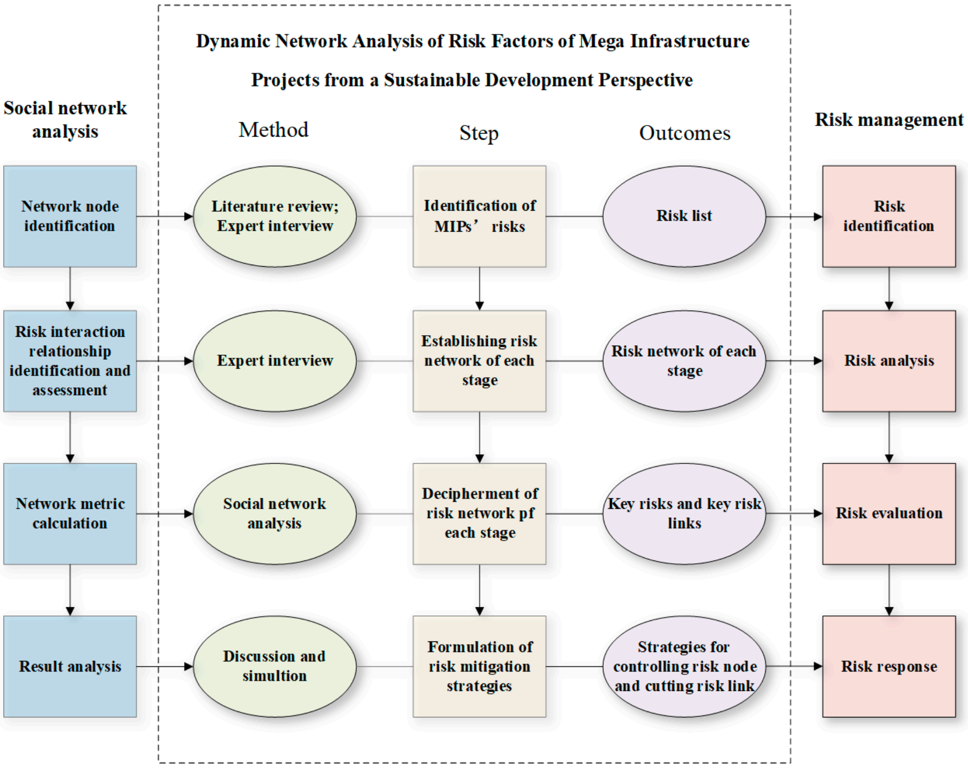

Figure 1. Main research framework.

3.2. Step 1: Identify MIPs' Risks

First, the literature relevant to the study was selected based on two principles, namely, (1) publications focused on the sustainable development of MIPs, and (2) publications must be accessible to a wide international audience. These two principles were used for avoiding articles that focussed only on specific areas. The keywords used to search for the literature included 'mega infrastructure project', 'sustainable development', and 'mega infrastructure project risk'. The search yielded 34 key publications. The Nvivo software package (QSR International, Burlington, MA, USA) was used to analyse the content of the publications to identify the risks encountered throughout the lifecycles of MIPs. The content analysis involved three processes, namely, (1) the open code process that identified 103 risks and 127 initial sentences related to the sustainable development of MIPs, (2) classification of the above items under four identified dimensions and four stages, and (3) summarising and comparing the risks and sentences and combining those with similar meaning to reduce the number of risks in the list to 96.

Second, to refine the preliminary list of risks to ensure that all risks are reasonable and understandable, thirteen experts were invited to be interviewed through phone calls or via email. Of these, eight experts were consented to be interviewed. Despite the small sample size, the findings are important, as these experts hold senior positions in their respective organizations and have an average of 14,375 years of practical or research experience in the MIP field (Table 1). Therefore, these experts were able to provide insights that offered meaningful contributions.

Table 1. Information about experts.

ID	Experience (Year)	Role	Organisation	Participation Stages
Expert 1	12	Scholar	University	Decision-making, Design, Construction, Operation stages
Expert 2	19	Project participant	Construction contractor	Construction, Operation stages
Expert 3	15	Project participant	Operator	Construction, Operation stages
Expert 4	19	Project participant	Designer	Design
Expert 5	20	Project participant	Construction contractor	Design, Construction, Operation stages
Expert 6	10	Government	Government	Decision-making, Construction, Operation stages
Expert 7	11	Scholar	University	Decision-making, Design, Construction, Operation stages
Expert 8	9	Scholar	University	Decision-making, Design, Construction, Operation stages

Furthermore, the experts have rich work experience and knowledge covering the life cycles of MIPs: a government officer from Chongqing Commission of Housing and Urban-Rural Development participated in the decision-making, construction, and operation stages of multiple MIPs; a designer from China Southwest Architectural Design and Research Institute has served as the chief designer of an MIP; two construction contractors from China State Construction International Investments Limited, one of whom has worked with a consulting company, a design company, and a contractor company, participating in the design, construction, and operation stages of MIPs; an operator from Hong Kong-Zhuhai-Macao Bridge Authority participated in the construction, operation, and maintenance of the main part of the bridge; three university professors have research experience on the risk management process encompassing the complete life cycle of MIPs. Such expansive experience assures the reliability of the experts' feedback for the study.

The experts were interviewed between 14 July 2021 and 23 August 2021 and their voices were recorded. The interviewees were asked three main questions: (1) Is the preliminary risks list complete? Is there anything more to add? (2) Are the risks correctly classified by the stages of MIPs and dimensions of risks? (3) Is the risk description ambiguous? The interviews resulted in the following revisions: (1) added one risk ('delayed approval') under the decision-making stage and two risks ('difficult financing' and 'designing cost overrun') under the design stage; (2) one risk ('seawater corrosion') was removed because seawater corrosion is not a common problem for all MIPs; and (3) according to engineering terminology, experts suggested that we change the nomenclature 'labour, materials, and equipment cost overruns' to 'construction and installation cost overruns'. The final list of risks is presented in Table 2.

Table 2. Risk list of MIPs.

Dimension	**Risk**	**MIP Life Cycle**			
		Decision-Making Stage	**Design Stage**	**Construction Stage**	**Operation Stage**
Economy	Wrong market demand forecasts (overrate)	EC1R1			
	Negative effect on the local industrial structure (tourism, agriculture, etc.)	EC1R2			
	Negative effect on the spatial layout of local industries	EC1R3			
	Costs caused by disputes with the community	EC1R4			
	Delay in project approval	EC1R5			
	Technical feasibility decision failure	EC1R6			
	Difficult financing		EC2R1		
	Misestimate in time and cost		EC2R2		
	Design deficiency		EC2R3		
	Land acquisition and resettling cost overruns		EC2R4		
	Designing cost overrun		EC2R5		
	Construction and installation cost overruns			EC3R1	
	Construction delay			EC3R2	
	Substandard quality			EC3R3	
	Disposal of construction waste cost overruns			EC3R4	
	Negative effect on local enterprises			EC3R5	
	Compensate for not meeting the Sustainable Development Goals			EC3R6	
	Ecological remediation cost overruns				EC4R1
	Devaluation of residents' assets (decrease in residents' income)				EC4R2
	Operation and maintain cost overruns				EC4R3
	Weak solvency ability				EC4R4
	Weak contribution on local economy				EC4R5
Society	Opaque project information (Closed design information)	SO1R1	SO2R5		
	Damages on participation of local residents and community	SO1R2	SO2R6	SO3R11	SO4R4
	Excessive government intervention	SO1R3	SO2R4	SO3R3	
	Bribery and corruption	SO1R4	SO2R7	SO3R2	
	Opportunism decision making	SO1R5			
	Damages on connectivity among communities	SO1R6			
	Difficulty of coordinating interest demand	SO1R7			
	Unreasonable resettlement		SO2R1		
	Non-matching with local culture		SO2R2		
	No access of the disabled		SO2R3		
	Damages of cultural heritage			SO3R1	
	Construction safety and accidents			SO3R4	
	Damages on employees' health			SO3R5	
	Damages on residents' safety (personal or property)			SO3R6	SO4R1
	Damages on residents' health			SO3R7	SO4R2
	Negative effect on employment(unemployment, underutilisation of local labour force)			SO3R8	SO4R6
	Negative impact on residents' life quality			SO3R9	SO4R8
	Inadequate facilities surrounding the projects			SO3R10	SO4R7
	Discoordination between contractor and public			SO3R12	
	Widen the gap between rich and poor				SO4R3
	No access to public resources to local residents				SO4R5

Table 2. *Cont.*

Dimension	Risk	MIP Life Cycle			
		Decision-Making Stage	Design Stage	Construction Stage	Operation Stage
Environment	Inadequate environmental effect assessment	EN1R1			
	Lack of environmental protection measures		EN2R1		
	Non-matching with natural environment		EN2R2		
	Air pollutant (greenhouse gases, toxic gases, dust)			EN3R1	EN4R1
	Water pollution			EN3R2	EN4R2
	Lights pollution			EN3R3	EN4R4
	Noises pollution			EN3R4	EN4R3
	Construction waste pollution (solid waste pollution)			EN3R5	
	Usage of not environmental-friendly construction materials			EN3R6	
	Overuse of construction materials			EN3R7	
	Overuse of energy			EN3R8	EN4R5
	Excessive consumption of non-renewable energy			EN3R9	EN4R6
	Soil health degradation (salinization, swamping, etc.)			EN3R10	
	Damages to natural heritage			EN3R11	
	Damages to the ecological balance			EN3R12	EN4R7
	Causing geological hazards (landslide, collapse, slope instability, soil erosion, etc.)			EN3R13	
	Occupy a lot of non-construction land (green land, agricultural land, animal habitat)			EN3R14	
Coordination	Unsatisfying national or local legislation	CO1R1			
	Decision-making mechanisms not involving all stakeholders	CO1R2			
	Weak and opaque decision-making process	CO1R3			
	Ambiguous responsibility and right sharing clauses		CO2R1		
	Inadequate investment and source sharing clauses		CO2R2		
	Lack of sustainable clauses in contract		CO2R3		
	Ambiguous sustainable management program		CO2R4		
	Lack of organisation culture on sustainability		CO2R5		
	Incomplete communication and coordination procedures		CO2R6		
	Inadequate communication and coordination among stakeholders			CO3R1	
	Non-complementary employee ability			CO3R2	
	Weak sustainability awareness			CO3R3	
	Inadequate experience			CO3R4	
	Team conflict(non-cooperation)			CO3R5	
	Unclear maintenance subjects of project sustainability				CO4R1
	Unclear monitor system of project sustainability				CO4R2
	Unclear monitor and maintenance organization of project sustainability				CO4R3
	Weak monitor and maintenance platform of project sustainability				CO4R4

3.3. Step 2: Establish Risk Network

The essential purpose of determining the risk network at each stage was to obtain the data on risk relationships. For this, two steps were taken. The first was to determine if a relationship between a pair of risks existed. The dualism, in this case, is expressed as, if risk i leads to the occurrence of risk j, the risk link $a_{i,j}$ equals 1, otherwise 0. On 2 September 2021, eight experts attended a brainstorming meeting to determine the relationships among the risks in the list of risks. In the first round of brainstorming, the eight experts gave their evaluations anonymously. In the second round, all experts met to discuss the risk relationships wherein their opinions differed and conducted a second risk relationship data evaluation. For this evaluation, it was decided that for a risk relationship to be accepted, it must have the acceptance of no fewer than five out of the eight experts. In the third round, if the evaluation results reached by the experts closely resembled the results obtained in the previous round, the brainstorming session was closed as the final binary directed adjacency risk matrix (*BDARM*, Equation (1)) was established.

$$BDARM = a_{i,j} \tag{1}$$

Next, the weight ($w_{i,j},$) for the risk interaction relationship ($a_{i,j}$) was determined to be 1. A Likert scale was used to quantify weights as follows: insignificant (1), mild (2), moderate (3), significant (4), and severe (5). On 7 September 2021, to determine the weight of risk interaction relationships, an independent validation focus group of the previous eight experts was formed. In the first round, the experts assessed the weight of risk interaction relationships anonymously. In the second round, the experts discussed the weights of risk interaction relationships and reached the preliminary evaluation results, and revisions were made. For example, in the design stage, three experts thought opaque project information (closed design information) had a weak effect (less than three) regarding bribery and corruption as a threat to the implementation of MIP. However, other experts described their experiences to assert that the risk link should be stronger. Therefore, the weightage of the link was unanimously raised to 4. At the end of the multi-round feedback, all experts agreed upon the effects of all risk links, and the final Weighted Risk Matrix (*WRM*; Equation (2)) was developed.

$$WRM = w_{i,j} \tag{2}$$

The input node code and edge data were entered into Gephi network analysis software. The above 98 risks and quantitative risk interaction relationships were modelled into four visual risk networks that covered the entire project lifecycle.

3.4. Step 3: Network Analysis

To find the law of MIPs' risk interaction evolution and formulate corresponding risk mitigation strategies, the following aspects of risk networks were analysed—the change of the network level, node/line level, group-level network metrics including network density (ND), node degree (NDE), the ratio of reachability to geo-distance (RRGD), node betweenness centrality (NBC), link betweenness centrality (LBC), direct inter-group interaction (DIGI), and global inter-group interaction (GIGI). Opsahl et al. indicated that the number and weights of risk links need to be considered together, and accomplished this focus using tuning parameter α [37]. To balance the number and weights of risk links, Wang et al. suggested that α be set to 0.5 [38]. Based on the above studies, Table 3 gives the improved formulae of these network metrics.

The seven metrics reflect the key risks and links in the risk network at each stage of a MIP. Network density indicates the overall network connectivity, calculated by the proportion of existing links to the maximum number of possible links. It lies between 0 and 1. NDE has two metrics—out-degree and in-degree. The out-degree indicates the direct effect of a node on its neighbouring nodes; the in-degree indicates the direct effect of a neighbouring node on a selected node. NBC or LBC represents the power of risk or a link's control over the network as an intermediary. RRGD has two metrics: the RRGD-Out and RRGD-In. The RRGD-Out value represents the global impact of a risk on the network as a source, and is the sum of the reciprocal of reachability and geo-distance from risk i to another risk. The RRGD-In value represents the global impact of another risk on the source risk, and is the sum of reciprocal of reachability and geo-distance from another risk to risk i. Direct inter-group interaction (DIGI) reflects the direct effect of one risk group on another and is the number of links originating from group n to group m. Global inter-group interaction (GIGI) reflects the global effect of one risk group on another, and is the sum of links originating from the reciprocal of reachability and geo-distance from group n to group m.

Table 3. Network metric.

Level	Metric	Formula		Notation
Network	ND	$Density(G) = \frac{\sum_{i,j\in N} w_{i,j}}{w_{max}N(N-1)}$	(3)	w_{max}: the maximum weight of all links.
Node/Link	NDE	$Outdegreer(i)_\alpha = k_i^{out} \times \left(\frac{s_i^{out}}{k_i^{out}}\right)^\alpha$ $= \left(\sum_{j\in N} a_{i,j}\right)^{1-\alpha} \left(\sum_{j\in N} w_{i,j}\right)^\alpha$	(4)	k_i^{out}: the number of links originating from risk i. s_i^{out}: the total weight of the links originating from risk i.
		$Indegree(i)_\alpha = k_i^{in} \times \left(\frac{s_i^{in}}{k_i^{in}}\right)^\alpha$ $= \left(\sum_{j\in N} w_{j,i}\right)^{1-\alpha} \left(\sum_{j\in N} a_{j,i}\right)^\alpha$	(5)	k_i^{in}: number of links directly toward risk i. s_i^{out}: total weight of links directly toward risk i.
	NBC/LBC	$Between(i)_\alpha = \sum_{i,k,f\in N,\ i\neq k\neq f} \frac{g_{k,f}^{w\alpha}(i)}{g_{k,f}^{w\alpha}}$	(6)	$g_{k,f}^{w\alpha}$: the total number of shortest paths from risk k to risk f and $g_{k,f}^{w\alpha}(i)$ and $g_{k,f}^{w\alpha}(i \to j)$: the number of shortest paths that pass through risk i and link $i \to j$.
		$Between(i \to j)_\alpha = \sum_{i,j,k,f\in N,\ i\neq j\neq k\neq f} \frac{g_{k,f}^{w\alpha}(i\to j)}{g_{k,f}^{w\alpha}}$	(7)	
	RRGD	$RRGD_i^{in} = \sum\limits_{j\in N} \frac{1}{d^{w\alpha}(j,i)}$ $RRGD_i^{out} = \sum\limits_{j\in N} \frac{1}{d^{w\alpha}(i,j)}$	(8)	$d^{w\alpha}(i,j)$: the shortest paths from risk k to risk j. $d^{w\alpha}(i,j) = min\left[\left(\frac{1}{w_{ih}}\right)^\alpha + \ldots + \left(\frac{1}{w_{hj}}\right)^\alpha\right]$.
Group	DIGI	$DIGI_{n,m} = \left(\sum\limits_{i\in n,j\in m} a_{i,j}\right)^\alpha \times \left(\sum\limits_{i\in n,j\in m} w_{i,j}\right)^{1-\alpha}$	(9)	
	GIGI	$GIGI_{n,m} = \sum\limits_{i\in n,j\in m} \left(\frac{1}{d^{w\alpha}(i,j)}\right)$	(10)	

4. Results

4.1. Network Level Results

The risk network in the decision-making stage is connected by 17 risk nodes through 191 links; the design stage includes 20 risk nodes and 266 risk links, the construction stage includes 37 risk nodes and 644 risk links; the operation stage includes 24 risk nodes and 292 risk links. The four risk networks are visualised in Figure 2, where the colour and shape of the nodes represent the risk dimensions and project stages, respectively. For example, EC1R4→SO1R2 indicates that EC1R4 has an effect on SO1R2. Risk nodes with more risk links are located more centrally in the network, whereas risk nodes with fewer risk links are placed closer to the boundary of the network. At the decision-making stage, a large area of blue nodes occupies the centre of the network map, indicating that a large number of risks in this stage are linked to social risks. In the design stage, a large area of orange risk nodes occupies the centre of the risk network, indicating that interactions with coordination risks account for most of the existing links. In the construction stage, a large number of red and orange nodes are in the centre of the risk network, indicating that economic risk and coordination risk play the most important roles in the risk network. In the operation stage, orange nodes occupy the centre of the network map, indicating that coordination risks play the most important role in the risk network.

The density of a risk network reflects its complexity. A higher network density means greater and stronger risk links in the network, which implies that managers face more challenges in risk management [36]. Figure 2 shows the network density in the four stages of the MIPs. The network densities of the decision-making, design, construction, and operation stages are 0.2964, 0.2852, 0.1816, and 0.1986, respectively. First, compared with the overall risk network density (0.0308) of MIPs calculated by Fang et al. [4], the density at each stage of this study was relatively high, indicating a stronger risk interaction relationship and more complex risk network at each stage.

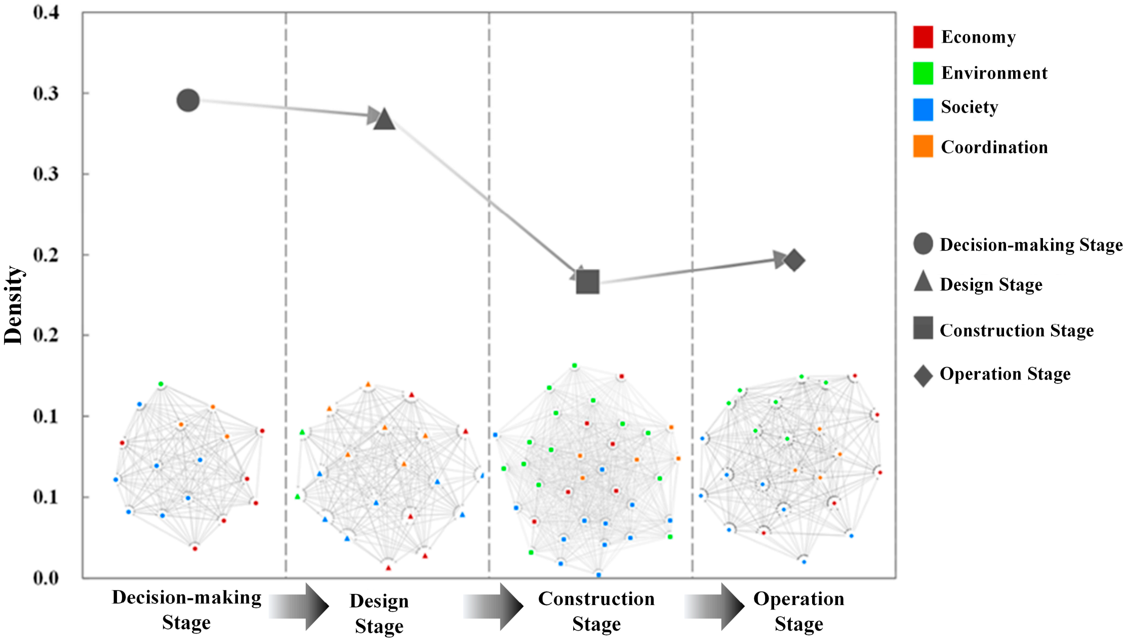

Figure 2. Four stage risk networks and the evolution of network density.

Second, the network density changes with the progress of MIPs, with a maximum in the decision-making stage and a minimum in the construction stage. This may be because, in the early stage, MIPs have relatively high uncertainty and involve fewer stakeholders, and risks spread faster among these few and close stakeholders. Although the construction stage has the most risk nodes and relatively few direct risk interaction relationships, all risks can be linked by indirect risk interaction relationships, which means that risk management in the construction stage is very complicated.

4.2. Node Level Results

4.2.1. NDE

The node degree reflects the degree of the relationship of the risk node with its direct neighbours in the network. Risks with low in-degree and high out-degree values may be source risks and have a greater direct effect on other risks. Risks with high in-degree and low out-degree values are regarded as cumulative risks because they have various sources and are more sensitive to the occurrence of other risks [4]. In this study, the top 40% of risk nodes at each stage sorted by in-degree are selected as in-degree key risks because 40% of the risk nodes have a larger in-degree than the mean of all in-degrees (21.4391). Similarly, the top 50% of the risk nodes at each stage sorted by out-degree are selected as out-degree key risks. Table 4 presents the in-degree and out-degree key risks at each stage.

At the decision-making stage, EC1R5 (delay in project approval) has the highest in-degree (25.6125); CO1R2 (decision-making mechanisms not involving all stakeholders) has the highest out-degree (30.5778). There are seven in-degree key risks, four of which are social risks. There are nine out-degree key risks, including six social risks. This demonstrates that, at the decision-making stage, social risks are not only susceptible to other risks, but can also affect other risks, that is, key hub risks, which are consistent with the results of network visualisation.

Table 4. In-degree key risks and out-degree key risks.

Stage	Decision-Making Stage		Design Stage		Construction Stage		Operation Stage	
	Code	Value	Code	Value	Code	Value	Code	Value
In-degree	EC1R5	25.6125	EC2R2	29.6648	EC3R1	51.4975	SO4R8	35.7211
	SO1R5	25.3969	SO2R7	27.8209	EC3R6	49.4874	EC4R5	28.5307
	CO1R1	23.2379	EC2R5	25.0799	SO3R12	47.7494	SO4R6	26.4953
	SO1R7	22.8035	SO2R2	25.0799	EC3R2	46.2493	EC4R2	25.7876
	EC1R4	20.3961	SO2R1	24.7992	SO3R9	45.8258	SO4R2	24.4949
	SO1R4	19.5959	EC2R1	22.9129	SO3R6	40.6448	SO4R5	24.2693
	SO1R2	18.1659	EC2R3	22.7596	SO3R2	40.0000	EC4R3	24.0000
			EC2R4	21.4942	SO3R7	39.5727	SO4R1	21.9089
					EC3R5	33.8231	EC4R1	21.6333
					EN3R12	30.5123	EN4R7	21.6333
					SO3R8	29.9500		
					SO3R11	29.6985		
					SO3R3	28.5307		
					SO3R5	28.1425		
					EN3R11	27.5681		
	Code	Value	Code	Value	Code	Value	Code	Value
Out-degree	CO1R2	30.5778	SO2R5	33.1663	CO3R3	64.0859	CO4R4	36.5240
	CO1R3	30.2985	CO2R6	31.7333	CO3R4	50.9117	CO4R2	32.4962
	SO1R1	26.2679	CO2R3	30.9839	CO3R2	45.9565	CO4R3	32.4962
	SO1R3	25.7488	CO2R4	30.9839	SO3R2	43.1277	SO4R4	32.1714
	SO1R4	24.0416	SO2R4	30.1993	CO3R5	36.7424	CO4R1	32.1248
	CO1R1	22.9129	CO2R5	29.3258	CO3R1	35.6651	EN4R7	22.2486
	SO1R5	22.2711	SO2R6	28.9828	EN3R1	33.6749	EN4R1	22.2261
	SO1R2	22.1359	SO2R7	28.9137	EN3R6	33.1663	EN4R2	22.2261
	SO1R7	20.1494	CO2R1	21.1660	EN3R2	32.7261	EN4R5	21.8174
			CO2R2	19.0788	EN3R9	31.4643	EN4R6	21.81742
					EN3R5	30.7571	SO4R7	16.6133
					EC3R3	29.9500	EN4R3	15.4919
					SO3R3	27.5681		
					EN3R13	27.1662		
					EN3R11	26.4953		
					EN3R4	26.0768		
					SO3R11	25.8070		
					EN3R10	25.7488		
					EN3R14	25.4165		

In the design stage, EC2R2 (misestimate in time and cost) has the highest in-degree, arriving by 29.6648; SO2R5 (opaque project information) has the highest out-degree, arriving by 33.1663. There are eight in-degree key risks, where economic risks account for five. There are six coordination risks and four social risks among the ten out-degree key risks. In the design stage, economic risks are more sensitive to other risks, and coordination risks are likely to have a greater effect on other risks.

In the construction stage, the highest in-degree (EC3R1, construction and installation cost overruns) was 51.4975, and the highest out-degree (CO3R3, weak sustainability awareness) was 64.0859. Among fifteen in-degree key risks, there are nine social risks. There are ten environmental risks out of nineteen out-degree key risks. At the construction stage, a large number of social risks are more likely to be directly affected by predecessors. In contrast, some environmental risks have a direct effect on successors.

At the operation stage, SO4R8 (negative impact on residents' life quality) and CO4R4 (weak monitor and maintenance platform of project sustainability) have the highest in-degree (35.7211) and the highest out-degree (36.5240), respectively. There are five social risks and four economic risks in ten in-degree key risks. Meanwhile, environmental risks and coordination risks account for six and four of the twelve out-degree key risks. At the operation stage, social and economic risks are more likely to be affected by other risks, and environmental and coordination risks are more likely to affect other risks.

Figure 3 shows a scatter plot of the out-degree and in-degree of 98 risk nodes in the MIPs' life cycle, and certain evolution trends are observed as the MIP progresses. First, in general, the average out-degree and in-degree of MIPs rise and then decline. The maximum out-degree (CO3R3; 64.0859) and in-degree (EC3R1; 51.4976) values of all risk nodes appear at the construction stage, indicating that the construction stage node degree is heterogeneously distributed in the network, and most risk nodes tend to be connected to a limited number of nodes.

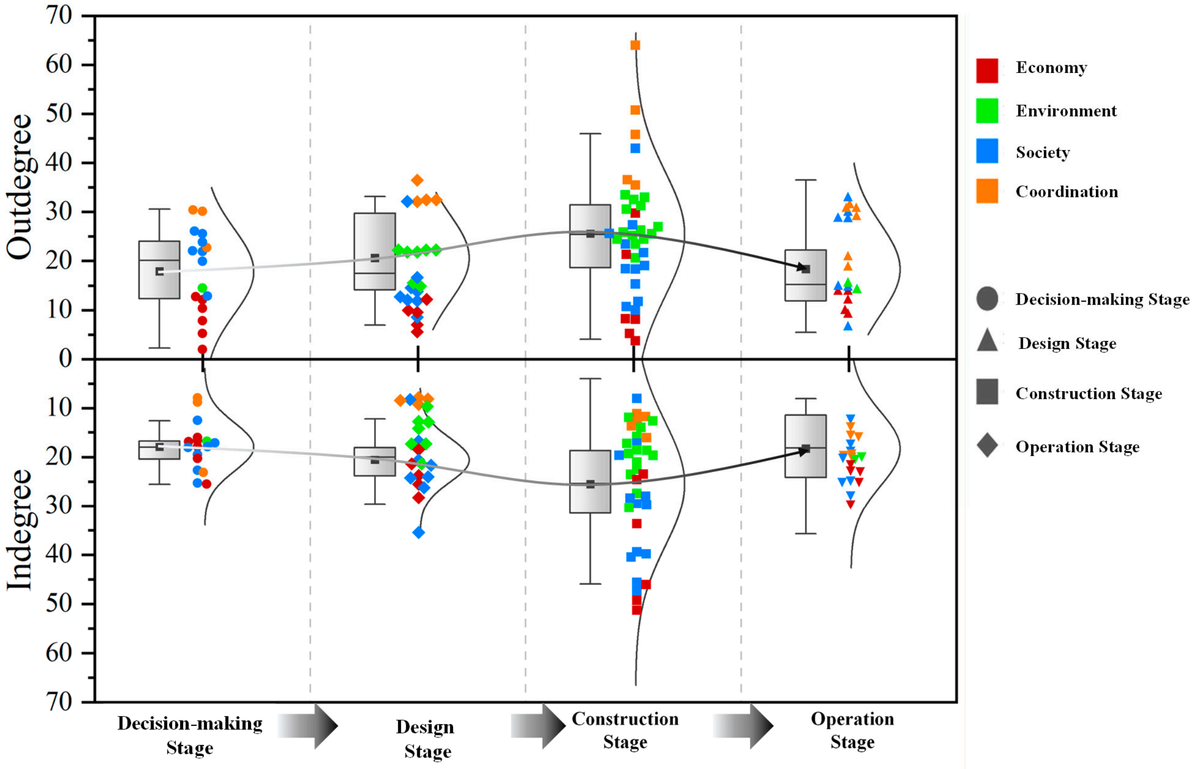

Figure 3. The evolution of out-degree and in-degree.

Second, the distribution of out-degree and in-degree of risk nodes of each dimension shows opposite trends in terms of importance. For example, in the four stages, economic risk has the lowest out-degree and the highest in-degree. This is consistent with the fact that, to offset the losses caused by the risks of other dimensions of sustainable development, MIPs usually need to pay greater economic costs, such as environmental restoration costs [39], construction delay costs, and resettlement compensation costs. Therefore, equal and comprehensive attention to the risks of the four sustainable development dimensions of MIPs is of great significance for reducing MIP costs.

4.2.2. RRGD

Unlike the node degree, which reflects the degree of relationship of the risk node with its direct neighbours in the network, RRGD reflects the global interactive relationship amongst risks in the network [38]. In this study, the top 40% of risk nodes at each stage sorted by RRGD-In were selected as RRGD-In key risks because 40% of the risk nodes have a larger RRGD-In than the mean of all RRGD-In (26.8024). Similarly, the top 45% of risk nodes at each stage sorted by RRGD-Out are selected as RRGD-Out key risks. Table 5 represents the RRGD-In key risks and RRGD-Out key risks at each stage.

Table 5. RRGD-In and RRGD-Out key risks.

Stage	Decision-Making Stage		Design Stage		Construction Stage		Operation Stage	
	Code	Value	Code	Value	Code	Value	Code	Value
RRGD-In	SO1R5	23.5597	EC2R2	26.8024	EC3R6	51.4976	SO4R8	33.7081
	EC1R5	23.3229	SO2R7	26.3228	SO3R12	49.4874	SO4R6	28.4022
	SO1R7	22.7525	SO2R1	26.1773	SO3R9	47.7493	SO4R2	28.0602
	CO1R1	21.0475	EC2R5	24.6650	EC3R1	46.2493	EC4R2	26.8667
	SO1R4	20.1544	EC2R3	24.6151	EC3R2	45.8258	EC4R5	26.5318
	EC1R4	19.4155	SO2R2	24.5475	SO3R6	40.6448	EN4R7	26.3771
	EC1R1	18.9989	EC2R1	23.9579	SO3R7	40.0000	SO4R1	25.5366
			CO2R3	23.4609	SO3R2	39.5727	EC4R3	25.4781
					SO3R11	33.8231	SO4R4	25.3722
					SO3R5	30.5123	EC4R1	24.7975
					EC3R5	29.9500		
					EN3R12	29.6985		
					SO3R8	28.5307		
					SO3R3	28.1425		
					EC3R3	35.0955		
	Code	Value	Code	Value	Code	Value	Code	Value
RRGD-Out	CO1R3	30.5778	SO2R5	30.1489	CO3R3	60.8803	CO4R4	34.2699
	CO1R2	30.2985	CO2R6	29.7060	CO3R4	48.0197	CO4R2	30.6223
	SO1R1	26.2679	SO2R4	28.2880	CO3R2	45.5057	SO4R4	29.8868
	SO1R3	25.7488	CO2R4	28.2665	SO3R2	45.4927	CO4R3	29.1920
	SO1R2	24.0416	CO2R3	27.9740	CO3R1	43.3313	CO4R1	28.8742
	CO1R1	22.9129	SO2R7	26.8024	CO3R5	41.9137	EN4R1	26.0308
	SO1R4	22.2711	CO2R5	26.0956	EN3R1	41.1415	EN4R2	26.0308
			SO2R6	25.8277	EN3R6	40.9073	EN4R5	25.3554
			CO2R1	23.2812	EN3R2	40.1097	EN4R6	24.9171
					EN3R9	39.0641	EN4R7	24.1085
					SO3R3	37.7851	SO4R7	22.6697
					EN3R11	37.4009		
					EN3R12	37.2099		
					EN3R5	37.1311		
					EN3R13	37.0631		
					SO3R11	36.7901		
					EC3R3	36.5868		

At the decision-making stage, SO1R5 (opportunism decision making) has the highest RRGD-In (23.5597); CO1R3 (weak and opaque decision-making process) has the highest out-degree, arriving by 30.5778. There are seven RRGD-In key risks, including three social risks and three economic risks. There are seven RRGD-Out key risks, four of which are social risks, and three of which are coordination risks. This indicates that, although direct interaction relationships play a leading role in the whole risk network, there is a certain degree of indirect influence—economic risk and coordination risks may indirectly affect social risk.

At the design stage, EC2R2 had the highest RRGD-In, arriving by 26.8024; SO2R5 had the highest RRGD-Out, arriving by 30.1489. Economic risks account for four of the eight RRGD-In key risks. There are five coordination risks and four social risks among nine RRGD-Out key risks. The above results indicate that the risk with a higher direct effect may have a higher global effect. For example, EC2R2 and SO2R5 have the largest node degrees and RRGD in the design stage.

In the construction stage, the highest RRGD-In (EC3R6: compensate for not meeting the Sustainable Development Goals) was 51.4976, and the highest RRGD-out (CO3R3) was 60.8803. Among the fifteen RRGD-In key risks, there are nine social risks. Environmental risks account for nine of the seventeen RRGD-Out key risks. At the construction stage, a large number of social risks are more likely to be directly and indirectly affected by predecessors. On the contrary, a large number of environmental risks have a direct and indirect effect on successors.

At the operation stage, SO4R8 and CO4R4 have the highest RRGD-In value (33.7081) and the highest RRGD-Out value (34.2699), respectively. Five and four of the ten RRGD-In key risks are social risks and economic risks. Meanwhile, environmental risks and coordination risks account for five and four of eleven RRGD-Out key risks.

Figure 4 shows the evolution trend of RRGD-In and RRGD-Out with the life cycle of MIPs. In general, RRGD-Out and RRGD-In have similar change trends and increase after reaching a maximum in the construction stage. From the view of dimensions, RRGD-Out and RRGD-In of environmental and social risks both increase first and then decrease, reaching a peak in the construction stage, which is twice that of the other stages. This shows that environmental and social dimension risks play an important role in global source risk and global cumulative risk in the construction stage, because most of the nodes are linked to the risks of these two dimensions. The RRGD-Out of economic risk undergoes a small change in the whole life cycle, and the RRGD-In of economic risk is significantly higher at the construction stage. In contrast, the RRGD-In of coordination risk undergoes a small change in the whole life cycle, and the RRGD-Out of coordination risk is significantly higher at the construction stage.

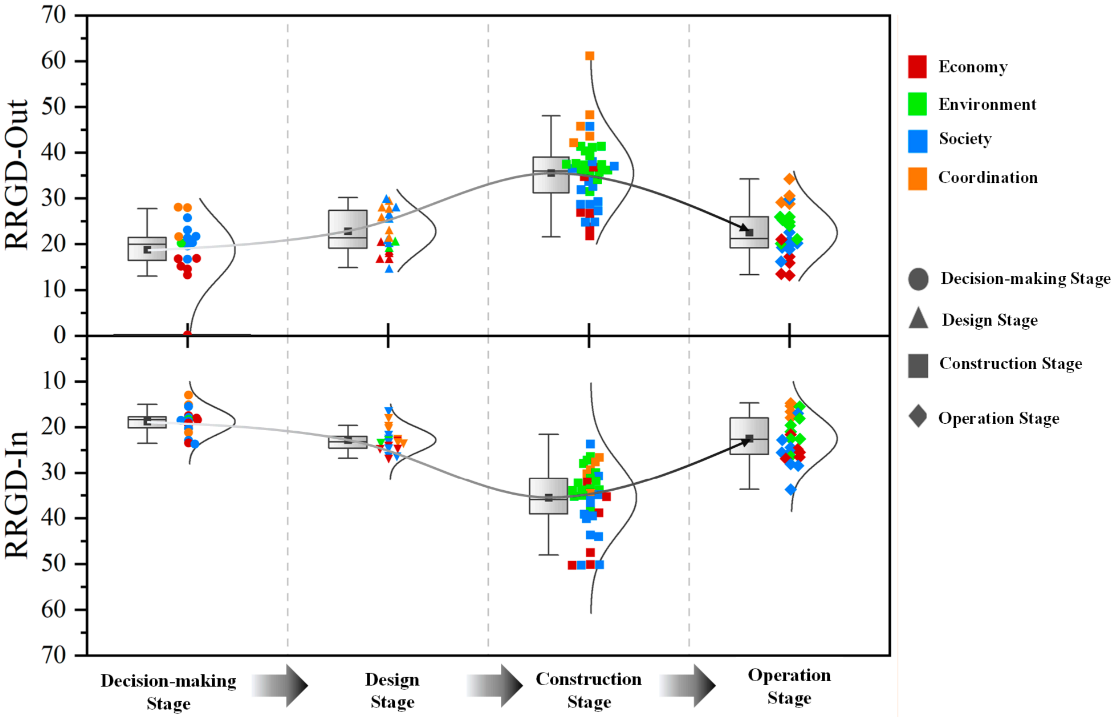

Figure 4. The evolution of RRGD-Out and RRGD-In.

4.2.3. NBC

Node betweenness centrality indicates the intermediary role that nodes play in bonding the various parts of the network. The higher the node betweenness centrality, the greater the control over the interaction relationships flowing through the network. In this study, the top 25% of the risks ranked by node betweenness centrality in each stage were selected as betweenness centrality key risks, because 25% of the risk nodes have higher betweenness centrality than the mean of all betweenness centrality (0.0226). Table 6 shows the betweenness centrality key risks for each stage.

Table 6. Betweenness centrality key risks.

Stage	Decision-Making Stage		Design Stage		Construction Stage		Operation Stage	
	Code	Value	Code	Value	Code	Value	Code	Value
NBC	SO1R4	0.0833	SO2R7	0.1287	SO3R2	0.1970	SO4R4	0.3864
	SO1R5	0.0788	CO2R3	0.0429	EC3R2	0.0947	SO4R2	0.0711
	SO1R2	0.0667	EC2R3	0.0365	SO3R12	0.0930	EC4R2	0.0665
	CO1R1	0.0649	CO2R4	0.0292	CO3R3	0.0360	SO4R8	0.0586
			EC2R5	0.0249	CO3R1	0.0306	EC4R4	0.0425
					EN3R1	0.0246	EC4R5	0.0425
					EN3R2	0.0228		
					SO3R11	0.0204		
					SO3R3	0.0189		

In the decision-making stage, SO1R4 (bribery and corruption) had the highest betweenness centrality (0.0833) and played a powerful hub role in the MIP risk network. There are three social risks and one coordination risk among the four betweenness centrality key risks. In other words, in the decision-making stage, the risks with large hub roles are social risks.

In the design stage, SO2R7 (bribery and corruption) had the highest betweenness centrality (0.1287). There are two coordination risks, two economic risks, and one social risk among the five betweenness centrality key risks, which play a large hub role in the design stage.

In the construction stage, the highest betweenness centrality (SO3R2, bribery and corruption) was 0.1970. Coordination risks, environmental risks, and economic risk accounted for four, two, and one of the seven betweenness centrality key risks, respectively. This indicates that the risks with a large hub role are social risks.

In the operation stage, SO4R4 (damages on participation of local residents and community) has the highest betweenness centrality (0.3864). The ten betweenness centrality key risk nodes include three social risks and three economic risks. This indicates that the risks with a large hub role are social and economic risks.

Figure 5 reflects the changing trend of node betweenness centrality with the MIPs' life cycle. First, 'bribery and corruption' has the highest betweenness centrality value in the decision-making stage, design stage, and construction stage of MIPs, and it gradually increases. This shows that multiple nodes are directly linked by this risk node, which plays an important role in global risk propagation. If 'bribery and corruption' are not controlled at the beginning of MIPs, they will pose greater consequences as MIPs progresses. This result is in line with practice; many scandals can be found in MIPs. In the project approval, bidding, and construction stage, bribery and corruption often occur, which not only lead to serious quality problems and safety incidents, but also cause public complaints and severely harm government image and credibility [40].

Second, from the overall trend, the betweenness centrality of risks shows a slight downward trend, and when it reaches the operational stage, there is an obvious rebound. From the view of dimensions, social risks always occupy relatively important hub roles in the risk network of MIPs, and their betweenness centrality maintains an upward trend. The changing trend in betweenness centrality of economic risks is similar to that of social risks. The betweenness centrality of coordination risks shows an inverted U-shaped change trend, and its value in the design stage and construction stage is higher than that in the decision-making stage and operation stage. The betweenness centrality of environmental risks is relatively stable. The high betweenness centrality risk should be treated with caution, because by controlling these risks, the link can be cut off, thereby reducing the actual loss of MIPs caused by the risk interaction.

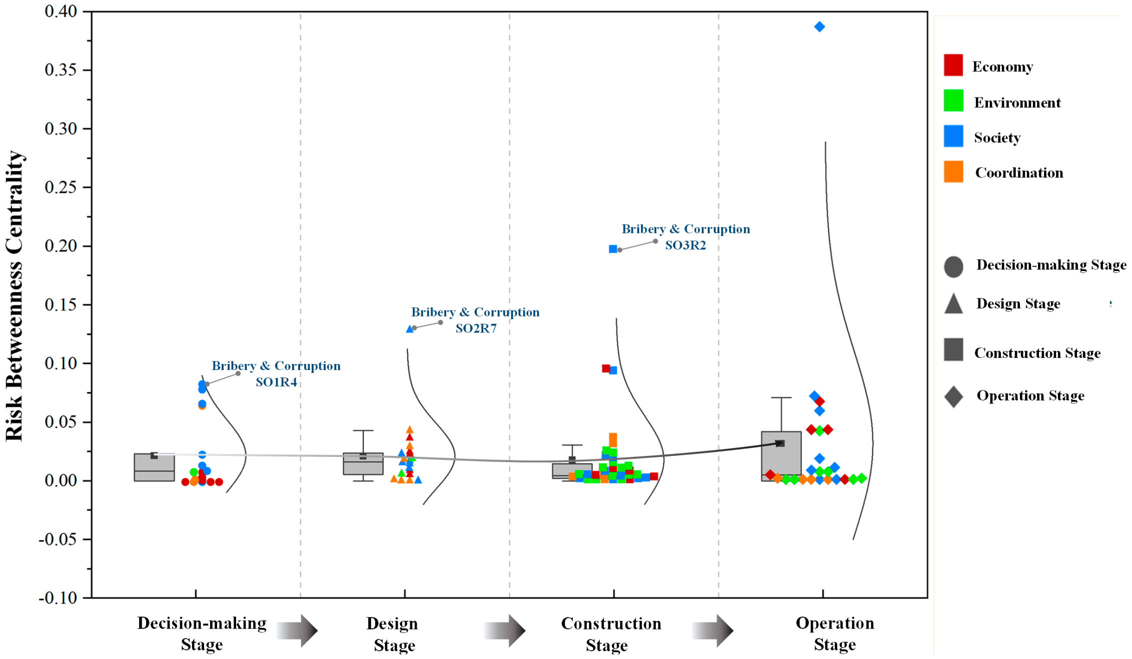

Figure 5. The evolution of node betweenness centrality.

4.3. Link Level Results

Link betweenness centrality is a typical indicator for identifying key links [8]. It helps identify the hub links in the network that play the role of the key channels for risk transmission. Risk managers can prevent risk interaction by controlling these risk links. In this study, the top 25% of risk links at each stage are sorted by link betweenness centrality. These links are selected as key risk links because 25% of them have a larger link betweenness centrality than the mean of all link betweenness centrality values (0.0043). Table 7 ranks the top ten key risk links in each stage by link betweenness centrality.

Table 7. Key risk link.

Stage		No.									
		1	2	3	4	5	6	7	8	9	10
Decision-making Stage	Start	EC1R4	EC1R1	SO1R4	SO1R4	SO1R2	SO1R5	SO1R6	EC1R2	SO1R6	EC1R6
	End	SO1R2	SO1R5	CO1R2	CO1R3	SO1R4	CO1R3	SO1R7	SO1R5	SO1R4	SO1R4
	Value	0.0625	0.0349	0.0331	0.0276	0.0221	0.0221	0.0202	0.0196	0.0193	0.0184
Design Stage	Start	EC2R4	SO2R3	EN2R2	SO2R2	EC2R3	EC2R1	EN2R1	EC2R5	EC2R5	EC2R2
	End	SO2R7	EC2R3	CO2R3	CO2R5	SO2R2	SO2R7	CO2R3	SO2R3	SO2R7	SO2R7
	Value	0.0390	0.0342	0.0303	0.0259	0.0250	0.0232	0.0215	0.0211	0.0211	0.0197
Construction Stage	Start	SO3R12	EC3R1	SO3R12	EC3R4	EC3R2	SO3R2	EC3R2	EC3R5	SO3R2	EN3R12
	End	CO3R1	SO3R2	CO3R3	SO3R2	EN3R2	EN3R9	EN3R1	SO3R2	EN3R6	SO3R2
	Value	0.0436	0.0293	0.0271	0.0263	0.0243	0.0236	0.0203	0.0197	0.0165	0.0161
Operation Stage	Start	SO4R2	EC4R2	EC4R4	EC4R5	SO4R8	SO4R4	EC4R1	SO4R4	SO4R4	SO4R4
	End	SO4R4	SO4R4	EC4R2	SO4R4	SO4R4	EN4R7	EC4R4	CO4R1	CO4R2	CO4R3
	Value	0.0915	0.0734	0.0589	0.0525	0.0480	0.0399	0.0389	0.0362	0.0362	0.0362

There are 47 key risk links in the decision-making stage, the top three links ranked by link betweenness centrality value include EC1R4—SO1R2 (0.0625; costs caused by disputes with the community—damages on participation of local residents and community), EC1R1—SO1R5 (0.0349; wrong market demand forecasts [overrate]—opportunism decision making), and SO1R4—CO1R2 (0.0331; bribery and corruption—decision-making mechanisms not involving all stakeholders)

There are 66 key risk links in the design stage, the top three links ranked by link betweenness centrality value include EC2R4—SO2R7 (0.0390; land acquisition and resettling cost overruns—bribery and corruption), SO2R3—EC2R3 (0.0342; no access of the disabled—design deficiency), and EN2R2—CO2R3 (0.0303; non-matching with natural environment—lack of sustainable clauses in contract).

The construction stage consists of 161 key risk links, the top three links ranked by link betweenness centrality value include SO3R12—CO3R1 (0.0436; discoordination between contractor and public—inadequate communication and coordination among stakeholders), EC3R1—SO3R2 (0.0293; construction and installation cost overruns—bribery and corruption), and SO3R12—CO3R3 (0.0271; discoordination between contractor and public—weak sustainability awareness).

The operation stage consists of 73 key risk links, the top three links ranked by link betweenness centrality value include SO4R2—SO4R4 (0.0915; damages on residents' health—damages on participation of local residents and community), EC4R2—SO4R4 (0.0734; devaluation of residents' assets [decrease in residents' income]—damages on participation of local residents and community), and EC4R4—EC4R2 (0.0589; weak solvency ability—devaluation of residents' assets [decrease in residents' income]).

The broken line in Figure 6 shows the changing trend of the average link betweenness centrality, and the heatmap reflects the average link betweenness centrality between dimensions. From a global perspective, the decision-making stage has the highest average link betweenness centrality, which indicates that the limited risk links in the decision-making stage become the common propagation path of many other risk nodes in the network. With the progress of MIPs, link betweenness centrality shows a U-shaped change trend and reaches a trough value (0.0025) in the construction stage. From the perspective of dimensions, the risk links from economic risks to social risks have the largest average betweenness centrality in the decision-making stage, and always remain in the top three positions in the entire life cycle of MIPs. In the design stage, the risk links from environmental risks to coordination risks have the largest average betweenness centrality. In the construction and operation stages, the risk links from social risks to coordination risks have the largest average betweenness centrality.

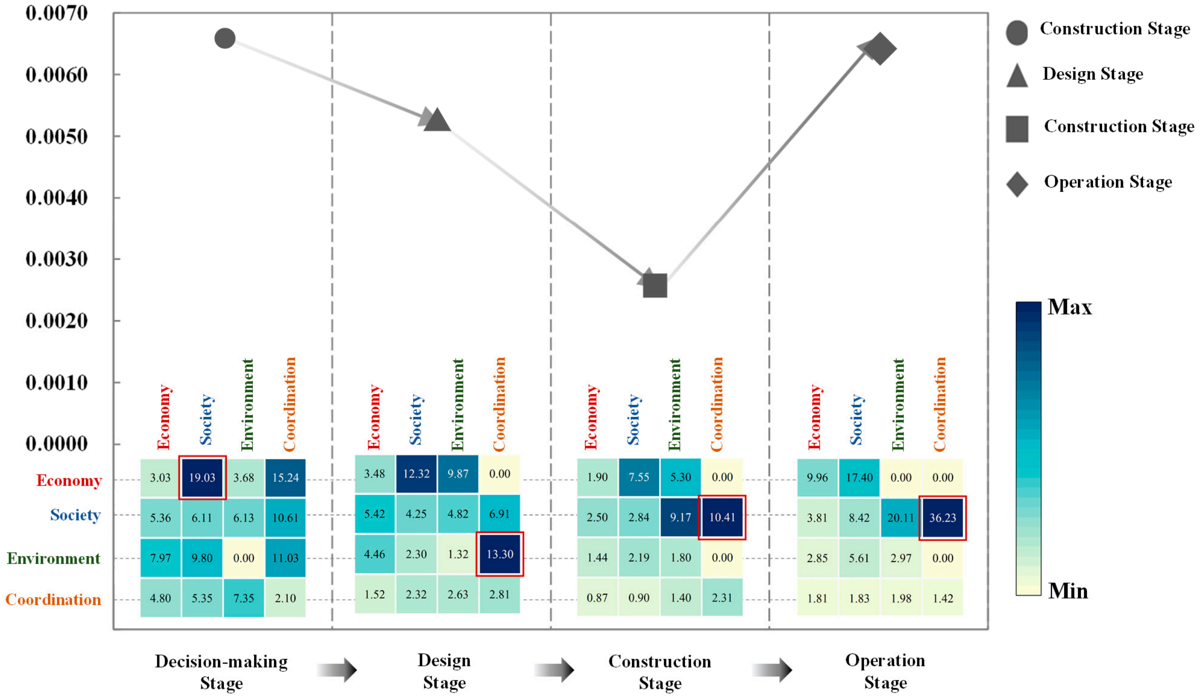

Figure 6. The evolution of link betweenness centrality. (Note: Because the value of link betweenness centrality is too small, to show the results clearly, all link betweenness centrality in the heat map is multiplied by 1000).

4.4. Risk Groups Results

4.4.1. DIGI

In this study, the risks of MIPs include four dimensions: economy, society, environment, and coordination. By calculating direct inter-group interactions, the direct interaction between dimensions can be identified, which can help risk managers communicate with each other to improve coordinated decision-making [4]. Figure 7 shows the direct inter-group interaction of the risk network in the four MIP stages.

(a) Decision-making Stage

	ECR	SOR	ENR	COR
ECR	29.73	15.17	1.00	5.66
SOR	52.31	75.41	8.49	17.66
ENR	3.74	6.63	2.24	2.00
COR	27.82	36.66	4.90	14.25

(b) Design Stage

	ECR	SOR	ENR	COR
ECR	27.11	26.08	6.93	0.00
SOR	47.90	62.64	12.00	35.36
ENR	8.83	4.00	8.00	8.83
COR	37.42	52.92	12.96	59.46

(c) Construction Stage

	ECR	SOR	ENR	COR
ECR	28.28	15.56	0.00	0.00
SOR	24.27	80.00	12.25	4.90
ENR	40.66	48.54	51.09	0.00
COR	24.90	34.48	43.31	29.39

(d) Operation Stage

	ECR	SOR	ENR	COR
ECR	28.98	22.20	25.26	0.00
SOR	69.54	141.73	18.03	17.94
ENR	91.21	143.19	152.11	0.00
COR	38.83	69.28	77.77	46.90

Figure 7. Direct inter-group interaction.

In the decision-making stage, the largest direct inter-group interaction is from social risks to economic risks (52.3068), followed by coordination risks to social risks (36.6606), and then by coordination risks to economic risks (27.8209). The results show that social risks, economic risks, and coordination risks are closely related, whereas environmental risks seem to be relatively isolated. This may be because the environmental impact of a project is not exposed during the planning and start-up stages, and the project participants do not consider its environmental risks. However, the insufficient environmental impact assessment (EIA) in the initial stage leads to mistakes in decision-making, which leads to a large number of environmental risks in the construction and operation phases of the project. For example, if a highway is planned to be constructed in an international wetland reserve, until the project construction and operation stages begin, the wetland will be damaged and the surrounding residents will be affected by noise, air pollution, and other environmental impacts.

In the design stage, the largest direct inter-group interaction is from coordination risks to social risks (52.1950), followed by social risks to economic risks (47.8957) and coordination risks to economic risks (37.4166). The results show that economic risks are directly affected by social and coordination risks. Therefore, project managers should pay attention to social risks and coordination risks in the early stages of MIPs if they want to reduce project costs and control economic risk.

In the construction stage, the largest direct inter-group interaction is from environmental risks to social risks (143.1887), followed by environmental risks to economic risks (91.2140), and coordination risks to environmental risks (77.7689). The results show that the risks of the four dimensions are closely related, indicating that the risk relationship in this dimension is relatively complex. Environmental risks become important hub risks for economic and coordination dimension risks.

In the operation stage, the largest direct inter-group interaction is from environmental risks to social risks (48.5386), followed by coordination risks to environmental risks (43.3128) and environmental risks to economic risks (40.6571). The results show that environmental risks are closely related to risks of all dimensions, which is consistent with Dadpour et al., where environmental risk plays a key role in generating propagation effects and increasing the complexity of the risk network [41].

In summary, the above results indicate that, in the early stages of MIPs, economic, social, and environmental risks are closely related, and environmental risks are relatively isolated. After entering the construction stage, environmental risks become closely related to the risks associated with other dimensions. Environmental problems may lead to serious social problems, and may also aggravate economic risks. Meanwhile, coordination problems may cause environmental deterioration, forming a vicious circle [41]. Therefore, there is a complex interaction between the risks of the four dimensions.

4.4.2. GIGI

The global inter-group interaction integrates the indirect and direct effects of risk propagation between the two risk groups [38]. Figure 8 shows the global inter-group interaction of the risk network in the four MIP stages.

(a) Decision-making Stage

	ECR	SOR	ENR	COR
ECR	29.73	15.17	1.00	5.66
SOR	52.31	75.41	8.49	17.66
ENR	3.74	6.63	2.24	2.00
COR	27.82	36.66	4.90	14.25

(b) Design Stage

	ECR	SOR	ENR	COR
ECR	27.11	26.08	6.93	0.00
SOR	47.90	62.64	12.00	35.36
ENR	8.83	4.00	8.00	8.83
COR	37.42	52.92	12.96	59.46

(c) Construction Stage

	ECR	SOR	ENR	COR
ECR	28.28	15.56	0.00	0.00
SOR	24.27	80.00	12.25	4.90
ENR	40.66	48.54	51.09	0.00
COR	24.90	34.48	43.31	29.39

(d) Operation Stage

	ECR	SOR	ENR	COR
ECR	28.98	22.20	25.26	0.00
SOR	69.54	141.73	18.03	17.94
ENR	91.21	143.19	152.11	0.00
COR	38.83	69.28	77.77	46.90

Figure 8. Global inter-group interaction.

Compared with direct inter-group interactions, global inter-group interactions are stronger. For example, economic risk→coordination risk in the design stage, economic risk→coordination risk and environmental risk→coordination risk in the construction stage, and economic risk→environmental risk in the operation stage have little direct inter-group interaction, but have high global inter-group interactions. In addition, the close interaction relationship between the dimensions in direct inter-group interaction and global inter-group interaction is similar.

5. Discussion

5.1. Dynamic Risk-Response Strategies According to Key Risks

After determining each risk node metric ranking, all rankings are integrated to obtain the final key risks in each stage of the MIPs. Careful attention should be paid to the risks that appear in three or more metric ranking lists. They play multiple roles with different functions to support risk networks. Combining the results of high node degree, high RRGD, and high betweenness centrality, Table 8 lists the key risks.

Table 8. The key risks of MIPs.

Decision-Making Stage		**Design Stage**		**Construction Stage**		**Operation Stage**	
Code	**Risk**	**Code**	**Risk**	**Code**	**Risk**	**Code**	**Risk**
SO1R4	Bribery and corruption	SO2R7	Bribery and corruption	SO3R2	Bribery and corruption	SO4R4	Damages on participation of local residents and community
CO1R1	Unsatisfying national or local legislation	CO2R3	Lack of sustainable clauses in contract	SO3R12	Discoordination between contractor and public	EN4R7	Damages on the ecological balance
SO1R5	Opportunism decision making	CO2R4	Ambiguous sustainable management program	EC3R2	Construction delay	SO4R8	Negative impact on residents' life quality
SO1R2	Damages on participation of local residents and community	EC2R5	Designing cost overrun	EN3R12	Damages to the ecological balance	EC4R5	Weak contribution on local economy
SO1R7	Difficulty of coordinating interest demand	EC2R3	Design deficiency	EC3R1	Construction and installation cost overruns	EC4R2	Devaluation of residents' assets (decrease in residents' income)
CO1R2	Decision-making mechanisms not involving all stakeholders	SO2R5	Opaque project information (Closed design information)	SO3R3	Excessive government intervention	SO4R2	Damages on residents' health
CO1R3	Weak and opaque decision-making process	EC2R2	Misestimate in time and cost	SO3R11	Damages on participation of local residents and community	CO4R4	
EC1R5	Delay in project approval			CO3R3	Weak sustainability awareness		
				CO3R1	Inadequate communication and coordination among stakeholders		
				EN3R1	Air pollutant (greenhouse gases, toxic gases, dust)		
				EN3R2	Water pollution		
				EC3R3	Substandard quality		
				EN3R11	Damages to natural heritage		

Thirty-five key risks in Table 8 should be controlled first because they either have a significant direct or indirect effect on other risks or severely increase the complexity of risk interactions. There are 13 social risks, 9 economic risks, 8 coordination risks and 5 environmental risks among thirty-five key risks. Surprisingly, economic risks do not account for the largest proportion in the list, although many scholars regard economic risks as an important obstacle to MIPs. However, this discovery also explains why some previous scholars have focused on the social risks of MIPs, such as Li et al. [42] and Yuan et al. [21]. In addition, it confirmed the importance and necessity of introducing coordinated dimensions, and this finding is similar to the discovery of Li et al. [29]. They believe that balancing the risks of the three dimensions of economy, society, and environment has an important effect on the sustainable development of MIPs, and regard collaborative management as an important driving force and effective strategy to balance the three dimensions. In addition, project managers need to check potential risk control points at each stage of MIPs and adopt different risk response strategies associated with different risks [14].

The decision-making stage includes eight key risks which are mainly concentrated on social, coordination, and economic risks. CO1R2 (decision-making mechanisms not involving all stakeholders) and CO1R3 (weak and opaque decision-making process) are the risks with high out-degree and RRGD-Out at this stage. In other words, these two risks not only directly trigger other risks, but are also important source risks in the global network; therefore, MIP participants should actively control their occurrence, clarify the decision-making process in the decision-making stage, formulate a complete decision-making mechanism, and allow all stakeholders to participate in the decision-making stage [43]. EC1R5 (delay in project approval) is the highest in-degree risk at this stage; it is located at one end of the risk network; therefore, managers should focus on its root causes. In the decision-making stage, it was found that some risks have a negative effect on the local industry (EC1R2, EC1R3), damages on participation of local residents and community (SO1R2), cause difficulty in coordinating interest demand (SO1R7), have inadequate environmental effect assessment (EN1R1), and unsatisfying national or local legislation (CO1R1), causing the project manager to make many decisions again, prolonging the project approval time. Therefore, the project participants should reasonably extend the project decision-making time and make a full assessment during the project feasibility study. SO1R4 (bribery and corruption), CO1R1 (unsatisfying national or local legislation), SO1R5 (opportunism decision making), and SO1R2 (damages on participation of local residents and community) are the most important hub risks at this stage and have high in-degree and out-degree values. For this risk type, project participants should not only pay more attention to the effect of upstream risks, but also decouple control from downstream risks [8]. In practice, local government officials or developers are prone to bribing politicians, social elites, and leaders of major organisations (SO1R4) to approve projects that are beneficial to them (SO1R5) but unsatisfying (CO1R1), and citizens must pay public officials to obtain project decision-making information (SO1R2, SO1R1). These behaviours cause damage to connectivity among communities (SO1R6), difficulty in coordinating interest demand (SO1R7), wrong market demand forecasts (EC1R1), and other consequences. Therefore, project participants should formulate a strong punishment mechanism for corrupt behaviour, allow the public and local communities to participate in MIPs' decision-making, fully use public supervision, and disclose project decision-making information to society through social media to reduce the occurrence of bribery and corruption [44].

The design stage includes seven key risks, concentrated on economic, social, and coordination risks. SO2R5 (opaque project design information) is the risk with a high RRGD-Out-degree at this stage. This indicates that designers need to take the initiative to share design information with other stakeholders, such as project owners, contractors, and governments. This would benefit all stakeholders in providing timely feedback on the project design and it can reduce design deficiencies (EC2R3), insufficient integration with local culture and environment (SO2R2, EN2R2), and misestimates in time and cost (EC2R2) caused by information closure [12]. EC2R2 (misestimate in time and cost) is a risk with a high RRGD-In value at the design stage. Project participants should actively find risk-mitigation strategies through a bottom-up method. For example, land acquisition and resettling cost overruns (EC2R4) can be reduced through reasonable project location planning and public opinion surveys, thereby reducing the cost of MIPs. CO2R3 (lack of sustainable clauses in contract) and CO2R4 (ambiguous sustainable management program) are risks with high out-degree, RRGD-Out values, and betweenness centrality. Owing to the lack of organizational culture on sustainability (CO2R5) in most Chinese MIPs, awareness regarding sustainable clauses is lacking when project contracts are drafted (CO2R3). Even if they are considered, the plans are not completed. Therefore, training project participants must improve their knowledge about sustainability practices and foster a culture of sustainable development within the organization. This can alleviate the lack of integrating project design with local culture and environment, and have project participants actively paying attention to the impact of MIPs on society and ecological environment. EC2R5 (designing cost overrun) and EC2R3 (design deficiency) are the risks with high in-degree, RRGD-in, and betweenness centrality. MIP stakeholders should focus on the upstream risks. For example, the project design should consider integration with the local culture and natural environment and utilisation of the disabled, and gather the opinions of other stakeholders to reduce project design deficiencies [12]. SO2R7 (bribery and corruption in the design stage) retains the same role as the decision-making stage and is the most important hub risk in the design stage. This means that, if there is no compulsory punishment and effective supervision for bribery and corruption in the design stage, the risks associated with bribery in the decision-making stage may also cause a chain reaction through this risk, resulting in more complex risk interactions and more serious risk consequences [44].

The construction stage includes 13 key risks, covering the four dimensions of sustainable development. EC3R1 (construction and installation cost overrun) is the risk with the highest in-degree and RRGD-in values at this stage. Construction delay (EC3R2), substandard quality (EC3R3), compensation for not meeting the sustainable development goals (EC3R6), and overuse of construction materials (EN3R7), all cause an increase in MIP construction and installation costs. Therefore, MIP managers should perform pre-work to reduce construction delays, regularly check the quality of the project to prevent quality failures, and strictly follow the sustainable clauses of contract to reduce compensation [45]. SO3R12 (discoordination between contractor and public), EC3R2 (construction delay), and EN3R12 (damages to the ecological balance) are the risks with high in-degree values, RRGD-IN, and betweenness centrality, and are hub risk nodes that are easily affected by other risks. Project participants should focus on controlling the upstream risks. For example, the public participation mechanism can be improved so that contractors and the public can communicate effectively [43], and non-construction land should not be occupied to protect ecological diversity. CO3R3 (weak sustainability awareness), CO3R1 (inadequate communication and coordination among stakeholders), EN3R1 (air pollution), EN3R2 (water pollution), EC3R3 (substandard quality), and EN3R11 (damages to natural heritage) are associated with a higher out-degree, RRGD-Out value, and betweenness centrality, and are hub nodes that easily affect other risks. Project participants should take the initiative to control this type of risk. These include improving sustainable practice knowledge and sustainability awareness of project participants, establishing efficient organizational communication channels to strengthen participants' coordination, and implementing recovery and treatment measures on project waste water and waste gas to reduce the destruction of the landscape and strengthen the quality inspection of the project. SO3R2 (bribery and corruption), SO3R3 (excessive government intervention), and SO3R11 (damages on participation of local residents and community) are hub risks with high in-degree and out-degree at this stage. For these risks, project participants should actively take preventive measures and closely monitor their potential effect on the surrounding risks. For example, to reduce excessive administrative intervention, the government should reasonably restrict and regulate its own behaviour and effectively perform its supervisory powers, which benefit contractors to give full play to their own advantages and enthusiasm, and promote the success of the project [46]. It is worth noting that if bribery and corruption are not controlled in the previous stage, the construction stage will have more serious consequences. For example, bribery and corruption occurring during the bidding process of the design stage may cause the bidders to reduce costs of the construction stage to recoup their benefits, trigger project quality issues and safety incidents, and even cause public complaints and serious damage to government image and reputation [40].

The operation stage includes seven key risks, covering four dimensions. CO4R4 (weak monitor and maintenance platform of project sustainability) is the risk with a high out-degree and RRGD-Out at this stage, and is an important source risk at this stage. Therefore, project participants should monitor the operation situation of the project management process in real time, implementation effects of management strategies, and project risks through informatization methods and strengthen platform construction [41]. SO4R8 (Negative impact on residents' life quality), EC4R5 (weak contribution toon local economy), EC4R2 (devaluation of residents' assets [decrease in residents' income]), and SO4R2 (damages to residents' health) are the risks with high in-degree and RRGD-In at this stage, and are also important cumulative risks at this stage. Project participants should actively control their upstream risks, especially for environmental problems caused by project operations. Therefore, completing the setting of buffer areas between the project and residential areas and actively treating pollutants such as waste gas and wastewater generated by project operations can reduce public dissatisfaction with the project. SO4R4 (damages on participation of local residents and community) and EN4R7 (damages to the ecological balance) are the most important hub risks at this stage. Therefore, project participants should prevent and strengthen solvation for the above two risks during the construction stage.

It should be noted that there are key risks with the same meaning in different stages. For example, bribery and corruption (SO1R4, SO2R7, SO3R2) exist in the decision-making, design, and construction stages; damages on participation of local residents and community (SO1R2, SO3R11, SO4R4) exists in the design, construction, and operation stages, and damage to the ecological balance (EN3R12, EN4R7) exists in the construction and operation stages. These risk nodes should be controlled early in their occurrence, as they not only have an effect on their stage, but may also act as a hub risk between stages, leading to complex risk interactions in the life cycle of MIPs [13].

5.2. Dynamic Risk-Response Strategies According to Critical Risk Interactions

Key risk links were selected by betweenness centrality, as shown in Table 7. Ideally, by severing some links, the propagation effect of the risk interaction relationship will be reduced, thereby reducing the overall risk exposure [8]. Because there are too many key risk links at each stage, to understand their actual meaning and effect on the sustainable development of MIPs, this study classifies them and determines the main challenges faced by MIPs at each stage under the effect of risk interaction. The risk links in the same challenge have similar characteristics and can be solved similarly.

The decision-making stage includes 47 key risk links. The two risk relationships 'SO1R2-EC1R2 (damages on participation of local residents and community—negative effect on the local industrial structure)' and 'SO1R1-EC1R1 (opaque project information—wrong market demand forecasts)' both describe that stakeholders cannot obtain correct and effective project decision-making information, leading to project evaluation errors. Therefore, they are classified as the same challenge. Following the same principles, four main challenges that may be encountered at this stage are determined: (1) some stakeholders cannot obtain effective project decision-making information, resulting in project decision-making errors and economic, social, and environmental problems; (2) speculation behaviours of decision-makers lead to a management crisis within the project and cause social conflicts; (3) projects do not meet the national or local sustainable policies and affect the local economic development and social stability; and (4) insufficient project feasibility studies (market analysis, technical decision-making, environmental evaluation, etc.) lead to project delays and public protests. Therefore, in the decision-making stage, decision-making information should be disclosed [43], and punitive measures should be formulated to prevent speculation by decision-makers. Additionally, full feasibility studies should be conducted on the project with professional help.

The design stage includes 66 key risk links, and five major challenges are determined: (1) closed project design information and a lack of reference to the opinions of stakeholders leads to a design deficiency in terms of environmental protection; (2) design and resettlement cost overruns, improper estimates, financing difficulties, and other economic problems cause social problems; (3) the bribery and corruption in the bidding process cause social public opinion problems and project economic problems; (4) the government's excessive administrative intervention leads to an imbalance in the coordination and management of projects; and (5) incomplete sustainability-related clauses and management plans in project contracts lead to management errors of project participants. Therefore, project design information should be shared with all stakeholders, all opinions should be integrated, strict supervision and punishment systems for bribery and corruption should be established [44], excessive government intervention reduced, and complete sustainability clauses and management plans ensured [43].

The construction stage includes 161 key risk links, summed into nine major challenges: (1) project construction may affect the health, safety, and quality of life of local residents, cause public dissatisfaction, and lead greater social risks; (2) construction has an effect on local employment and enterprise production and operation, leading to a local economic downturn and causing social problems; (3) safety accidents during construction stage threaten the safety and health of project participants, causing cost overruns, construction period delays, environmental, and social problems; (4) excessive administrative intervention causes internal project management imbalance; (5) bribery and corruption in order to hide the occurrence of environmental problems caused by the project lead to worse environmental pollution and arouse public resistance; (6) limited public participation as a stakeholder and various conflicts between the construction party and the public intensify public dissatisfaction with the projects, and lead to project economy loss; (7) construction does not meet the sustainable development goals, causing environmental pollution and ecological damage, which affect the normal life of residents, cause public resistance and claims, and cause economic losses; (8) project participants lack sustainability awareness and do not pay attention to environmental protection and public opinion, leading to environmental pollution problems and social conflicts; and (9) incoordination and contradictions within projects causes problems in project management. Therefore, it is necessary to train project participants in sustainable knowledge and safe construction, establish a diversified project management team, increase communication methods and channels between project internal personnel and external stakeholders, and accept public supervision [44].

The operation stage includes 73 key risk links, and four major challenges are identified: (1) negative effects on residents' life quality and unemployment lead to a decrease in income and loss of rights and interests in public resources, which, in turn, lead to public protests and a decline in the local economy; (2) the operation process prevents public participation and lacks public supervision, and causes environmental pollution problems; (3) project operation causes ecological damage and environmental pollution around projects, which affects residents' life quality and causes social problems; and (4) unreasonable project operation, overrun of operation and maintenance costs, weak project debt repayment ability, and insufficient contribution to the local economy, which will cause social and economic problems. Therefore, it is necessary to complete the mechanism of public participation in the operation stage [47], encourage and accept social supervision, actively seek professional help to assist in project operations, and deal with and control environmental pollution caused by project operations in a timely fashion.

5.3. Validation of the Effectiveness of the Strategies

First, deleting key risk nodes and cutting off key risk links at each stage network are used to simulate the realization of the mitigation above strategies [48]. The original risk networks were optimised into new risk networks. The new risk network in the decision-making stage is composed of nine risk nodes and 23 risk links; the design stage is composed of 13 risk nodes and 72 risk links; the construction stage is composed of 24 risk nodes and 192 risk links; and the operation stage is composed of 17 risk nodes and 104 risk links. Figure 9 illustrates the new network for each stage. By comparing the new risk networks in Figure 9 with the original risk network in Figure 2, the network interaction is significantly reduced.

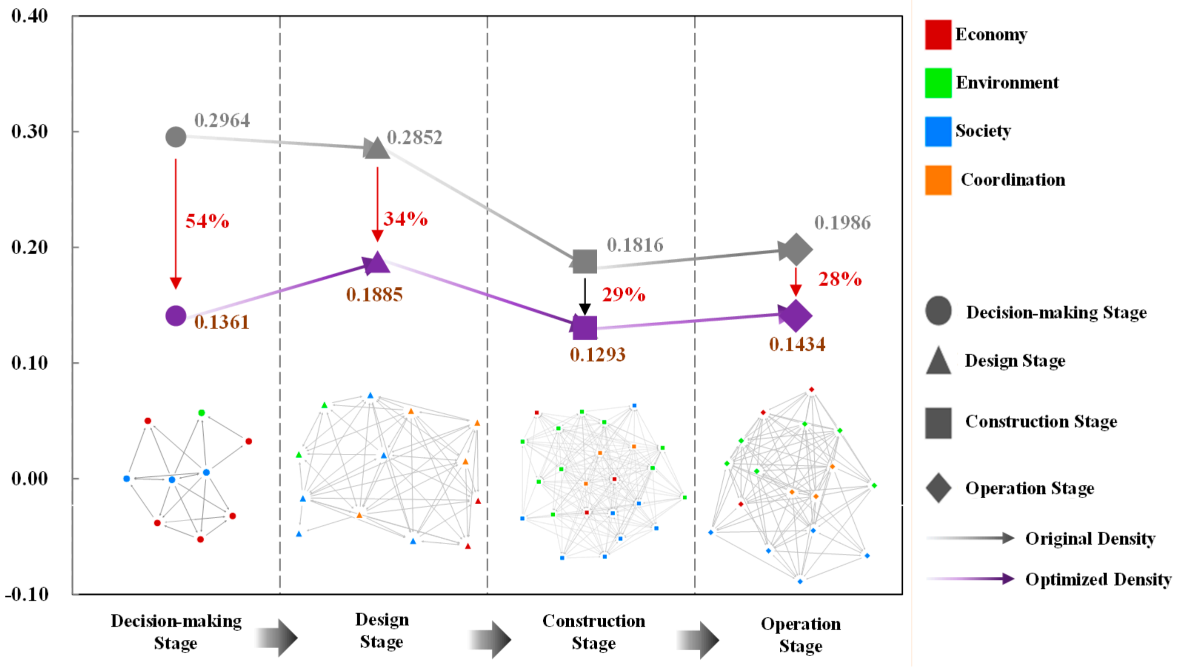

Figure 9. Evolution of network density of optimized risk network.

Second, the effectiveness of risk mitigation strategies is evaluated by calculating the network density of new networks and it is established that the network density decreases significantly, as shown in Figure 9. The network density in the decision-making stage decreases from 0.2964 to 0.1361, a 54% decrease; in the design stage, it decreases from 0.2852 to 0.1885, a 34% decrease; in the construction stage, it decreases from 0.1816 to 0.1293, a 29% decrease; and in the operation stage, it decreases from 0.1986 to 0.1434, a 28% decrease. The above results demonstrate that the complexity of risk networks can be significantly reduced by implementing mitigation strategies for the identified key risks and key risk relationships at each stage of the project.

6. Conclusions

To achieve the sustainable development of MIPs and implement appropriate risk mitigation strategies, it is necessary to identify the risks related to the sustainable development of MIPs, to have a deep understanding of the risk interactions in various stages of MIPs, and to clarify which key risks and key risk relationships will lead to the failure of MIPs. To solve these problems, this study expanded the research perspective by taking into consideration the multiple dimensions of sustainable development and the multiple stages of a project life cycle to determine the risk of MIPs. Semi-structured interviews were conducted with 8 experts to determine risk relationships and weights. The improved SNA method was used to establish a risk network model of MIPs in four stages. The dynamic changes of network-level, node-level, link-level, and group-level network indicators were calculated and analysed, and the key risks and key links of each stage were determined. These findings were used to put forward a detailed and specific risk response control strategy, and to simulate and verify the feasibility, practicability, and superiority of this strategy. The findings of this project can be summarised in three main points.

First, this study revealed the changing trends of risk network indicators at all levels of MIPs, proving that the risk network of MIPs is dynamic and complex. The largest and smallest network densities appear in the decision-making stage (0.2964) and construction stage (0.1986), respectively. The node degree and RRGD show an inverted U-shaped trend, reaching a maximum during the construction stage. Node betweenness centrality shows a continuous and slight growth trend, reaching a maximum during the operation stage. Link betweenness centrality presents a U-shaped trend, reaching a minimum during the construction stage. Second, this study found that the risks of different dimensions of sustainable development have different close relationships at different stages. During the decision-making and design stages of MIPs, economic, social and coordination risks are closely related, and environmental risks are relatively isolated. After the construction stage, however, environmental risks are closely related to other risk dimensions. Finally, at different stages of MIPs, most of the key risks and key risk relationships are different, with a small number of key risks with the same meaning. The risks that encompass multiple stages, such as bribery and corruption (SO1R4, SO2R7, SO3R2) and damages on participation of local residents and community (SO1R2, SO3R11, SO4R4), should be controlled in the early stages of occurrence.

This study makes both theoretical and practical contributions. The results are of practical importance to participants of MIPs as it will assist in improving their understanding of MIPs' risks and risk interaction relationships from a sustainable development perspective. They can then formulate reasonable risk mitigation strategies, and promote the realisation of sustainable development of MIPs. In terms of academics, this study has provided new perspectives and methods for the field of MIP risk management. These include: expanding the definition of MIPs in light of sustainable development, and introducing the use of multi-stage SNA and innovative multi-level network metrics to consider the number and weight of risk links. It furthermore realistically simulated MIPs' risk interaction relationships. Nevertheless, this study has had some limitations that need to be addressed. Firstly, only eight experts were invited to evaluate the risk relationships. They might not be able to fully represent the actual conditions. But the findings are helpful in the risk management of MIPs, and researchers can increase the interview sample for further investigations. Secondly, only the common risks of MIPs were researched to enhance the universality of the results. However, in practice, different types of MIPs pose very specific risks (for example, nuclear power plants have radiation risks). Future researchers may consider choosing a specific type of MIP as a research object to improve the pertinence of the results. Finally, this study selected discrete networks to develop risk networks at each stage of the MIPs. This ignores the risk interaction relationships between different stages of the project. Therefore, the risk interaction is another important area of research for future researchers.

Author Contributions: Conceptualization, Y.L. and P.X.; Formal analysis, Y.L. and P.X.; Investigation, Y.L. and J.G.; Methodology, Y.L., P.X. and K.Y.; Software, K.Y.; Validation, Y.L., K.Y. and J.G.; Visualization, Y.L. and P.X.; Writing—original draft, Y.L. and P.X.; Writing—review and editing, Y.L., P.X. and J.G. Y.L. and P.X. contributed equally to this paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Social Science Fund of China, grant number 21AGL033.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

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

References

1. Kardes, I.; Ozturk, A.; Cavusgil, S.T.; Cavusgil, E. Managing global megaprojects: Complexity and risk management. *Int. Bus. Rev.* **2013**, *22*, 905–917. [CrossRef]
2. Flyvbjerg, B. What you should know about megaprojects and why: An overview. *Proj. Manag. J.* **2014**, *45*, 6–19. [CrossRef]
3. Flyvbjerg, B. *The Oxford Handbook of Megaproject Management*; Oxford University Press: Oxford, UK, 2017.
4. Fang, C.; Marle, F.; Zio, E.; Bocquet, J.-C. Network theory-based analysis of risk interactions in large engineering projects. *Reliab. Eng. Syst. Saf.* **2012**, *106*, 1–10. [CrossRef]
5. Wang, L.; Sun, T.; Qian, C.; Goh, M.; Mishra, V.K. Applying social network analysis to genetic algorithm in optimizing project risk response decisions. *Inf. Sci.* **2020**, *512*, 1024–1042. [CrossRef]
6. Wang, L.; Goh, M.; Ding, R.; Pretorius, L. Improved simulated annealing based risk interaction network model for project risk response decisions. *Decis. Support Syst.* **2019**, *122*, 113062. [CrossRef]

7. Guan, L.; Abbasi, A.; Ryan, M.J. A simulation-based risk interdependency network model for project risk assessment. *Decis. Support. Syst.* **2021**, *148*, 113602. [CrossRef]
8. Zhang, Y.; Tsai, C.-H.; Liao, P.-C. Rethinking risk propagation mechanism in public–private partnership projects: Network perspective. *J. Infrastruct. Syst.* **2020**, *26*, 04020011. [CrossRef]
9. Chang, T.; Deng, X.; Hwang, B.-G. Investigating political risk paths in international high-speed railway projects: The case of Chinese international contractors. *Sustainability* **2019**, *11*, 4157. [CrossRef]
10. Lu, Y.; Zhang, Y. Toward a Stakeholder Perspective on Safety Risk Factors of Metro Construction: A Social Network Analysis. *Complexity* **2020**, *2020*, 8884304. [CrossRef]
11. Chen, L.; Lu, Q.; Li, S.; He, W.; Yang, J. Bayesian Monte Carlo Simulation–Driven Approach for Construction Schedule Risk Inference. *J. Manag. Eng.* **2021**, *37*, 04020115. [CrossRef]
12. Etemadinia, H.; Tavakolan, M. Using a hybrid system dynamics and interpretive structural modeling for risk analysis of design phase of the construction projects. *Int. J. Constr. Manag.* **2021**, *21*, 93–112. [CrossRef]
13. Shrestha, A.; Chan, T.-K.; Aibinu, A.A.; Chen, C.; Martek, I. Risks in PPP water projects in China: Perspective of local governments. *J. Constr. Eng.Manag.* **2017**, *143*, 05017006. [CrossRef]
14. Tang, H.; Wang, G.; Miao, Y.; Zhang, P. Managing Cost-Based Risks in Construction Supply Chains: A Stakeholder-Based Dynamic Social Network Perspective. *Complexity* **2020**, *2020*, 8545839. [CrossRef]
15. Shen, L.; Tam, V.W.Y.; Gan, L.; Ye, K.; Zhao, Z. Improving sustainability performance for public-private-partnership (PPP) projects. *Sustainability* **2016**, *8*, 289. [CrossRef]
16. Tao, K.; Guo, D.; Wang, Y.; Wang, X. Study on risk conduction coupling mechanism and measure of building energy conservation Renovation Project. *J. Eng. Manag.* **2017**, *31*, 6. [CrossRef]
17. Project Management Institute. *The Project Management Body of Knowledge (PMBOK Guide)*, 5th ed.; Project Management Institute: Newtown Square, PA, USA, 2013.
18. Ongkowijoyo, C.S.; Gurmu, A.; Andi, A. Investigating risk of bridge construction project: Exploring Suramadu strait-crossing cable-stayed bridge in Indonesia. *Int. J. Disaster Resil. Built Environ.* **2020**, *12*, 127–142. [CrossRef]
19. Thamhain, H. Managing risks in complex projects. *Proj. Manag. J.* **2013**, *44*, 20–35. [CrossRef]
20. Gijzel, D.; Bosch-Rekveldt, M.; Schraven, D.; Hertogh, M. Integrating Sustainability into Major Infrastructure Projects: Four Perspectives on Sustainable Tunnel Development. *Sustainability* **2020**, *12*, 6. [CrossRef]
21. Yuan, J.; Li, W.; Guo, J.; Zhao, X.; Skibniewski, M.J. Social risk factors of transportation PPP projects in China: A sustainable development perspective. *Int. J. Environ. Res. Public Health* **2018**, *15*, 1323. [CrossRef]
22. Malik, S.; Fatima, F.; Imran, A.; Chuah, L.F.; Klemeš, J.J.; Khaliq, I.H.; Asif, S.; Aslam, M.; Jamil, F.; Durrani, A.K. Improved project control for sustainable development of construction sector to reduce environment risks. *J. Clean. Product.* **2019**, *240*, 118214. [CrossRef]
23. Hueskes, M.; Verhoest, K.; Block, T. Governing public–private partnerships for sustainability: An analysis of procurement and governance practices of PPP infrastructure projects. *Int. J. Proj. Manag.* **2017**, *35*, 1184–1195. [CrossRef]
24. Liu, B.; Xue, B.; Chen, X. Development of a metric system measuring infrastructure sustainability: Empirical studies of Hong Kong. *J. Clean. Product.* **2021**, *278*, 123904. [CrossRef]
25. *The IS Rating Scheme, Version 2.0*; Infrastructure Sustainability Council of Australia: Sydney, Australia, 2018.
26. *ISI Envision, Version 3*; Institute for Sustainable Infrastructure: Washington, DC, USA, 2018.
27. Inter-American Development Bank. *What Is Sustainable Infrastructure: A Framework to Guide Sustainability across the Project Cycle*; Inter-American Development Bank: New York, NY, USA, 2018.
28. KKordi, N.E.; Belayutham, S.; Che Ibrahim, C.K.I. Mapping of social sustainability attributes to stakeholders' involvement in construction project life cycle. *Constr. Manag. Econ.* **2021**, *39*, 513–532. [CrossRef]
29. Li, Y.; Xiang, P.; You, K.; Guo, J.; Liu, Z.; Ren, H. Identifying the key risk factors of mega infrastructure projects from an extended sustainable development perspective. *Int. J. Environ. Res. Public Health* **2021**, *18*, 7515. [CrossRef]
30. Yucelgazi, F.; Yitmen, İ. An ANP Model for Risk Assessment in Large-Scale Transport Infrastructure Projects. *Arab. J. Sci. Eng.* **2019**, *44*, 4257–4275. [CrossRef]
31. Afzal, F.; Yunfei, S.; Junaid, D.; Hanif, M.S. Cost-risk contingency framework for managing cost overrun in metropolitan projects: Using fuzzy-AHP and simulation. *Int. J. Manag. Proj. Bus.* **2020**, *13*, 1121–1139. [CrossRef]
32. Tavakolan, M.; Etemadinia, H. Fuzzy weighted interpretive structural modeling: Improved method for identification of risk interactions in construction projects. *J. Constr. Eng. Manag.* **2017**, *143*, 04017084. [CrossRef]
33. Xu, H.; Zhang, Y.; Li, H.; Skitmore, M.; Yang, J.; Yu, F. Safety risks in rail stations: An interactive approach. *J. Rail Transp. Plan. Manag.* **2019**, *11*, 100148. [CrossRef]
34. Cao, D.; Shao, S. Towards Complexity and Dynamics: A Bibliometric-Qualitative Review of Network Research in Construction. *Complexity* **2020**, *2020*, 8812466. [CrossRef]
35. Ongkowijoyo, C.S.; Doloi, H.; Mills, A. Participatory-based risk impact propagation and interaction pattern analysis using social network analysis. *Int. J. Disaster Resil. Built Environ.* **2019**, *10*, 363–378. [CrossRef]
36. Yu, L.; Liu, Q.; Hua, R.; Fu, Y. Risk Analysis of Cash on Delivery Payment Method by Social Network Analysis and Fuzzy Petri Net. *IEEE Access* **2020**, *8*, 174160–174168. [CrossRef]

37. Opsahl, T.; Agneessens, F.; Skvoretz, J. Node centrality in weighted networks: Generalizing degree and shortest paths. *Soc. Netw.* **2010**, *32*, 245–251. [CrossRef]
38. Wang, X.; Xia, N.; Zhang, Z.; Wu, C.; Liu, B. Human safety risks and their interactions in China's subways: Stakeholder perspectives. *J. Manag. Eng.* **2017**, *33*, 05017004. [CrossRef]
39. Babatunde, S.O.; Ekundayo, D.; Udeaja, C.; Abubakar, U.O. An investigation into the sustainability practices in PPP infrastructure projects: A case of Nigeria. *Smart Sustain. Built Environ.* **2020**, *11*, 110–125. [CrossRef]
40. Reeves-Latour, M.; Morselli, C. Bid-rigging networks and state-corporate crime in the construction industry. *Soc. Netw.* **2017**, *51*, 158–170. [CrossRef]
41. Dadpour, M.; Shakeri, E.; Nazari, A. Analysis of stakeholder concerns at different times of construction projects using Social network Analysis (SNA). *Int. J. Civ. Eng.* **2019**, *17*, 1715–1727. [CrossRef]
42. Li, W.; Yuan, J.; Ji, C.; Wei, S.; Li, Q. Agent-Based Simulation Model for Investigating the Evolution of Social Risk in Infrastructure Projects in China: A Social Network Perspective. *Sustain. Cities Soc.* **2021**, *73*, 103112. [CrossRef]
43. Kivilä, J.; Martinsuo, M.; Vuorinen, L. Sustainable project management through project control in infrastructure projects. *Int. J. Proj. Manag.* **2017**, *35*, 1167–1183. [CrossRef]
44. Wan, X.; Wang, R.; Wang, M.; Deng, J.; Zhou, Z.; Yi, X.; Pan, J.; Du, Y. Online Public Opinion Mining for Large Cross-Regional Projects: Case Study of the South-to-North Water Diversion Project in China. *J. Manag. Eng.* **2022**, *38*, 05021011. [CrossRef]
45. Banihashemi, S.; Hosseini, M.R.; Golizadeh, H.; Sankaran, S. Critical success factors (CSFs) for integration of sustainability into construction project management practices in developing countries. *Int. J. Proj. Manag.* **2017**, *35*, 1103–1119. [CrossRef]
46. Sierra, L.A.; Yepes, V.; Pellicer, E. A review of multi-criteria assessment of the social sustainability of infrastructures. *J. Clean. Product.* **2018**, *187*, 496–513. [CrossRef]
47. Yuan, H. Achieving sustainability in railway projects: Major stakeholder concerns. *Proj. Manag. J.* **2017**, *48*, 115–132. [CrossRef]
48. Yu, T.; Shen, G.Q.; Shi, Q.; Lai, X.; Li, C.Z.; Xu, K. Managing social risks at the housing demolition stage of urban redevelopment projects: A stakeholder-oriented study using social network analysis. *Int. J. Proj. Manag.* **2017**, *35*, 925–941. [CrossRef]