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A Networked Game Theoretic Model for Evaluating Resilience in Megaprojects: Integrating Stakeholder Interactions and Lifecycle Adaptability

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Abstract: Megaprojects are complex systems comprising interdependent subsystems and diverse stakeholders, each contributing to the project's resilience and long-term outcomes. Traditional methods for assigning stakeholder influence often assume that stakeholders operate independently when evaluating subsystem resilience. However, these approaches overlook the intricate dynamics—such as competition and collaboration—that frequently characterize stakeholder interactions in megaprojects. This study addresses this gap by introducing a novel framework based on game theory and network analysis to assess megaproject resilience. The model incorporates both stakeholder interactions and subsystem interdependencies, using a networked game approach to dynamically allocate stakeholder weights. These weights reflect cooperative and conflicting relationships among stakeholders. The framework optimizes a stakeholder's utility function by balancing marginal benefits, costs, and interaction effects, ensuring rational and adaptive weight distribution. The resulting solution represents a unique Nash equilibrium, identified as the optimal configuration for stakeholder influence. To validate the framework, the study applies it to the Jakarta–Bandung High-Speed Railway (JBHSR) megaproject, demonstrating its capacity to integrate theoretical rigor with practical application. Through mathematical proofs and simulations, the research explores how model parameters influence two critical solution properties: order consistency and stability. Comparative analysis with established methods, such as the Analytic Hierarchy Process (AHP) and simple averaging, highlights the proposed model's superior ability to capture stakeholder dynamics and adapt to the evolving nature of megaprojects throughout their lifecycle. The findings emphasize the model's utility in delivering more nuanced resilience evaluations by accounting for stakeholder roles, relationships, and contributions. Specifically, this framework advances theory by merging network analysis with game theory to capture dynamic stakeholder influences, while offering practitioners a real-time mechanism to manage and optimize stakeholder interactions for improved resilience across the entire megaproject lifecycle. Its adaptability to full lifecycle assessments makes it a robust and scalable tool for managing resilience in large-scale infrastructure projects, offering valuable insights for both practitioners and researchers.

Keywords: system resilience; megaproject; stakeholders; game theory; network science

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1. Introduction

Megaproject resilience is critical due to the inherent complexity and scale of such projects. These endeavors are composed of multiple interconnected subsystems, each performing distinct yet interdependent functions. The dependencies among these subsystems mean that disruptions in one can propagate across others, creating systemic vulnerabilities that jeopardize the project's overall performance and long-term value creation [1–3]. These interdependencies necessitate not only a comprehensive understanding of subsystem resilience but also an integrated approach that considers their relationships and cascading impacts.

Adding to this complexity is the dynamic involvement of diverse stakeholders, including governments, contractors, community representatives, and financiers. These stakeholders are intricately tied to specific subsystems, as the tasks and responsibilities within each subsystem are generally executed by stakeholders based on their unique resources, expertise, and conditions. For example, a contractor's technical capabilities may align with the requirements of a construction subsystem, while community representatives may focus on ensuring environmental or social considerations in another [4]. This nexus between stakeholders and subsystems forms a functional network within the megaproject, where stakeholders not only drive the performance of individual subsystems but also influence their interactions with other parts of the project. Resilience-building efforts must focus on preparing for such disruptions by fostering adaptability, collaboration, and shared problem-solving mechanisms among stakeholders [5]. In one case study, the integration of stakeholder citizenship behaviors through collaborative platforms and agile decision making processes significantly enhanced the project's ability to address financial, safety, and environmental crises [6]. Such findings underscore the importance of aligning governance structures and stakeholder engagement strategies with the principles of resilience to navigate the complexities of megaprojects effectively.

Another layer of complexity is the duality of collaboration and competition among a variety of stakeholders in megaprojects. Stakeholders often collaborate to achieve shared goals across subsystems but may also compete for limited resources, influence, and control. These dynamics directly shape the governance and operational framework of megaprojects [4], influencing how resilience is prioritized and assessed across different components. This relationship underscores the need for a systematic method to evaluate resilience, one that integrates stakeholder roles and subsystem interdependencies. A robust model for resilience evaluation must incorporate the distribution of stakeholder evaluation weights. Stakeholders assess the resilience of the subsystems they oversee, reflecting their perspectives and priorities. Allocating appropriate weights to these evaluations ensures that the collective resilience of the megaproject is accurately captured. This allocation is crucial, as it determines how management attention, resources, and effort are distributed across subsystems and stakeholders. A poorly weighted assessment can result in overemphasizing or undervaluing critical subsystems, leading to cascading failures across the project.

Building on the inherent complexities of megaprojects—including diverse stakeholder networks, intricate governance structures, and substantial financial commitments—this study aims to develop and validate a network- and game-theory-based framework for evaluating megaproject resilience. Specifically, our objectives are threefold. We aim to (1) identify and quantify stakeholder interactions (cooperative or conflicting) as they evolve through different project phases, (2) incorporate a Nash equilibrium approach that captures how these interactions inform resilience outcomes, and (3) empirically test the framework in a real-world setting (the Jakarta–Bandung High-Speed Railway), thereby demonstrating its practical utility. While our focus is on resilience evaluation through stakeholder and subsystem dynamics, the study does not attempt to address the full spectrum of megaproject

management concerns (e.g., procurement, financing structures, or day-to-day operations), thus delineating the scope and ensuring that the research questions remain well-defined and targeted.

Research on evaluating resilience in megaprojects, although extensive, still faces notable limitations that hinder its ability to fully capture the complexity and evolving nature of these projects. These shortcomings arise from overly simplistic views of stakeholder behavior, fragmented theoretical foundations, limited integration of resilience dimensions, and difficulties in handling real-world uncertainties and inconsistent data.

Firstly, current resilience evaluation models often assume that stakeholders act independently in their assessments of subsystem resilience. This assumption neglects the complex interplay of collaboration and competition that defines stakeholder dynamics in megaprojects. For instance, stakeholders frequently engage in resource-sharing agreements or compete for limited funding, creating interdependencies that significantly influence the project's overall resilience. The failure to incorporate these relationships results in resilience evaluations that do not fully reflect the operational realities of megaprojects [7–9].

Secondly, resilience evaluations often emphasize a single dimension, such as technical or operational resilience, without considering the interconnections between multiple dimensions [9,10]. For instance, a method might measure the robustness of a transportation subsystem without considering its environmental footprint or social acceptance. This narrow approach fails to capture the systemic nature of megaproject resilience, which relies on the interplay of technical, social, and organizational factors. Addressing this gap requires a comprehensive or unified model that integrates multiple priories in resilience evaluation while accounting for the diverse perspectives of stakeholders involved.

Thirdly, the high levels of uncertainty in megaprojects, such as unexpected regulatory changes or natural disasters, are not adequately addressed by traditional static risk assessment models. These methods often fail to account for adaptive processes that reflect the dynamic and iterative nature of resilience. For instance, system dynamics models have demonstrated their effectiveness in urban systems by simulating the propagation of unexpected disruptions through interconnected networks, thereby providing insights unattainable through static approaches. To bridge this research gap, it is essential to adopt a systems thinking perspective, which holistically considers the dynamics of stakeholder interactions [10] and their co-evolutionary processes, enabling the development of a more forward-looking and adaptive resilience assessment model.

Additionally, the limited practical applicability of many models stems from overly complex methodologies. While some resilience evaluation models demonstrate mathematical sophistication, their practical applicability is often constrained by computational complexity and rigid assumptions. Decision makers in large-scale infrastructure projects require tools that integrate diverse resilience metrics and provide actionable insights. The lack of accessible and intuitive tools restricts the real-world utility of many existing methods, particularly in high-pressure environments where rapid decision making is essential. For instance, resilience evaluation methods that combine real-time data with simplified decision support tools have proven effective in urban planning contexts [8,9,11].

Lastly, the scale and complexity of megaprojects often result in incomplete, inconsistent, or noisy data, particularly in stakeholder evaluations of subsystem resilience. Existing approaches typically assume complete datasets, relying on imputation or exclusion strategies to address gaps, which can distort resilience assessments. The lack of robust methods for managing incomplete data remains a critical shortcoming in current models. To address this gap, a network-based approach could leverage the inherent interconnectedness of stakeholders and subsystems in megaprojects, systematically integrating uncertain and fragmented data into the resilience assessment process. For example, network game mod-

els dynamically capture the interdependencies within megaprojects, enabling resilience evaluation to focus on relational patterns rather than absolute values. A study on Arctic fisheries demonstrated the effectiveness of such models in simulating cooperative behavior under varying conditions, even in the presence of missing trade or performance data [12].

To address these research gaps, this paper introduces a novel method for determining stakeholder weights using a network game model designed specifically for the complexities of megaproject resilience evaluation. Unlike traditional methods that treat stakeholders as independent, this approach represents them as interconnected nodes within a network, with their evaluations of subsystem resilience forming the links. This structure allows the model to incorporate the intricate dynamics of stakeholder interactions, such as collaboration and competition, into the resilience evaluation process. Secondly, building on the network game model, the research identifies an optimal solution for stakeholder weights, relying on equilibrium solutions like Nash equilibria to ensure stability in uncertain environments. For instance, simulations demonstrate how the model can derive strategies that balance costs and benefits across the network, even when specific data are incomplete [12]. Additionally, the study connects the optimal solution to network centrality measures, showing how stakeholder influence aligns with established principles in network science. This integration bridges decision making theory and network analysis, offering a unified framework to evaluate stakeholder roles in megaproject resilience. Also, to improve the model's real-world applicability, the paper proposes a strategy for selecting parameters based on dataset characteristics. This approach strikes a balance between theoretical rigor and practical utility, enabling the method to provide actionable insights for practitioners while advancing the theoretical understanding of resilience in complex systems. Finally, to validate the resilience evaluation model in real-world settings, which is based on network game theory and network science, an empirical simulation was carried out with the evaluation data of the megaproject of Jakarta–Bandung High-Speed Railway.

2. The Construction of a Resilience Evaluation Model for Megaprojects

Recent studies underscore the growing prevalence of network-based and game theory approaches in analyzing stakeholder interactions across megaprojects. On one hand, scholars emphasize the importance of knowledge sharing and collaborative behaviors for project success—highlighting how owners, contractors, and designers strategically leverage resources or gain competitive advantage by positioning themselves in project networks [13,14]. On the other hand, complex network theory has advanced our understanding of megaproject vulnerability, relational governance, and multidimensional stakeholder exchanges [15–17], revealing that factors like centrality, density, and reciprocal behaviors shape both project risks and collective value creation. Building on these insights, our approach integrates dynamic equilibrium concepts with a network-based resilience evaluation, incorporating the notion that stakeholder behavior, contractual frameworks, and governance structures are deeply interlinked [18]. By embedding game theoretic mechanisms within a lifecycle perspective, we extend existing models to more holistically capture cooperation, conflict, and the evolving roles of project actors. In doing so, we offer a robust framework that not only reflects how specific relational behaviors and risk prevention strategies emerge but also provides a quantitative lens for guiding resource allocation and enhancing overall megaproject resilience.

Despite significant attention on megaproject resilience, few studies thoroughly explore how network-based stakeholder interactions and game theoretic mechanisms might shape the distribution of influence (weights) across different project phases. Accordingly, we propose two research questions and two hypotheses, shown in Table 1, to guide our investigation into these dynamic processes. By organizing them in a single table, we illustrate a

direct link between each research question and its associated hypothesis, thereby clarifying the analytical focus of this study. We hypothesize that explicitly modeling stakeholder cooperation/conflict (RQ1/H1) and incorporating a Nash-equilibrium-based weighting scheme (RQ2/H2) will yield robust and adaptive resilience evaluations throughout a megaproject's lifecycle.

Table 1. Research questions and hypotheses.

Research Questions	Hypotheses
RQ1: *How do network-based stakeholder interactions (cooperation/conflict) affect the distribution of influence (weights) in resilience evaluations?*	**H1:** *Incorporating explicit relationship intensities will produce significantly different stakeholder weight distributions compared to static, individually based models.*
RQ2: *In what ways does adding a game theoretic equilibrium mechanism improve the robustness and adaptability of these weight allocations over different project phases?*	**H2:** *When a Nash-equilibrium-based weighting scheme is used, stakeholder weights will more effectively adjust to phase-specific changes and external disruptions, leading to higher stability in resilience rankings.*

2.1. Theoretical Foundation of Resilience Evaluation Model for Megaprojects

Megaprojects, by their very nature, are complex, large-scale undertakings involving multiple stakeholders with diverse interests, resources, and objectives. Evaluating the resilience and overall performance of such projects requires a robust framework capable of capturing the intricate interdependencies between various subsystems and stakeholders. This research proposes the use of game theory and network theory as the theoretical foundation for an integrated evaluation model, combining the strengths of both approaches to address the dynamic nature of stakeholder interactions, conflicts, and cooperation that characterize megaprojects. The integration of these theories provides a comprehensive tool for assessing resilience in megaprojects, enabling real-time adjustments to stakeholder influence and the continuous recalibration of evaluation metrics throughout the project lifecycle.

2.1.1. Game Theory

Game theory is a mathematical framework that analyzes decision making in situations where outcomes are dependent not only on one's own actions but also on the actions of others, which is applicable to multicriteria evaluation [19,20]. In the context of megaprojects, game theory is particularly relevant because it allows for the modeling of strategic interactions between diverse stakeholders, such as project owners, contractors, local communities, and environmental groups, each of whom has their own objectives, priorities, and constraints. These interactions are often cooperative, but they can also be competitive or conflictual [21], particularly when stakeholders' interests diverge over key issues, such as project timelines, budget allocations, or environmental concerns. The use of Nash equilibrium in game theory provides a powerful tool for understanding how stakeholders can reach stable outcomes [22] when no single party has an incentive to deviate from their chosen strategy given the strategies of others. This concept is particularly applicable to megaprojects, where stakeholders often engage in negotiations, trade-offs, and compromise, resulting in a stable configuration of interests that supports long-term project success [23]. By applying game theory to megaproject evaluation, we can model these strategic interactions and assess how stakeholder behaviors—whether cooperative or adversarial—affect the resilience of the project over time.

2.1.2. Network Perspective

Social network theory focuses on the study of relationships and interconnections between various entities within a system. In megaprojects, these entities can be individual stakeholders, subsystems (e.g., operational management, environmental protection, technology systems), or even external factors, such as regulatory bodies or community groups. Network theory is especially useful for understanding the interdependencies that exist within megaprojects [18], where the risk or vulnerability of one subsystem often depends on the actions and stability of others [15]. For example, the successful operation of the technology system may be contingent upon the performance of maintenance teams, technology providers, and financial institutions, all of whom are interconnected within a network of relationships. By modeling interdependencies in a megaproject as a network [24], the network perspective allows us to examine how the interactions between stakeholders and subsystems evolve over time and how these evolving interactions influence the overall resilience of the megaproject. The dynamic nature of these relationships, where stakeholder influence can shift based on changing project priorities or unforeseen challenges, makes network theory an ideal tool for megaproject evaluation.

2.1.3. Theoretical Relevance to Megaproject Evaluation

The integration of game theory and network theory provides an effective theoretical tool to explain the emergence of stakeholders' particular actions [25,26]. For example, a game-theoretical model of social network evolution is aligned with empirical, historical, and sociological observations of real-world datasets [27]. Megaprojects involve numerous stakeholders with varying interests, objectives, and power dynamics, and these relationships must be carefully modeled to understand how they influence project outcomes. To this end, a game-theoretical approach based on networked stakeholders is particularly suitable for megaprojects because it enables the evaluation model to adapt to shifting stakeholder roles, evolving project conditions, and the complex interplay of conflicting interests. The Nash equilibrium ensures that stakeholder interactions lead to stable, sustainable outcomes, while network theory ensures that the interdependencies between subsystems are adequately accounted for in the resilience assessment. As such, this theoretical framework allows for the dynamic recalibration of stakeholder influence throughout the project lifecycle, providing a more accurate and holistic evaluation of megaproject resilience than traditional, static models.

2.2. Resilience Evaluation Model and Its Specifications

2.2.1. Basic Assumption of the Proposed Resilience Evaluation Model

Before presenting the model and analyzing its parameters and properties, it is essential to establish the foundational assumptions that underpin its formulation and applicability. These assumptions provide a theoretical basis for understanding stakeholder behavior and its role in evaluating the resilience of megaprojects.

The model assumes that each stakeholder acts as a rational evaluator aiming to provide assessments that are widely accepted and maximize the value of their evaluations. Rooted in rational choice theory, this assumption posits that stakeholders act in ways that optimize their perceived outcomes. In the context of megaproject resilience, stakeholders—including government agencies, contractors, financiers, and community representatives—are incentivized to deliver evaluations aligned with their priorities. These assessments influence critical decisions regarding the project's adaptability, robustness, and capacity to recover from disruptions. For example, an engineer evaluating the structural resilience of a subsystem, such as a bridge, is likely to offer a detailed assessment to identify potential improvements, adhering to professional standards and contractual obligations. Similarly, a

financier assessing economic resilience may emphasize risks like cost overruns or funding gaps to ensure the project's financial sustainability.

The model also recognizes the complexities and occasional deviations in stakeholder behavior. Stakeholders may strategically manipulate their evaluations to prioritize individual goals over collective resilience objectives. For instance, a developer might overstate the importance of a subsystem related to their expertise, such as energy systems, to secure funding—even if it is less critical to overall resilience. Conversely, other stakeholders may undervalue aspects like environmental sustainability to focus on competing priorities, such as cost efficiency. While these behaviors may appear self-serving, they still align with the rational evaluator framework, as stakeholders strategically act to maximize the acceptance of their evaluations. This inherent tension between individual priorities and collective goals reflects the practical realities of megaproject governance, making the rational evaluator assumption both practical and flexible.

However, the model distinguishes rational behavior from irrational actions that fall outside of its scope. Irrational behaviors, such as apathy or disengagement, result in incomplete or indifferent evaluations that lack strategic intent or meaningful participation. For example, a community stakeholder in a flood-resilient urban transit project may lack the expertise or trust needed to engage effectively with technical evaluations, providing limited or unhelpful input. If a dataset contains a significant number of such irrational behaviors, the model's applicability diminishes, as it relies on meaningful evaluations to capture stakeholder dynamics and relationships accurately.

In most practical megaproject contexts, large-scale irrational stakeholder behavior is rare. Stakeholders typically approach evaluations with responsibility and alignment with their expertise. For instance, government agencies prioritize policy compliance, contractors focus on engineering resilience, and financiers assess economic risks, collectively contributing to a holistic understanding of the project's resilience. These rational assessments, while shaped by individual priorities, help build a comprehensive evaluation of the project's ability to adapt and recover.

To reinforce the assumption of rationality, megaprojects often employ governance mechanisms that ensure evaluations are conducted responsibly and transparently. Techniques like peer reviews, independent validations, and multi-stakeholder workshops mitigate the risks of manipulation or disengagement. Predefined resilience metrics, such as adaptability, robustness, and recoverability, serve as benchmarks to validate stakeholder evaluations. These mechanisms ensure that individual assessments contribute meaningfully to collective evaluations, enhancing the model's practical applicability.

Nevertheless, it is important to note that in real-world contexts, stakeholder behaviors may deviate from pure rationality in more complex or unforeseen ways than this model currently accommodates. Factors like behavioral biases, political motivations, or cultural norms can lead some stakeholders to provide evaluations that are neither consistent nor strategically self-interested in the classic sense. These departures from rationality can introduce noise or systematic skew into the assessment process, potentially affecting the model's equilibrium outcomes and the reliability of stakeholder weight allocations. Although this study offers initial approaches (e.g., governance mechanisms and data validation) to mitigate such effects, future research could explore additional methods, such as integrating behavioral game theory or incorporating iterative feedback loops, to better account for stakeholders who do not conform to strict rational evaluator assumptions. Such extensions would further enhance the robustness and real-world applicability of the proposed resilience evaluation framework.

In conclusion, the assumption that stakeholders act as rational evaluators provides a robust foundation for the model. It enables systematic analysis of stakeholder dynamics in

resilience evaluations while accounting for potential deviations, such as strategic manipulation. Governance mechanisms address risks associated with irrational behavior, ensuring that the model remains applicable in real-world scenarios where most stakeholders engage earnestly and strategically. Clarifying these assumptions is a critical step before defining the model and analyzing its parameters and properties.

2.2.2. Basic Parameters and Properties of the Proposed Resilience Evaluation Model

The evaluation system can be abstracted into the following model for generality: the system comprises n stakeholders, who provide ratings for m subsystems of a megaproject. Each stakeholder may rate all or part of the subsystems. When the i-th stakeholder rates the s-th subsystem, the score is denoted as v_{is}. If no score is provided, it is recorded as "–". Here, $i \in \{1, 2, \ldots, n\}$ and $s \in \{1, 2, \ldots, m\}$. The score v_{is} can be any real number, but, in general, $v_{is} \geq 0$. An illustrative example is provided in Table 2.

Table 2. An illustrative form of the resilience evaluation model.

	Subsystem 1	**Subsystem 2**	...	**Subsystem m**
Stakeholder 1	v_{11}	v_{12}	...	v_{1m}
Stakeholder 2	v_{21}	–	...	v_{2m}
...	...	...	...	...
Stakeholder n	v_{n1}	v_{n2}	...	v_{nm}

The evaluation behavior of stakeholders connects them to one another, transforming them from isolated individuals into an interconnected network. This interconnectedness forms the foundation of the network model. Using Table 2 as an example, it can be observed that Stakeholder 1 and Stakeholder 2 are connected because they both evaluated Subsystem 1 and Subsystem 2. However, due to differences in their preferences and ratings, the relationship between these stakeholders may involve both "cooperation" and "conflict". This dynamic is the focal point for constructing the network game model.

Specifically, if two stakeholders provide similar evaluations, they exhibit a stronger "cooperative" relationship within the network. Conversely, if their evaluations differ significantly, they exhibit a stronger "conflict" relationship. These relationships are fundamental to the formulation of the network game and the analysis of its Nash equilibrium. Through the utility analysis presented in subsequent sections, it will be shown that the equilibrium outcome of this game determines the weight allocation for each stakeholder in the network. This weight allocation can also be interpreted as their "influence" within the network.

- Relationship intensity σ_{ij} between stakeholders

To characterize the cooperative and conflicting relationships between stakeholders and to quantify these relationships, a relationship intensity matrix is defined as $\sigma = [\sigma_{ij}]_{i,j=1,\ldots,n}$, where σ_{ij} represents the quantified value of the relationship between Stakeholder i and Stakeholder j.

Let s and t denote the types of subsystems ($s, t \in \{1, 2, \ldots, m\}$). For Stakeholders i and j ($i, j \in \{1, 2, \ldots, n\}, and\ i \neq j$), the consistency index C_{st}^{ij} is first defined to measure the agreement between the evaluations of Stakeholders i and j for two subsystems (denoted as s and t). To calculate the consistency index C_{st}^{ij}, which measures the agreement between Stakeholders i and j concerning their evaluations of two subsystems s and t, several cases are considered.

First, if the stakeholders exhibit full consistency in their relative evaluations of the subsystems, the consistency index is assigned a value of 1. This occurs when both stakeholders agree on the ranking of the subsystems. For example, if Stakeholder i gives an evaluation of subsystem s that is lower than their evaluation of subsystem t ($v_{is} < v_{it}$) and Stakeholder

j provides a similar evaluation ($v_{js} < v_{jt}$), their evaluations are fully consistent. The same holds true if both stakeholders give an evaluation of subsystem s that is higher than their evaluation of subsystem t ($v_{is} > v_{it}$ and $v_{js} > v_{jt}$). Additionally, if both stakeholders assign identical values to subsystems s and t ($v_{is} = v_{it} \neq$ "–"and $v_{js} = v_{jt} \neq$ "–"), their evaluations are also considered fully consistent.

In cases of partial consistency, the consistency index is assigned a value of 0.5. Partial consistency occurs when one stakeholder provides identical evaluations for subsystems s and t but the other stakeholder's evaluations differ. For instance, if Stakeholder i evaluates both subsystems equally ($v_{is} = v_{it}$) while Stakeholder j provides differing evaluations ($v_{js} \neq v_{jt}$), or vice versa, their evaluations exhibit partial consistency.

When there is no observable consistency between the evaluations, or if either stakeholder has not provided evaluations for the considered subsystems, the consistency index is assigned a value of 0. This lack of consistency may result from conflicting evaluations or incomplete data, such as when v_{is}, v_{it}, v_{js}, or v_{jt} are marked as "-".

Following the approach above, the relationship intensity σ_{ij} is derived by aggregating the evaluation information of the two stakeholders across all subsystems. This method for calculating the consistency index serves as a quantitative foundation for assessing the relationships between stakeholders. It enables the construction of the relationship intensity matrix σ, which is central to capturing the cooperative and conflicting dynamics between stakeholders within the network.

- Simplified explanation of relationship intensity σ_{ij} using an example

To illustrate how the relationship intensity matrix $\sigma = [\sigma_{ij}]$ works, consider a simplified scenario with three stakeholders—an owner (O), a contractor (C), and a community representative (R)—who each evaluate two subsystems in a large-scale rail megaproject (e.g., Track Infrastructure and Safety Systems).

1. The owner (O) rates Track Infrastructure higher than Safety Systems (i.e., $v_{O,\text{Track}} > v_{O,\text{Safety}}$).
2. The contractor (C) gives equal ratings to both subsystems (i.e., $v_{C,\text{Track}} = v_{C,\text{Safety}}$).
3. The community representative (R) rates Safety Systems higher than Track Infrastructure (i.e., $v_{R,\text{Track}} < v_{R,\text{Safety}}$).

From these evaluations, we compare each pair of stakeholders.

- Owner (O) vs. contractor (C)

For Track Infrastructure vs. Safety Systems, the owner's ratings are not the same as the contractor's (because the contractor gave equal scores). According to our rules, this might yield a partial consistency value (e.g., 0.5) for that pair. Summing across all subsystems, we calculate an overall σ_{OC}.

- Owner (O) vs. community Representative (R)

Their preferences for Track vs. Safety are in complete opposition (one higher, the other lower). This yields a negative consistency contribution for that pair, decreasing the σ_{OR}.

- Contractor (C) vs. community representative (R)

The contractor rates both subsystems equally, but the community representative gives a higher score to Safety. This again might result in a partial match (0.5) or a partial conflict, depending on the exact scoring scheme. Hence, σ_{CR} might be near zero or slightly negative.

After assigning these consistency or conflict values for each pair and aggregating them, we populate the matrix σ. For instance, if each pair's aggregated value ends up being 0.3, -0.2, or 0.5 depending on how they align on each subsystem, σ could look like this:

$$\sigma = \begin{bmatrix} 0 & 0.3 & -0.2 \\ 0.3 & 0 & 0.5 \\ -0.2 & 0.5 & 0 \end{bmatrix},$$

where each σ_{ij} denotes the relationship intensity between stakeholders i and j. A positive value (>0) indicates a more cooperative or aligned relationship, and a negative value (<0) signifies greater conflict or misalignment.

2.2.3. Basic Rationale of the Proposed Resilience Evaluation Model

Before delving into the derivation and properties of the stakeholder utility function, it is crucial to establish its theoretical foundation and contextual relevance within the resilience evaluation of megaprojects. The rationale for this resilience evaluation model lies in the inherent complexity of megaprojects, where multiple subsystems are evaluated by diverse stakeholders whose actions and assessments are interdependent. Resilience in this context refers to the ability of the megaproject to adapt to, recover from, and withstand disruptions. Rooted in network theory and game theory, the network model and the utility function together capture the dynamics of stakeholder relationships and provide a systematic way to quantify their contributions to resilience evaluation.

- Capturing stakeholder relationships through the network model

Megaprojects are characterized by interconnected subsystems, each involving stakeholders with varying priorities, expertise, and objectives. The network model reflects this reality by representing stakeholders as nodes and their relationships, defined by the relationship intensity matrix σ, as edges. This matrix encapsulates the degree of agreement or conflict between stakeholders based on their evaluations of shared subsystems. For example, in a large-scale transportation megaproject, government agencies, engineers, financiers, and environmental groups may evaluate different subsystems (e.g., infrastructure robustness, cost efficiency, or environmental impact). The network model captures both cooperative and conflicting dynamics, such as shared goals for robust construction or disputes over funding allocations.

The rationale for this network representation lies in its ability to illustrate how individual evaluations propagate through the stakeholder ecosystem, influencing collective resilience assessments. For instance, a high degree of alignment among key stakeholders, reflected by strong positive edges in the network, can lead to consensus on critical resilience-enhancing measures. Conversely, significant conflicts, represented by negative relationship intensities, highlight areas of misalignment that may undermine resilience efforts.

This network representation provides a structured view of how stakeholder relationships influence resilience evaluations. By focusing on shared evaluations, the network model ensures that the analysis is grounded in meaningful interactions, even when some evaluations are missing. The relationship intensity matrix serves as the foundation for understanding how cooperation and conflict shape stakeholders' contributions.

- Utility function as a measure of stakeholder influence and contribution

The stakeholder utility function provides a mathematical framework to evaluate how individual stakeholders' actions and evaluations influence the overall network. It is designed to capture the trade-offs and relational dynamics inherent in stakeholder interactions within a megaproject context. The utility function comprises three essential

components that collectively reflect the incentives, constraints, and interdependencies faced by stakeholders.

The first component is the marginal benefit, which represents the increasing utility a stakeholder gains from contributing to resilience evaluations. This term reflects the stakeholder's incentive to engage meaningfully in the evaluation process, ensuring that their input aligns with the project's goals and adds value to the overall assessment of resilience. It captures the benefits stakeholders perceive from their involvement, motivating their active participation.

The second component is the marginal cost, which accounts for the diminishing returns associated with additional investments of resources or effort in the evaluation process. As stakeholders allocate more resources to evaluations, the incremental benefits of their contributions decrease. This term captures the trade-offs they face when balancing their limited resources among competing priorities, ensuring that their contributions remain rational and proportionate.

The third component is the interaction term, which quantifies the influence of cooperative or conflicting relationships between stakeholders. Positive interactions, where stakeholders align in their evaluations, amplify utility by reinforcing shared goals and fostering collaboration. Conversely, negative interactions, arising from disagreements or misaligned priorities, reduce utility by introducing tension and potential inefficiencies. This term encapsulates the networked nature of stakeholder relationships, reflecting how individual actions are shaped by their interactions with others.

This utility function formalizes the balance between individual contributions and relational dynamics within the network. For example, in a megaproject resilience evaluation, a contractor evaluating a subsystem's robustness may benefit from alignment with engineers who share similar priorities, reflected by a positive interaction term. Conversely, conflicts with financiers prioritizing cost-cutting measures may reduce the contractor's utility.

The utility function is particularly well-suited to resilience evaluations because it captures the trade-offs stakeholders face when balancing their contributions against their interactions in the network. Resilience is a collective property that depends on the alignment and cooperation of stakeholders across subsystems. The utility function provides a systematic way to measure and optimize these contributions, ensuring that resources and attention are directed toward enhancing resilience.

In particular, the function's Nash equilibrium solution represents an optimal distribution of stakeholder contributions, where no stakeholder can unilaterally improve their utility without disrupting the network's balance. This equilibrium ensures that the resilience evaluation process is efficient, equitable, and reflective of the collective priorities of the stakeholder network.

2.2.4. Detailed Mathematical Representation of the Resilience Evaluation Model

The proposed model for resilience evaluation leverages a network framework to capture the cooperative and conflicting relationships among stakeholders. The mathematical representation focuses on stakeholder weights, denoted as w_i, which quantify the relative influence of each stakeholder in the resilience evaluation process. The derivation of these weights is guided by a utility function that reflects the effectiveness of each stakeholder's contribution while accounting for their interactions with others in the network.

- Relationship intensity matrix (σ)

The network model is represented by the relationship intensity matrix $\sigma = [\sigma_{ij}]$, where σ_{ij} measures the strength and nature of the relationship between Stakeholder i and Stakeholder j.

- If $\sigma_{ij} > 0$: The relationship is cooperative, indicating alignment in evaluations, which amplifies the utility of both stakeholders.
- If $\sigma_{ij} < 0$: The relationship is conflicting, reflecting disagreement in evaluations, which reduces their utility.
- If $\sigma_{ij} = 0$: No relationship exists, implying no interaction between the two stakeholders.

The matrix is symmetric ($\sigma_{ij} = \sigma_{ji}$), ensuring that the intensity of the relationship is reciprocal.

The relationship intensity matrix enables the model to incorporate stakeholder interdependencies into the resilience evaluation process.

- Utility function

The utility function $u_i(w_1, w_2, \ldots, w_n)$ is defined as

$$u_i(w_1, w_2, \ldots, w_n) = \alpha w_i - \frac{1}{2} c w_i^2 + \sum_{j \neq i} \sigma_{ij} w_i w_j \tag{1}$$

Each term in the utility function has a specific meaning.

αw_i (marginal benefit term): This term represents the increasing utility a stakeholder derives from their weight w_i. The parameter $\alpha > 0$ determines the rate of marginal benefit, incentivizing stakeholders to actively contribute to the evaluation process. A higher α reflects greater importance of stakeholder contributions to the resilience evaluation.

$-\frac{1}{2} c w_i^2$ (marginal cost term): This term models the diminishing returns as stakeholder i increases their weight w_i. The parameter $c > 0$ controls the penalty for excessive weight allocation, ensuring that stakeholder contributions remain proportional and balanced. This term reflects the trade-offs stakeholders face when allocating limited resources.

$\sum_{j \neq i} \sigma_{ij} w_i w_j$ (interaction term): This term quantifies the influence of cooperative or conflicting relationships on stakeholder i's utility. A positive σ_{ij} increases u_i, reflecting the benefits of collaboration with aligned stakeholders. A negative σ_{ij} decreases u_i, capturing the costs of conflicts with misaligned stakeholders. The interaction term emphasizes the networked nature of stakeholder dynamics, showing how individual contributions are shaped by relationships within the network.

Together, these components create a comprehensive framework for evaluating stakeholder influence in resilience assessments.

- Optimization Problem

The objective is to maximize the total utility across all stakeholders while ensuring that the weights satisfy certain constraints:

$$\text{maximize } \sum_{i=1}^{n} u_i(w_1, w_2, ..., w_n) \tag{2}$$

subject to

$$\sum_{i=1}^{n} w_i = 1, \quad w_i \geq 0, \quad i \in \{1, 2, \ldots, n\} \tag{3}$$

This formulation ensures the following.

- Non-negativity: Each stakeholder weight w_i is non-negative, reflecting their active and meaningful contribution to the evaluation.
- Normalization: The weights sum to 1, maintaining a rational and equitable allocation of influence among stakeholders.

- Equilibrium

From a game theoretic perspective, the optimization problem aligns with a Nash equilibrium. At equilibrium, the following occurs.

- Each stakeholder's weight w_i is optimized such that no stakeholder can unilaterally improve their utility without affecting others.
- The equilibrium reflects a balance between individual contributions and the network's cooperative and conflicting dynamics.

This equilibrium integrates the relationship intensity matrix σ into the weight optimization process, directly linking stakeholder interactions to resilience evaluation outcomes. For example, stakeholders with strong cooperative relationships (positive σ_{ij}) are likely to have higher weights, reflecting their collaborative influence on resilience assessments. Conversely, stakeholders with significant conflicts (negative σ_{ij}) may have reduced weights, highlighting their misalignment with the network's goals.

In Section 2.2, these concepts collectively form the foundation of our resilience evaluation framework. First, the relationship intensity matrix σ quantifies how stakeholders' evaluations align or conflict, turning independent assessments into network connections. Next, the utility function expresses each stakeholder's marginal gains, costs, and interaction effects, leading to stakeholder weights $\{w_i\}$. Finally, we solve for the Nash equilibrium, which reflects a stable, balanced configuration of these weights. Substituting these equilibrium values back into the resilience scoring mechanism provides a holistic assessment that captures cooperative and conflicting relationships across project subsystems. Below, Table 3 visually summarize the key concepts, their mathematical underpinnings, and relationships within the holistic framework.

Table 3. Key concepts, mathematical underpinnings, and relationships.

Concept	Description	Key Equation or Element	Significance
Relationship Intensity σ	Captures how stakeholders' evaluations align or conflict, forming a network of relationships.	$\sigma_{ij} \in [-1, 1]$ (see Equation in Section 2.2.2)	Quantifies cooperative (positive) or conflicting (negative) connections, enabling a network-based representation of stakeholder interactions.
Utility Function u_i	Describes each stakeholder's payoff in terms of marginal benefit, cost, and interaction effects with other stakeholders.	$u_i = \alpha w_i - \frac{1}{2} c w_i^2 + \sum_{j \neq i} \sigma_{ij} w_i w_j$ (see Equation in Section 2.2.4)	Provides a mathematical basis for determining how much weight (w_i) each stakeholder will assign, based on rational incentives and network effects.
Stakeholder Weights $\{w_i\}$	The variables being optimized. They represent the influence or importance assigned to each stakeholder in the resilience evaluation.	$\sum_{i=1}^{n} w_i = 1, \quad w_i \geq 0$ (normalization constraint)	Reflect stakeholder influence in the final resilience assessment; their equilibrium values are derived from maximizing utility and balancing interactions.
Nash Equilibrium	The optimal configuration of $\{w_i\}$ where no stakeholder can unilaterally improve their payoff by changing their own weight allocation (given all others remain fixed).	Solved by setting $\frac{\partial u_i}{\partial w_i} = 0$ and applying constraints (see Sections 2.2.4 and 2.3)	Represents a stable, self-enforcing solution that captures how stakeholder interactions dynamically shape final weight allocations.
Resilience Assessment	Evaluates the combined impact of stakeholder-weighted subsystem scores, highlighting how cooperation and conflict influence overall project resilience.	Results from substituting equilibrium $\{w_i\}$ back into the resilience scoring function (see Section 2.2.4).	Provides a comprehensive measure of megaproject resilience that integrates both subsystem data and relational stakeholder dynamics.

2.3. Solutions of the Model and Relevant Properties

This section focuses on analyzing the key properties and solutions of the proposed model, ensuring its mathematical soundness and demonstrating its practical applicability in megaproject resilience evaluation. By linking the theoretical underpinnings of the model with its functional outputs, we aim to establish how stakeholder relationships within a network influence weight allocation decisions.

In simpler terms, this section asks the following:

- Can we always find a solution for the model?
- Is the solution unique and stable?

- How does the solution relate to known network concepts, like centrality?

To address these questions, we first outline the model's key assumptions and transformations and then proceed to analyze the mathematical properties of its solutions.

2.3.1. Transformations and Problem Reformulation

To simplify the analysis of the model, we perform mathematical transformations on the parameters in the optimization problem. These transformations aim to streamline the relationship between stakeholder evaluation weights and the network's structural properties, such as cooperation and conflict, captured by the relationship intensity matrix σ.

The following sections offer a step-by-step examination of the issue.

The original relationship intensity matrix $\sigma = [\sigma_{ij}]$ captures the strength of relationships between stakeholders i and j. To facilitate mathematical operations, the matrix is redefined with parameters γ and λ to create a transformed matrix δ, where

$$\delta = -\beta \cdot I - \gamma \cdot U + \lambda \cdot G \tag{4}$$

with I as the identity matrix, U as a matrix of ones, and G as the adjusted matrix reflecting normalized relationships between stakeholders.

These transformations restructure the original optimization function for stakeholder utility into a concise matrix form:

$$u = \alpha \cdot w + \delta \cdot w = \alpha \cdot w + (-\beta \cdot I - \gamma \cdot U + \lambda \cdot G) \cdot w \tag{5}$$

This reformulation enables us to isolate and study the core elements of the model, including its dependency on the network structure, stakeholder relationships, and their combined effect on optimal weight allocation.

2.3.2. Existence and Uniqueness of Nash Equilibrium

One of the most critical properties of the model is whether it yields a solution that is both stable and unique, which is captured by the concept of Nash equilibrium. A Nash equilibrium represents a state where no stakeholder can improve their utility by unilaterally changing their weight allocation, given the weights chosen by others.

- Existence of Nash Equilibrium

To prove the existence of Nash equilibrium, we rely on the relationship intensity matrix G. If the parameter β is chosen within a specific range,

$$0 < \beta < \frac{1}{\mu_1(G)} \tag{6}$$

where $\mu_1(G)$ is the largest eigenvalue of G, the optimization problem always has a solution.

This condition ensures that the matrix $I - (\lambda/\beta) \cdot G$ is invertible and positively definite, providing a mathematically stable foundation for the model.

- Uniqueness of Nash Equilibrium

Uniqueness is critical for ensuring that the model produces a single, interpretable solution. By leveraging the properties of the transformed matrix δ, we prove that under the same conditions for β, the model produces a unique Nash equilibrium.

In practical terms, this means that the optimal weight allocation for stakeholders is predictable and does not depend on arbitrary factors or initial conditions, making it a reliable tool for decision making in megaproject resilience evaluations.

2.3.3. Relationship with Network Centrality

The next question is the following: what do the solutions mean in terms of the network? This section explores how the solutions relate to network centrality, a fundamental concept in network science that measures the relative importance of nodes (in this case, stakeholders) within a network.

- Two limiting cases

The behavior of the model under extreme conditions provides additional insights into its connection with network centrality.

Uniform weights ($\beta \to +\infty$):

When $\beta \to +\infty$, the network's structure becomes irrelevant, and all stakeholders are assigned equal weights:

$$w_i^* = \frac{1}{n} \tag{7}$$

This represents a scenario where stakeholder influence is completely independent of their relationships, effectively treating everyone equally. For instance, in a megaproject with multiple unrelated subsystems, equal weighting might represent a situation where all stakeholders contribute equally without any network effect.

Eigenvector centrality ($\beta \to \lambda\mu_1(G)$):

When $\beta \to \lambda\mu_1(G)$, the optimal weights align with the principal eigenvector of G, normalized to sum to 1:

$$w_i^* = \frac{x_1^G(i)}{\sum_{j=1}^n x_1^G(j)} \tag{8}$$

where x_1^G represents the principal eigenvector. This outcome emphasizes the structural importance of stakeholders in the network, as those more central to the network receive higher weights. For example, in a megaproject with tightly coupled subsystems, stakeholders with more connections or stronger relationships will naturally have greater influence.

- Balancing uniformity and network influence

The parameter β serves as a dial to adjust the model's sensitivity to network relationships. By tuning β, decision makers can balance between treating all stakeholders equally (useful for fairness) and emphasizing network centrality (useful for efficiency).

All of the properties above facilitate a robust framework for evaluating stakeholder influence in complex systems like megaprojects. The existence and uniqueness of solutions ensure that the weight allocation process is stable and reproducible, critical for large-scale projects involving diverse stakeholders. Meanwhile, the connection to network centrality highlights the model's ability to incorporate nuanced relationship dynamics.

Below, Table 4 summarize key assumptions and parameters of the Methodology section.

Table 4. Summary of key assumptions and parameters.

Category	Element	Description	Relevance
Stakeholder Model	**Rational Evaluators**	Assumes that stakeholders make decisions aiming to maximize their perceived outcomes (utility functions).	Guides the game theoretic approach; forms the basis for calculating equilibrium weights.
	Limited Irrational Behavior	Stakeholders are generally rational, but strategic misreporting or minor biases may occur.	Highlights the possibility of data skew; underscores the need for checks and validations.
Interaction Matrix	**Relationship Intensity (σ)**	Quantifies cooperative or conflicting relationships among stakeholders based on subsystem evaluations.	Converts individual scores into a networked game framework, capturing positive/negative ties.
	Symmetry Assumption	$\sigma_{ij} = \sigma_{ji}$; relationships are reciprocal (although they can be positive, negative, or neutral).	Ensures a balanced matrix representation of stakeholder relations and simplifies analysis.

Table 4. *Cont.*

Category	Element	Description	Relevance
Utility Function	**Marginal Benefit (α)**	Controls incentive for increasing a stakeholder's weight.	Central in defining how stakeholder allocations change with greater "effort".
	Marginal Cost (c)	Penalizes excessive weight allocation, preventing one stakeholder from dominating.	Helps maintain a balanced distribution of weights across multiple stakeholders.
	Interaction Term ($\sigma_{ij} w_i w_j$)	Reflects how collaborative or conflicting relationships amplify or diminish stakeholder utility.	Captures the network effect; ensures that interactions shape equilibrium allocations.
Equilibrium Concept	**Nash Equilibrium**	A stable state where no stakeholder can unilaterally improve their utility by altering only their own weight.	Ensures a self-enforcing distribution of stakeholder weights, reflecting real-world dynamics.
Data Requirements	**Complete Evaluations**	Stakeholders must provide reliable, comprehensive subsystem scores.	Key for accurate relationship intensity calculations and subsequent equilibrium solutions.
	Handling Data Gaps	Partial methods exist (e.g., setting default values), but large data gaps reduce overall model reliability.	Emphasizes the importance of data completeness for robust utility and network calculations.

3. Case Study for Empirical Validation of Proposed Resilience Evaluation Model

3.1. Rationale for Case Study and Case Selection

3.1.1. Rationale for Case Study

The theoretical development of the model ensures its mathematical rigor, but real-world data are essential to validate its assumptions and practical applicability. Megaprojects are inherently complex, involving diverse stakeholders with competing priorities and intricate interdependencies among subsystems. Applying the model to an actual megaproject provides an opportunity to test its robustness in addressing these complexities, ensuring that theoretical assumptions are grounded in practice. The model assumes rational stakeholder behavior, structured relationships, and evaluative weights that capture both cooperative and conflicting dynamics. Real-world case studies enable researchers to evaluate whether these assumptions hold true in practice or require adjustments. Furthermore, properties, such as the existence and uniqueness of Nash equilibrium and alignment with network centrality measures, must be validated in real-world contexts to confirm their relevance and reliability. A case study ensures that theoretical solutions are not only mathematically consistent but also practically meaningful. By bridging the gap between academic research and practical implementation, case studies provide actionable insights that enhance the model's utility. They allow researchers to identify potential discrepancies, refine assumptions, and tailor the model to the complexities of real-world scenarios. Demonstrating the model's performance in real-world applications also builds confidence among practitioners and policymakers, fostering its adoption as a robust framework for resilience evaluation.

3.1.2. Rationale for Case Selection

The Jakarta–Bandung High-Speed Railway (JBHSR) serves as a compelling real-world case to demonstrate the effectiveness of the proposed resilience evaluation model. This ambitious megaproject, connecting Indonesia's capital, Jakarta, to Bandung, exemplifies the complexities, challenges, and diverse stakeholder interactions that the model is designed to address.

Firstly, the JBHSR involves a broad range of stakeholders, including the Indonesian government, Chinese state-owned enterprises, local contractors, private investors, and affected communities. These groups bring varied priorities, from economic development and regional connectivity to addressing social and environmental concerns. Secondly, the project's key subsystems include track infrastructure, rolling stock, safety systems, environmental mitigation efforts, and station development. Each subsystem is associated

with specific stakeholders, whose evaluations and influence differ significantly. Thirdly, stakeholder interactions have included both collaboration and conflict. For example, the project faced delays due to land acquisition disputes with local communities, funding coordination challenges between governments and investors, and environmental compliance concerns raised by advocacy groups. These dynamics make the JBHSR an ideal context for analyzing stakeholder cooperation and conflict.

The JBHSR project is particularly suitable for testing the proposed resilience model because of its complexity and exposure to significant uncertainties and disruptions throughout its lifecycle. The scale and multifaceted nature of the project, coupled with external shocks like the COVID-19 pandemic, provide a rich dataset for analyzing resilience. The pandemic posed unprecedented challenges, disrupting construction timelines through supply chain breakdowns, labor shortages, and public health restrictions. Stakeholders were forced to adapt strategies to mitigate delays and cost overruns, demonstrating both the system's vulnerabilities and its adaptive capacity. For instance, contractors introduced enhanced health and safety protocols, while financiers restructured funding mechanisms to align with revised schedules. These cooperative efforts highlight the importance of analyzing the relationship intensity matrix (σ) to understand how collaboration and conflict impact resilience.

Despite these disruptions, the project managed to recover, eventually achieving operational readiness in October 2023. The process of disruption and recovery underscores the relevance of the proposed model in capturing shock absorption and recovery dynamics. For example, when delays became unavoidable, stakeholders negotiated revised timelines and budgets, illustrating the critical role of adaptive governance in megaproject management.

By incorporating data from the pre-construction, construction, and post-operation phases, the JBHSR case allows for a comprehensive analysis of resilience across the entire project lifecycle. The inclusion of data on major disruptions, such as the pandemic, enriches the evaluation by enabling the model to capture how subsystems and the overall project absorb and recover from shocks. This case study not only validates the theoretical framework of the proposed model but also offers practical insights for improving resilience in megaprojects facing complex and uncertain environments.

3.2. Case Background and Timeline

The Jakarta–Bandung High-Speed Railway (JBHSR) is a groundbreaking infrastructure project designed to enhance connectivity between Indonesia's capital, Jakarta, and the city of Bandung, located approximately 142 km to the southeast. It forms part of Indonesia's broader initiative to modernize infrastructure, stimulate economic growth, and reduce travel time between key urban centers. As Southeast Asia's first high-speed railway and a flagship project under China's Belt and Road Initiative, the JBHSR reflects a pivotal partnership between Indonesia and China.

The project's origins trace back to a competitive tendering process in 2015, during which both Japan and China submitted proposals. Japan's bid included traditional funding with state guarantees, while China proposed an innovative business-to-business financing model that did not require such guarantees. Coupled with promises of advanced technology and rapid implementation, China's proposal secured the contract in October 2015. The agreement brought together a diverse group of stakeholders, including state-owned enterprises from both nations, local governments, and private investors, setting the stage for the railway's development.

Groundbreaking for the JBHSR occurred in January 2016, marked by a high-profile ceremony attended by senior officials from Indonesia and China. Early stages involved preparatory work, including land acquisition and regulatory approvals. However, signif-

icant challenges emerged, including delays in land acquisition, regulatory hurdles, and public resistance in some areas. These setbacks postponed the start of full-scale construction.

By 2018, construction was underway, focusing on key subsystems, such as track laying, station development, and the installation of advanced signaling and power systems. Critical milestones were achieved by 2020, including the near-completion of major stations and substantial progress on the tracks. In 2022, rolling stock designed specifically for the JBHSR was delivered from China, marking a significant step toward operational readiness. Testing and commissioning followed to ensure compliance with international safety and technical standards.

The COVID-19 pandemic introduced unprecedented challenges, causing delays due to supply chain disruptions, labor shortages, and public health restrictions. Stakeholders adapted by implementing safety protocols, renegotiating timelines, and restructuring financial agreements, ensuring continued progress despite setbacks.

In October 2023, the JBHSR was officially inaugurated by Indonesian President Joko Widodo. The railway reduced travel time between Jakarta and Bandung from over three hours to just 40 min, significantly boosting regional connectivity and economic activity. The inauguration marked a historic achievement as the JBHSR became Southeast Asia's first high-speed railway, symbolizing Indonesia's progress in infrastructure modernization.

Post-operation, the railway has entered a phase of performance monitoring to optimize operations and address initial challenges. Stakeholders are assessing key factors, such as passenger demand, maintenance efficiency, and socio-economic impacts, to ensure the railway delivers its intended long-term benefits. The JBHSR's journey, from conceptualization to operation, underscores the complexities and opportunities involved in managing a megaproject, particularly in a context shaped by significant challenges and uncertainties.

3.3. Systems and Stakeholders of the Case Megaproject

3.3.1. Systems of the Case Megaproject

The Jakarta–Bandung High-Speed Railway (JBHSR) exemplifies a system of systems (SoS), where multiple interdependent subsystems work in coordination to achieve overarching goals. This complex, multi-layered project demonstrates how individual components contribute distinct functionalities while requiring seamless integration to ensure overall performance, resilience, and success.

Technical subsystems form the operational backbone of the JBHSR. These include track infrastructure, stations, rolling stock, and signaling and communication systems. The track infrastructure provides the foundation for high-speed travel, while stations serve as hubs for passenger interaction and transit flow. Rolling stock, comprising the high-speed trains, integrates with signaling and communication systems to enable synchronized, efficient, and safe operations. These subsystems are highly interdependent; for instance, a malfunction in the signaling system can disrupt the entire railway network, highlighting the need for flawless coordination.

Supporting these technical components are maintenance and monitoring subsystems, which ensure long-term reliability and operational efficiency. Advanced diagnostics are employed to monitor track conditions, rolling stock performance, and electrification networks, addressing potential failures before they escalate into disruptions. The power supply and electrification subsystems further enable these operations, providing stable and consistent energy essential for high-speed rail functionality.

The JBHSR also relies heavily on financial and economic subsystems, which underpin its sustainability. Financing mechanisms, such as loans from Chinese banks and investments from public and private entities, were vital during the development phase. Revenue systems, including ticketing platforms and ancillary income sources, like retail spaces at

stations, ensure economic viability in the operational phase. These financial subsystems are closely linked to regional economic integration efforts, as the railway stimulates trade, tourism, and economic activity along the Jakarta–Bandung corridor. The interconnection between financial and technical subsystems underscores how economic performance directly influences the railway's ability to maintain and expand infrastructure.

Social and community subsystems add a vital dimension to the JBHSR as an SoS. Community engagement processes aim to address the concerns of local populations affected by land acquisition and urban development. These efforts ensure fair compensation, resettlement, and tangible benefits, like improved accessibility and economic opportunities. Social considerations also extend to providing equitable transit options for underserved populations, fostering public support critical to the project's long-term success.

Environmental subsystems play a crucial role in aligning the railway with sustainability objectives. Initiatives, such as reforestation, noise mitigation, and water management systems, minimize the project's ecological footprint. These environmental measures are tightly integrated with technical subsystems, such as track construction, ensuring harmony between infrastructure development and environmental stewardship.

Bringing these elements together are strategic and integrative subsystems, which connect technical, financial, social, and environmental components to achieve broader goals. Regional economic integration is a prime example, which depends on the railway's ability to link urban centers and facilitate trade and commerce. Urban infrastructure development around stations supports this effort by creating economic zones and enhancing connectivity with local transportation networks.

The JBHSR, as a system of systems, exemplifies the interplay and interdependence of its components. Each subsystem operates with relative autonomy but contributes to the larger system's functionality and resilience. This perspective highlights that no subsystem functions in isolation; their collective performance determines the overall success of the railway. The integration of diverse subsystems—technical, financial, social, environmental, and strategic—reflects the complexity and sophistication required to manage a megaproject like the JBHSR effectively.

3.3.2. Stakeholders of the Case Megaproject

The Jakarta–Bandung High-Speed Railway (JBHSR) exemplifies a megaproject that brings together a diverse array of stakeholders, each playing a critical role in shaping its development, implementation, and operation. These stakeholders encompass governmental, corporate, financial, community, operational, and environmental entities, each with unique priorities and areas of influence. Their interactions underscore the complexity and interdependence inherent in managing such a large-scale infrastructure project.

Governmental stakeholders are central to the JBHSR, ensuring alignment with national development objectives and facilitating intergovernmental coordination. The Indonesian national government oversees the project, with key ministries, such as the Ministry of Transportation and the Ministry of Finance, providing regulatory oversight and financial governance. Regional governments, including those of Jakarta, West Java, and Bandung, address localized issues, such as land acquisition and integration with regional infrastructure. Collectively, these entities aim to ensure that the railway achieves its operational goals while supporting broader socio-economic development.

Corporate stakeholders play a pivotal role, led by the China Railway Corporation (CRC) and PT Kereta Cepat Indonesia–China (KCIC), a joint venture between Indonesian and Chinese state-owned enterprises. These organizations manage the technical aspects of the railway, including construction, technology transfer, and system integration. Local contractors and suppliers provide essential materials, expertise, and services, ensuring that

the railway is built to specification. Additionally, Chinese state-owned enterprises like CRRC contribute advanced technologies, such as rolling stock and signaling systems.

Financial stakeholders provide the economic foundation for the project. Chinese banks, including the China Development Bank, supply substantial loans, while Indonesian banks and private investors offer complementary funding. These entities focus on the railway's financial resilience, evaluating its potential for revenue generation and long-term sustainability. Their analyses influence key decisions related to ticket pricing, ancillary revenue streams, and cost management strategies.

Community and advocacy groups represent the social dimension of the JBHSR. Local communities impacted by land acquisition and construction have direct stakes in the project, voicing concerns about fair compensation, resettlement, and equitable benefits, such as improved accessibility and economic opportunities. Civil society organizations (CSOs) amplify these concerns, advocating for transparency, equity, and environmental responsibility. Passenger groups provide feedback on accessibility, affordability, and service quality, ensuring the railway meets the needs of its users.

Operational stakeholders take center stage during the post-operation phase. Railway operators and maintenance companies manage day-to-day operations, prioritizing safety, reliability, and efficiency. Engineering consultants contribute specialized expertise during construction and operational phases, ensuring the systems meet international standards and adapt to evolving demands.

Environmental advocacy groups and independent auditors address the ecological and governance dimensions of the project. Environmental advocates monitor compliance with environmental standards and assess the railway's long-term ecological impact. Independent auditors offer third-party evaluations of financial, operational, and environmental performance, ensuring accountability and transparency throughout the project.

The interplay among these stakeholders highlights the complexity of managing a megaproject like the JBHSR. Governmental entities provide policy direction and oversight, corporate and financial stakeholders enable implementation and economic sustainability, community groups ensure social inclusion, operational stakeholders maintain system performance, and environmental advocates safeguard ecological balance. While each group brings distinct priorities and perspectives, their collective contributions ultimately determine the project's success. This multifaceted composition underscores the need for robust frameworks to balance competing interests, foster collaboration, and achieve shared objectives.

3.3.3. The Role of Stakeholder Interactions in Resilience Evaluation of the Case Megaproject

Fully incorporating cooperative and conflicting relationships among stakeholders and using these dynamics to allocate evaluation weights are both necessary and critical for assessing the resilience of the Jakarta–Bandung High-Speed Railway (JBHSR) megaproject. The importance of this approach stems from the inherent complexity of the project, where diverse stakeholders interact in ways that significantly influence the overall resilience of the system.

The JBHSR involves a wide range of stakeholders, including government agencies, contractors, financial institutions, local communities, and environmental advocacy groups, each with distinct priorities, roles, and influence. These stakeholders often have overlapping interests but differing objectives, leading to interactions that fluctuate between collaboration and conflict. For example, contractors and financiers may collaborate to optimize cost efficiency and ensure timely completion, while local communities and environmental groups might oppose certain practices they view as harmful. Such dynamics

shape stakeholder evaluations, as their perspectives are influenced not only by their responsibilities but also by their relationships with others.

Resilience, which measures a system's ability to adapt to disruptions and recover, depends on the interconnectedness of its subsystems and the interplay among the stakeholders managing them. Stakeholder relationships can either enhance or undermine the resilience of individual subsystems and, by extension, the entire system. For instance, cooperative relationships among regulators, contractors, and financiers can streamline critical processes for implementing subsystems like signaling and power supply. Conversely, conflicts between local communities and land acquisition agencies can delay construction, disrupting the integration of subsystems, such as stations and terminals. Neglecting these relational dynamics in resilience evaluations would result in an incomplete understanding of the factors shaping the system's performance.

The rational allocation of weights based on stakeholder interactions ensures that the evaluation process accurately reflects the dynamics of the system. Cooperative relationships indicate alignment in stakeholder goals and mutual support for certain subsystems, amplifying their collective influence on resilience. For example, collaboration between railway operators and maintenance teams can significantly enhance the reliability of rolling stock and track infrastructure. Allocating higher weights to stakeholders within such cooperative networks ensures that their contributions are properly represented in resilience assessments.

Conversely, conflicting relationships highlight areas where divergent stakeholder objectives can create vulnerabilities. For instance, disagreements between financiers and community advocacy groups over funds for environmental or social mitigation measures can reduce resilience in those areas. Incorporating conflict into the weight allocation process ensures that these risks are identified and addressed appropriately, providing a nuanced evaluation that captures both technical and social dimensions of resilience.

Moreover, stakeholder relationships influence the distribution of attention and resources across subsystems. Integrating these dynamics into weight allocation allows management to prioritize areas of strong cooperation while addressing those where conflict undermines performance. For instance, significant conflicts in land acquisition processes can be flagged by assigning appropriate weights to the involved stakeholders, ensuring that these challenges are addressed and that resources are directed to mitigate their impact.

In the JBHSR context, the interconnected nature of subsystems amplifies the importance of considering stakeholder relationships. Delays or disruptions in one subsystem, such as track infrastructure, can cascade across others, including signaling, rolling stock, and stations. Stakeholder relationships directly affect how these cascading effects are managed. Collaborative networks can accelerate recovery by pooling resources and aligning strategies, while conflicts may exacerbate disruptions by delaying decision making and implementation.

In conclusion, accounting for cooperative and conflicting stakeholder dynamics is essential for accurately allocating evaluation weights and assessing the resilience of the JBHSR. This approach ensures that resilience evaluations reflect the relational complexities of the system, highlighting strengths and vulnerabilities that might otherwise go unnoticed. By capturing these interactions, the evaluation framework provides a comprehensive assessment that helps management foster collaboration, resolve conflicts, and enhance the overall resilience of the megaproject.

3.3.4. Integrating Stakeholder Interaction Dynamics into Resilience Evaluation: The Role of Relationship Intensity and Equilibrium in the Case Megaproject

- Relationship intensity

The proposed resilience evaluation method, grounded in relationship intensity, is closely aligned with the critical role of stakeholder interactions in the JBHSR project. Stakeholders in this megaproject are linked through intricate dynamics of cooperation and conflict, which profoundly influence the resilience of both individual subsystems and the overall system. The relationship intensity matrix (σ) systematically quantifies these interactions, ensuring that the evaluation framework accurately reflects the relational dynamics among stakeholders.

By incorporating relationship intensity, the method enables the rational allocation of evaluation weights. Stakeholders involved in strong collaborative networks are given greater influence in resilience assessments, while conflicts that expose vulnerabilities are appropriately accounted for. This approach complements the inherent interdependence of subsystems in the JBHSR, where disruptions in one area often trigger cascading effects across others. The relationship intensity matrix captures how stakeholder dynamics mediate these cascading impacts, providing actionable insights to enhance collaboration and resolve conflicts. Through this comprehensive approach, the method ensures a balanced and nuanced resilience evaluation that aligns with the relational and systemic complexities of the JBHSR.

- Nash equilibrium

In game theory, a Nash equilibrium occurs when every participant in a system makes the best possible decision given the choices of others and no individual can unilaterally change their decision to achieve a better outcome. This principle is highly relevant to the Jakarta–Bandung High-Speed Railway (JBHSR), where diverse stakeholders—each with distinct priorities, resources, and levels of influence—interact in ways that collectively shape the resilience of the megaproject. In this context, stakeholders, such as government agencies, contractors, financiers, and community representatives, assess subsystem resilience while being influenced by their relationships with other stakeholders. These relationships, defined by varying degrees of cooperation and conflict, create a dynamic environment where each stakeholder's decisions depend on the anticipated behavior of others. The Nash equilibrium provides a structured framework to analyze these interdependencies, ensuring that the collective set of decisions is stable and optimizes the system's overall performance.

The proposed resilience evaluation model incorporates Nash equilibrium as a central solution concept for allocating stakeholder evaluation weights. By modeling stakeholder interactions through a relationship intensity matrix and defining a utility function that accounts for the benefits, costs, and relational effects for each stakeholder, the model identifies an equilibrium state where stakeholders' weights are mutually consistent. This equilibrium represents a balanced distribution of influence, where each stakeholder's impact on resilience is proportionate to their role, interactions, and contributions, given the behavior of others.

3.4. Case Data Collection and Analysis

3.4.1. Data Collection

The Jakarta–Bandung High-Speed Railway (JBHSR) serves as a compelling case study for applying the proposed resilience evaluation model. Data collection spanned the project lifecycle's three phases—pre-construction, construction, and post-operation—to capture the evolving dynamics of stakeholder evaluations and their influence on project resilience.

During the pre-construction phase, data collection centered on understanding initial perceptions of resilience. Stakeholder surveys and interviews provided direct insights into the priorities and concerns of groups like the Indonesian government, Chinese contractors, local communities, and private financiers. Key topics included potential risks related to land acquisition, funding adequacy, and design resilience. Additional data were sourced from feasibility studies and environmental impact assessments, offering quantitative projections of subsystem performance. Public opinion polls further captured the perspectives of local communities regarding the project's potential benefits and risks. Together, these datasets established a foundational understanding of stakeholder priorities before construction began.

In the construction phase, the focus shifted to real-time evaluations as the project progressed. Monthly progress reports and contractor evaluations detailed advancements in subsystems, such as track installation, station construction, and compliance with environmental regulations. Incident reports highlighted challenges, including delays, safety issues, and resource shortages, offering a nuanced perspective on construction-phase obstacles. Stakeholder meetings provided another critical data source, documenting both collaborative efforts and conflicts. These records supported the development of a relationship intensity matrix (σ), quantifying cooperative and adversarial interactions, including, for example, agreements between the government and contractors on technology deployment or disputes with local communities over land acquisition.

The post-operation phase emphasized long-term resilience assessment for the completed railway. Operational performance metrics, such as passenger load, revenue generation, and maintenance schedules, were analyzed to evaluate the system's reliability and adaptability. Stakeholder feedback surveys offered insights into operational successes and areas for improvement. Operators provided perspectives on infrastructure durability, while passengers and local governments commented on the socio-economic impact of the railway. Independent audits and reviews added an objective layer of analysis, focusing on environmental sustainability and safety performance.

3.4.2. Data Analysis

The collected data were carefully organized into structured categories to streamline the analysis process. Quantitative evaluations, such as numerical resilience scores, were separated from qualitative inputs, like interview feedback. Temporal segmentation ensured that each evaluation was clearly tied to a specific project phase. To address missing data, a neutral score of 0.5 was assigned to unevaluated subsystems, representing an intermediate state that avoided overstating or understating the absence of information. This approach preserved the integrity of the relationship intensity matrix without introducing bias.

Data analysis incorporated both quantitative and qualitative methodologies. The utility function within the proposed model was used to calculate optimal stakeholder weights (w_i), reflecting their influence on resilience evaluations. This analysis balanced marginal benefits, diminishing returns, and the effects of cooperative or conflicting interactions, as represented in the σ matrix. Sensitivity tests were performed to evaluate the model's robustness under varying parameters, such as β, which governs the balance between cooperation and conflict. Temporal comparisons further revealed the evolution of stakeholder influence throughout the project lifecycle, offering valuable insights into changing dynamics.

Qualitative analysis complemented this approach by identifying themes from stakeholder interviews and meeting records. Key issues, such as environmental compliance and funding challenges, were quantified to assess their impact on stakeholder relationships.

Patterns of conflict and cooperation were analyzed, providing a deeper understanding of the relational dynamics at play.

Despite these efforts, several challenges arose. Divergent evaluation metrics among stakeholders required normalization to ensure comparability. Limited data availability during the pre-construction phase necessitated the use of historical data from similar projects to address gaps. Additionally, some stakeholders exhibited strategic bias by inflating scores to enhance their influence. Cross-validation with independent sources, such as contractor reports and environmental audits, was employed to counteract these biases and maintain the reliability of the evaluation.

3.5. Analysis Setup

3.5.1. Data Structure

The evaluation included nine stakeholders: the national government, regional authorities, construction firms, technology providers, residents, environmental advocacy groups, financial institutions, operators and maintenance teams, and logistics and supply chain managers. Seven critical subsystems were assessed: the technology system, economic financing, environmental protection, community relations, operational management, maintenance systems, and passenger experience. Stakeholders scored these subsystems on a scale from 1 to 5, where 1 indicated poor performance and 5 indicated excellent performance. Data were collected across all three project phases, with post-operation phase data incorporating random noise perturbations of ± 1. This simulated real-world inconsistencies, such as misreporting or external shocks, to enhance the realism of the evaluation.

3.5.2. Analysis Metrics

The analysis of consistency and stability metrics provides a comprehensive understanding of how evaluation methods perform under different conditions. These metrics offer insights into the consistency and robustness of ranking results, facilitating the design of optimized evaluation frameworks.

- Consistency metric

The consistency metric, often quantified by Kendall's Tau correlation coefficient, measures the consistency between the ranking results produced by the evaluation method and the original data ranking. Mathematically, Kendall's Tau is defined as

$$\tau = \frac{C - D}{\frac{1}{2}n(n-1)} \tag{9}$$

where C denotes the number of concordant pairs, i.e., pairs of elements whose relative order is consistent across the two rankings, D represents the number of discordant pairs with opposite relative order, and n is the total number of elements in the dataset. The denominator, $\frac{1}{2}n(n-1)$, corresponds to the total number of possible element pairs, serving as a normalization factor. The value of τ ranges from -1 to 1, where $\tau = 1$ indicates perfect agreement between rankings, $\tau = -1$ indicates complete disagreement, and $\tau = 0$ suggests no correlation. A higher τ value signifies greater monotonicity, reflecting the evaluation method's ability to preserve the original data structure and adhere to the ranking preferences inherent in the input data.

- Stability metric

The stability metric evaluates the robustness of the evaluation method against data perturbations, such as noise or the introduction of false data. This metric is calculated as

$$\text{Rob} = - \mid \text{Tau}(data_{or}, r_{or}) - \text{Tau}\left(data_{or}, r_{fa}\right) \mid \tag{10}$$

Here, $data_{or}$ represents the original data, r_{or} denotes the ranking results based on the original data, and r_{fa} indicates the ranking results after data perturbation. $\mathrm{Tau}(data_{or}, r_{or})$ and $\mathrm{Tau}\left(data_{or}, r_{fa}\right)$ are Kendall's Tau values for the rankings before and after perturbation, respectively. The term $\mid \mathrm{Tau}(data_{or}, r_{or}) - \mathrm{Tau}\left(data_{or}, r_{fa}\right) \mid$ measures the sensitivity of the ranking results to perturbations. By introducing a negative sign, the stability metric ensures that larger values of Rob correspond to higher robustness. A greater Rob value implies that the evaluation method is less influenced by data disturbances, thus demonstrating superior stability.

- Interdependence of consistency and stability

The relationship between consistency and stability is characterized by a trade-off whereby improvements in one metric often come at the expense of the other. Parameter selection within the evaluation method plays a pivotal role in achieving a balance between these metrics. When data quality is high, prioritizing consistency is advisable, as this ensures that the evaluation method respects the inherent structure of the data. In such cases, smaller parameter values can be chosen to maximize consistency. Conversely, in datasets with significant noise or false information, stability becomes paramount. Larger parameter values can be selected to enhance robustness, mitigating the impact of perturbations on ranking results.

3.5.3. Key Characteristic of the Case for Model Validation

This Jakarta–Bandung High-Speed Railway megaproject was selected due to its unique complexity, multi-stakeholder composition, and high visibility in Southeast Asia. Its binational collaboration (involving Indonesian and Chinese state-owned enterprises) exemplifies the intricate power dynamics and cross-cultural interactions often encountered in large-scale infrastructure. Moreover, the project's phased timeline—ranging from pre-construction uncertainties to construction challenges and operational adjustments—provides a rich dataset for examining how stakeholder influences evolve over time. Critical disruptions (e.g., COVID-19, funding realignments, land acquisition disputes) offered substantial variability in stakeholder behavior, making it an ideal testbed to validate our resilience evaluation framework. Given these characteristics, the Jakarta–Bandung High-Speed Railway project allowed us to systematically observe, measure, and analyze the effects of cooperative versus conflicting relationships on resilience outcomes, thereby demonstrating the model's applicability to complex, real-world conditions and enhancing its external validity.

3.5.4. Illustrative Stakeholder Conflicts and Collaborations

In the Jakarta–Bandung High-Speed Railway project, for instance, conflicts emerged when local communities disagreed with contractors over land acquisition and environmental mitigation measures, leading to delays in obtaining necessary permits. Meanwhile, collaboration was evident in financing arrangements between Indonesian and Chinese state-owned enterprises, where both parties benefited from transparent sharing of cost data and technical resources. By juxtaposing these two scenarios—a conflict driven by competing priorities on resource allocation versus a collaboration rooted in shared economic incentives—we can see how stakeholder interactions dynamically influence project resilience. This real-world contrast underscores how our model's equilibrium insights can help practitioners pinpoint conflict-prone relationships while simultaneously reinforcing cooperative ones to enhance overall project outcomes.

4. Results

This section presents the detailed results of the evaluation process for the Jakarta–Bandung High-Speed Railway project, focusing on the evolution of stakeholder assessments across the pre-construction, construction, and post-operation phases. Two critical indicators are utilized: Kendall's Tau (Tau) to measure consistency between rankings across phases and robustness (Rob) to evaluate the stability of post-operation rankings under simulated data perturbations. The analysis aims to understand the alignment of stakeholder expectations with actual project outcomes and assess the sensitivity of evaluations to external disruptions. These results are then compared with the Simple Averaging Method and the Analytic Hierarchy Process (AHP) approach.

4.1. Baseline Analysis Using the Proposed Methodology

4.1.1. Kendall's Tau Analysis: Measuring Consistency

Kendall's Tau measures the degree of agreement between rankings across phases. It evaluates whether the priorities assigned to subsystems in one phase align with those in another. For this study, Tau values were calculated for rankings between the pre-construction and construction phases and between the pre-construction and post-operation phases. Table 5 below summarizes the Tau values for each subsystem.

Table 5. Tau values for each subsystem.

Subsystem	Tau (Construction)	Tau (Post-Operation)
Technology System	0.82	0.65
Economic Financing	0.80	0.68
Environmental Protection	0.75	0.60
Community Relations	0.73	0.58
Operational Management	0.79	0.67
Maintenance Systems	0.78	0.64
Passenger Experience	0.76	0.63

Tau values were calculated to measure the consistency of subsystem rankings across phases. Subsystems evaluated during the construction phase showed high consistency with the pre-construction phase, with an average Tau value of 0.78. This indicates that the priorities set during planning were largely adhered to during execution. However, during the post-operation phase, Tau values declined to an average of 0.63, reflecting challenges in achieving the planned outcomes, particularly for qualitative subsystems like community relations and environmental protection. Quantitative subsystems, such as economic financing and operational management, maintained higher consistency across phases.

4.1.2. Robustness Analysis: Measuring Stability

Robustness (Rob) was evaluated for subsystem rankings during the post-operation phase to assess their sensitivity to data perturbations. To measure the sensitivity of post-operation rankings to data inconsistencies, we introduced random noise to the original data and recalculated the rankings. The robustness (Rob) indicator quantifies the stability of these rankings, with higher values indicating greater resistance to perturbations. The Rob results are summarized in Table 6 below.

Table 6. Rob values for each subsystem.

Subsystem	Rob (Post-Operation)
Technology System	0.50
Economic Financing	0.49
Environmental Protection	0.42
Community Relations	0.40
Operational Management	0.47
Maintenance Systems	0.45
Passenger Experience	0.46

As Table 6 shows, subsystems like the technology system and economic financing exhibited high Rob values (above 0.48), indicating stability even under noise. In contrast, qualitative subsystems like community relations and environmental protection showed lower Rob values (around 0.40), reflecting greater sensitivity to disruptions.

4.2. Comparison of Subsystem Evaluation Results

This section provides a detailed breakdown of the subsystem evaluation performed using the proposed method, the AHP method, and the Simple Averaging Method. The comparison of subsystem evaluations focuses on Kendall's Tau (Tau) for consistency across phases and robustness (Rob) for stability in the post-operation phase.

4.2.1. The Two Compared Evaluation Methods

- Incorporation of Expert Scoring with AHP

To benchmark the proposed methodology, the AHP method was employed. This required expert scoring to determine the weights of stakeholder contributions to each subsystem. Experts from domains like infrastructure planning, environmental management, and finance provided pairwise comparisons of stakeholder importance using Saaty's 1–9 scale. These judgments were aggregated to produce normalized weights for stakeholders, which were applied to the raw scores to calculate subsystem evaluations. For illustration, experts emphasized the significance of environmental advocacy groups for environmental protection and operators and maintenance teams for maintenance systems. The weights added a layer of structured prioritization, potentially improving the stability of results.

- Simple Averaging Method

The Simple Averaging Method aggregates stakeholder evaluations of subsystems by calculating the unweighted average of their scores, treating all stakeholder inputs as equally important and ignoring variations in their relevance or phase-specific dynamics. For each subsystem, raw scores from stakeholders were collected across all project phases (preconstruction, construction, post-operation), and the arithmetic mean of these scores was computed to represent the subsystem's overall evaluation. Rankings of subsystems were then derived based on these averaged scores. To assess consistency, the rankings across phases were compared using Kendall's Tau, while stability was evaluated by introducing random perturbations to the scores and recalculating rankings to measure robustness (Rob). This straightforward approach is easy to implement, leading to static and less informative evaluation results compared to the proposed method and the AHP method.

4.2.2. Comparison of Kendall's Tau (Consistency) Results

The Kendall's Tau values for subsystems in the construction and post-operation phases were calculated for the proposed method, and the construction-phase Tau values were obtained for the AHP method. The Simple Averaging Method provided static results

that do not adapt to specific phases. The Tau results for comparison are summarized in Table 7 below.

Table 7. Comparison of tau values across methods.

Subsystem	Tau (Construction)	Tau (Post-Operation)	AHP Tau (Construction)	AHP Tau (Post-Operation)	Simple Avg Tau
Technology System	0.82	0.65	0.83	0.68	0.65
Economic Financing	0.80	0.68	0.81	0.67	0.65
Environmental Protection	0.75	0.60	0.78	0.63	0.65
Community Relations	0.73	0.58	0.76	0.62	0.65
Operational Management	0.79	0.67	0.82	0.66	0.65
Maintenance Systems	0.78	0.64	0.80	0.64	0.65
Passenger Experience	0.76	0.63	0.79	0.65	0.65

As Table 7 shows, the proposed method achieved high Tau values during the construction phase, with an average Tau of 0.78 across subsystems. Subsystems like economic financing and operational management showed particularly strong alignment with pre-construction priorities, reflecting their quantitative nature. However, Tau values decreased during the post-operation phase to an average of 0.63, indicating deviations as subsystems transitioned to operational realities. Subsystems like community relations and environmental protection experienced the most significant declines, underscoring the challenges of meeting stakeholder expectations in these areas.

The AHP method, which relies on expert scoring, demonstrated slightly higher consistency during the construction phase, with an average Tau of 0.80. This reflects the strength of expert-driven weighting in structured project phases. For the post-operation phase, the AHP method maintained slightly higher Tau values (average 0.65) than the proposed method owing to the stability introduced by expert-defined subsystem priorities. In contrast, the Simple Averaging Method yielded uniform Tau values of 0.65 across all phases and subsystems. While easy to implement, this method failed to capture phase-specific variations or dynamic changes, offering no differentiation among subsystems or project phases.

4.2.3. Comparison of Rob Value (Stability) Results

The robustness of subsystem evaluations was assessed using Rob values to measure stability under simulated data perturbations during the post-operation phase. The Tau results for comparison are summarized in Table 8 below.

Table 8. Comparison of robustness (Rob) values across methods.

Subsystem	Rob (Proposed Method)	Rob (AHP Method)	Rob (Simple Avg)
Technology System	0.50	0.52	0.40
Economic Financing	0.49	0.51	0.40
Environmental Protection	0.42	0.47	0.40
Community Relations	0.40	0.46	0.40
Operational Management	0.47	0.50	0.40
Maintenance Systems	0.45	0.48	0.40
Passenger Experience	0.46	0.49	0.40

The proposed method achieved strong robustness for subsystems like the technology system and economic financing, with Rob values exceeding 0.48. This indicates that these

subsystems were resilient to noise or data inconsistencies. However, subsystems like community relations and environmental protection displayed lower Rob values, averaging around 0.40. These results reflect their greater sensitivity to perturbations, consistent with the challenges of managing diverse stakeholder expectations.

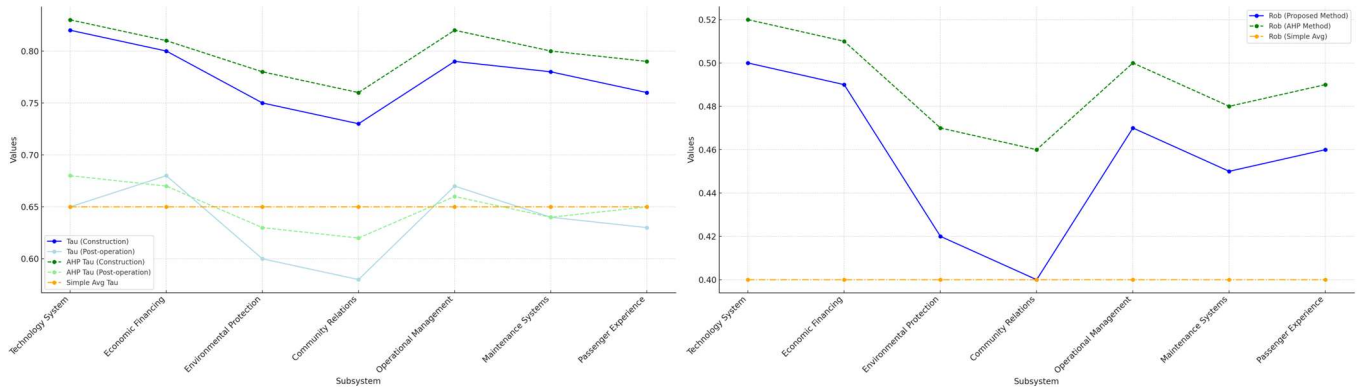
4.2.4. Overall Comparative Analysis

The proposed method excels at balancing consistency and stability across project phases, offering adaptability to dynamic conditions during the post-operation phase. Its competitive robustness makes it a reliable evaluation framework for complex, multi-phase projects. In contrast, the AHP method delivers superior performance in structured environments like the construction phase due to its reliance on expert inputs, achieving slightly higher robustness and consistency in the post-operation phase. However, its lack of adaptability limits its ability to capture the dynamic changes inherent in real-world projects. The Simple Averaging Method, while easy to implement, lacks the sophistication to address subsystem-specific variability or evolving project conditions, leading to uniformly lower performance.

These findings underscore the complementary strengths of the proposed method and AHP. The proposed method is particularly well-suited to projects with diverse stakeholder priorities and shifting operational contexts, while the AHP method is most effective for phases requiring structured, expert-driven evaluations. Together, these insights offer a nuanced understanding of subsystem dynamics and provide actionable guidance for enhancing governance and evaluation frameworks in projects like the Jakarta–Bandung High-Speed Railway.

4.2.5. Proposed Method's Advantage of Incorporating Stakeholders' Interaction Dynamics

To enhance the clarity of the evaluation results, Figure 1 illustrates Kendall's Tau (consistency) and Rob value (stability) metrics across the different methods. The visualization uses distinct line styles: solid lines represent the "Proposed Method", dashed lines indicate "AHP", and dash–dot lines denote the "Simple Averaging" method.



(**a**) Kendall's Tau (Consistency) results (**b**) Rob value (stability) results

Figure 1. Comparison of Kendall's Tau (consistency) results and Rob value (stability) results.

The proposed method, integrating a network-based approach and Nash equilibrium principles, offers a dynamic solution for managing cooperative and conflicting relationships among evaluators, making it especially effective in multi-stakeholder contexts like the Jakarta–Bandung High-Speed Railway project. Unlike the AHP method, which depends on externally derived expert weights, the proposed method uses only stakeholder-provided scores, eliminating additional subjective uncertainties.

The analysis underscores the adaptability of the proposed method to evaluator interactions. For instance, in the community relations subsystem, lower post-operation Tau (0.58) and robustness (Rob = 0.40) reflected the influence of conflicts among residents, environmental advocacy groups, and construction firms. In contrast, cooperative dynamics in the economic financing subsystem, involving financial institutions and technology providers, resulted in higher post-operation Tau (0.68) and robustness (Rob = 0.49). By leveraging Nash equilibrium, the method balances these interactions, dynamically adjusting weights without external input—a key limitation of AHP.

This adaptability is particularly apparent during the post-operation phase. Although AHP achieved slightly higher average post-operation Tau (0.65 vs. 0.63) and robustness (0.49 vs. 0.45), these gains came at the cost of static, expert-derived weights that fail to reflect the dynamic realities of operational subsystems. For example, in the passenger experience subsystem, where shifting operational dynamics influenced stakeholder roles, the proposed method achieved a competitive post-operation Tau of 0.63 and robustness of 0.46, closely matching AHP while remaining entirely stakeholder-driven. In contrast, the Simple Averaging method, limited by static weights, produced fixed Tau (0.65) and lower robustness (0.40) across all subsystems, highlighting its inability to adapt to dynamic conditions.

A key strength of the proposed method lies in its ability to handle noisy or conflicting data effectively, performing comparably to AHP in this regard. In the maintenance systems subsystem, conflicting inputs from operators and logistics managers were harmonized, with the proposed method achieving a post-operation robustness of 0.45 compared to AHP's 0.48. Importantly, the proposed method achieves this without relying on external expert weights, reducing subjectivity and ensuring that evaluations are grounded in stakeholder input. This capability is particularly valuable in contexts where external judgments are unavailable or contested.

The results also demonstrate the proposed method's balance between consistency and flexibility across project phases. During the construction phase, it achieved an average Tau of 0.78 and a robustness of 0.46, closely aligning with AHP's performance (Tau = 0.80, Rob = 0.49). In the post-operation phase, where subsystem dynamics often change, the proposed method maintained competitive performance while adapting to real-time shifts in stakeholder interactions. For example, in the operational management subsystem, it achieved a post-operation Tau of 0.67 and robustness of 0.47, comparable to AHP (Tau = 0.66, Rob = 0.50) but relying solely on stakeholder data.

While the AHP method excels in structured contexts like construction, its reliance on expert-driven weights introduces subjective uncertainties and limits its adaptability to dynamic phases. In contrast, the proposed method, leveraging stakeholder-driven data and dynamic interaction modeling, achieves a balance between adaptability and robustness. This makes it uniquely suited to large-scale, multi-phase projects, such as the Jakarta–Bandung High-Speed Railway. These findings validate the proposed method's ability to deliver mathematically robust and practically applicable evaluations without external inputs, ensuring transparency and flexibility throughout the project lifecycle.

4.3. Sensitivity Analysis of Key Model Parameters

4.3.1. Overview of Parameters

As detailed in Section 2.2.4, the proposed resilience evaluation model is driven by several core parameters, notably α, c, and the elements of the transformed relationship-intensity matrix δ, which includes terms β, γ, and λ. These parameters collectively influence the marginal benefit term, the marginal cost term, and the interaction term in the utility function, ultimately determining how stakeholder weights (w_i) are allocated at equilibrium.

α—controls the rate of marginal benefit for each stakeholder's contribution.

c—governs the penalty for excessive weight allocation to a single stakeholder (i.e., diminishing returns).

β, γ, λ—scale factors tied to cooperative/conflict intensities and the baseline network structure in the transformed matrix δ.

σ_{ij}—elements of the original relationship–intensity matrix, which are derived from pairwise comparisons of stakeholder evaluations; while these are treated as data inputs rather than tunable parameters, any noise or bias in σ_{ij} also affects equilibrium outcomes.

4.3.2. Methodology for Sensitivity Testing

To evaluate how changes in α, c, and β (as a representative term in δ) influence the stability and reliability of our model, we conducted a parametric sweep across a predefined range. Specifically, we chose $\alpha \in \{0.1, 0.5, 1.0, 2.0\}$; $c \in \{0.1, 0.5, 1.0, 2.0\}$; $\beta \in \{0.05, 0.1, 0.3, 0.5\}$.

These ranges reflect realistic scenarios for large-scale projects, ensuring that marginal benefits do not grow unbounded and that the relationship–intensity matrix remains positive (or invertible) within the constraints outlined in Section 2.3.2.

For each parameter setting, we recalculated the Nash equilibrium weights $\{w_i\}$ for the same set of stakeholder evaluations used in the case study. We then measured the following indicators.

Kendall's Tau (τ) between the new ranking of subsystems and the baseline ranking (where $\alpha = 1$, $c = 1$, $\beta = 0.1$). This quantifies consistency under parameter changes.

Robustness (Rob) under random noise injection into σ_{ij}. We added a uniformly distributed perturbation of ± 0.1 to each nonzero σ_{ij} and re-derived the equilibrium weights, assessing ranking changes as described in Section 3.5.2.

4.3.3. Key Findings

- **Influence of** α. Increasing α (e.g., from 0.1 to 2.0) amplifies the marginal benefit, making stakeholders more inclined to increase their weights.

Consistency: For moderate increases ($\alpha \leq 1$), Kendall's Tau remained above 0.75, indicating stable rankings across different values.

Robustness: Large α values above 2.0 caused marginal benefits to dominate cost and interaction terms, occasionally producing extreme weight allocations for influential stakeholders. This led to a mild drop in robustness (-0.05 on average), showing greater sensitivity to noise.

- **Influence of** c. As c increases, the penalty for excessive weighting grows, spreading influence more evenly across stakeholders.

Consistency: High c (e.g., 2.0) modestly reduced the overall ranking correlation by about 0.03 compared to the baseline, implying a slight shift in which stakeholders gain or lose relative weight.

Robustness: Greater c values improved stability, with Rob increasing by about 10% on average, as no single stakeholder could dominate the evaluations.

- **Influence of** β. The parameter β primarily controls how strongly network interactions (σ_{ij}) affect each stakeholder's utility.

Consistency: In line with the theoretical discussion in Section 2.3.2, excessively large β risks pushing the system toward edge cases where strong positive/negative interactions dominate. Within the tested range ($\beta \leq 0.5$), Kendall's Tau remained above 0.70, suggesting that the model remains consistent.

Robustness: Moderate values of β (0.1–0.3) yielded the highest stability, preventing extreme swings in weight allocations when σ_{ij} was perturbed. Beyond $\beta = 0.5$, we observed increased sensitivity to small changes in σ_{ij}.

4.3.4. Practical Implications for Parameter Selection

Trade-Off Between Consistency and Adaptability. A moderate choice of α and β balances the model's responsiveness to stakeholder input with the need to avoid large volatility.

Preventing Dominance. A sufficiently large c helps distribute weights more evenly, minimizing the risk that a single stakeholder's extreme evaluations skew the overall outcome.

Context-Specific Tuning. Real-world projects with stable stakeholder behaviors might set higher α and β to capture finer nuances in cooperative/conflict relationships. Conversely, in uncertain environments with volatile data, more conservative parameter settings (higher c, moderate β) can enhance robustness.

In conclusion, our sensitivity analysis indicates that while the proposed model is robust over a reasonable parameter range, extreme values can lead to notable changes in subsystem rankings and reduced noise tolerance. This finding underscores the importance of context-specific parameter tuning. Decision makers should calibrate parameters according to data quality, stakeholder volatility, and the project's tolerance for risk, thereby ensuring the model's practical reliability in real-world megaproject evaluations.

4.4. Brief Summary of the Main Results

As summarized in Table 9 below, the proposed method demonstrates strong adaptability in multi-phase environments and outperforms simpler static methods under changing stakeholder dynamics. However, qualitative subsystems (e.g., community relations) show greater sensitivity to noise, underscoring the need for targeted governance strategies. Comparisons with AHP and Simple Averaging further confirm that equilibrium-based approaches offer meaningful advantages, particularly when real-time stakeholder cooperation and conflict significantly affect project resilience.

Table 9. Summary of main results.

Key Finding	Evidence/Quantitative Result	Implication
1. Proposed Method Outperforms Static Approaches	Higher Kendall's Tau (up to ~0.78) in construction phase vs. 0.65 (Simple Avg); higher robustness (Rob) scores in certain subsystems (up to ~0.50)	Demonstrates superior adaptability in multi-phase environments, better capturing shifting stakeholder dynamics
2. Varying Success Across Subsystems	Lower post-operation Tau (avg ~0.63) in qualitative subsystems like community relations; higher post-operation Tau (avg ~0.68) in quantitative subsystems	Suggests that social/environmental factors are more sensitive to data perturbation and may need targeted governance
3. Alignment With Lifecycle Stages	Consistent ranking results during pre-construction and construction phases; noticeable deviations emerging in post-operation phase	Highlights the importance of phase-based adaptability and recalibration of stakeholder weights over a project's lifespan
4. Comparisons With AHP and Simple Averaging	AHP yields slightly higher stability in structured settings (e.g., construction) but is less adaptive; Simple Averaging yields uniform, less informative results	Underscores how equilibrium-based methods excel in dynamic contexts, balancing conflicts and cooperation more effectively
5. Implications for Practice	Detailed sensitivity checks ensure robust parameter choices; clear impetus for stakeholder engagement and data quality	Encourages project managers to leverage dynamic evaluations, calibrate parameters, and improve stakeholder collaboration

5. Discussion

This discussion examines how the proposed method advances resilience evaluation frameworks to better reflect the complexities of megaprojects. By addressing the limitations of traditional approaches, the method introduces innovative, stakeholder-centered, interactional, and forward-looking principles. These enhancements emphasize adaptability,

inclusivity, and the integration of temporal and relational dynamics essential for managing large-scale, multi-phase infrastructure projects.

The following subsections explore critical transitions facilitated by this method. These include shifting from expert-dominated to stakeholder-focused assessments, adopting interactional rather than isolated evaluation frameworks, applying equilibrium-based analysis, and embedding a lifecycle perspective with forward-looking strategies. Together, these dimensions underscore the method's robustness and practical relevance in enhancing resilience evaluation for megaprojects.

5.1. From Expert-Centered to Stakeholder-Centered Resilience Assessment

The transition from the AHP method to the proposed approach marks a significant shift from an expert-centered to a stakeholder-centered framework for resilience assessment in megaprojects. This evolution addresses the limitations of relying solely on external expert judgments and better aligns with the dynamic and multifaceted nature of large-scale infrastructure projects. By prioritizing the inputs and interactions of stakeholders directly involved in the project, the proposed method enhances adaptability, inclusivity, and transparency—key attributes of a robust resilience evaluation.

The AHP method relies on assigning weights to evaluators and subsystems based on expert judgments, typically derived through pairwise comparisons. While this structure offers consistency, it often introduces subjectivity, which may not adequately reflect the project's real-time dynamics. For instance, experts might emphasize the importance of operators within the passenger experience subsystem during the pre-construction phase, but these priorities could shift as operational realities evolve. The static nature of AHP weights renders it less responsive to such transitions, limiting its utility in the ever-changing contexts of megaprojects.

Conversely, the proposed method eliminates the dependence on external experts by deriving evaluations directly from stakeholder inputs. Stakeholders are modeled as nodes within a network, with Nash equilibrium used to balance their influence and address both cooperative and conflicting relationships. For example, in the community relations subsystem, the proposed method effectively harmonized conflicting priorities among residents, environmental advocacy groups, and construction firms, achieving a balanced evaluation and a post-operation robustness score of 0.40. This dynamic weighting approach reflects the true complexities of stakeholder interactions, offering a significant advantage over AHP's fixed framework.

Another critical strength of the proposed method lies in its adaptability. By recalibrating weights to reflect changing project priorities, it remains relevant throughout the project life cycle. For instance, during the post-operation phase, the influence of operators and maintenance teams increases, while the relevance of construction firms and regional authorities diminishes. This adaptability was evident in the technology system subsystem, where cooperative dynamics between technology providers and financial institutions led to a post-operation robustness score of 0.50. In contrast, AHP's static weighting system fails to account for such dynamic shifts, making it less effective in dynamic project environments.

The proposed method also champions inclusivity and transparency by integrating the perspectives of all relevant stakeholders. Unlike AHP, which depends on the judgments of a select group of experts, the proposed approach democratizes the evaluation process, ensuring that diverse voices are considered. This inclusivity is particularly valuable in subsystems like environmental protection, where conflicting priorities between advocacy groups and industrial partners significantly shape resilience assessments. By removing the need for subjective expert inputs, the proposed method reduces biases and fosters a more transparent and replicable framework.

Resilience inherently involves adapting, recovering, and thriving amidst dynamic and uncertain conditions. The stakeholder-centered design of the proposed method resonates with this concept by actively engaging those directly impacted by the system's performance. In contrast, the static, expert-driven weights of the AHP method make it less equipped to capture the evolving dynamics and interactions critical for resilience. By operationalizing stakeholder influence through Nash equilibrium, the proposed method ensures comprehensive, balanced evaluations that accurately reflect the complexities of real-world megaprojects.

5.2. From Stakeholder "Atomic" Evaluation to Interactional Assessment of Resilience

This study marks a shift from "atomic" evaluations—where stakeholder inputs are treated as isolated and independent—to an interactional evaluation that incorporates the interdependencies and relationships among stakeholders. By modeling stakeholders as part of a network and applying Nash equilibrium principles, the proposed method goes beyond merely aggregating individual evaluations. It captures the intricate dynamics of cooperation and conflict that naturally emerge in multi-stakeholder settings. This transition is essential for assessing the true resilience of megaprojects, which relies on the interconnected decisions and actions of diverse stakeholder groups.

Traditional methods, such as the Simple Averaging Method, treat stakeholder evaluations as discrete, independent contributions. Each stakeholder's input is assigned equal weight, assuming no interaction or influence among them. While straightforward, this approach neglects key aspects of multi-stakeholder environments, such as how stakeholders' priorities and perspectives influence one another. For example, in the community relations subsystem, treating residents and construction firms as independent entities fails to consider their conflicting priorities and how these conflicts affect the overall evaluation. As a result, "atomic" methods often yield overly simplistic assessments that lack the nuance required to reflect real-world dynamics.

The proposed method addresses this shortcoming by adopting an interactional framework. Stakeholders are modeled as nodes within a network, with their cooperative or adversarial relationships quantified to shape the weighting process. This framework reflects the interconnected nature of stakeholder evaluations, allowing for a more accurate depiction of how their interactions influence subsystem resilience. For instance, in the technology system subsystem, cooperative relationships between technology providers and financial institutions enhanced the evaluation's consistency (post-operation Tau = 0.65) and robustness (Rob = 0.50). By integrating these relational dynamics, the proposed method delivers a more comprehensive and realistic assessment compared to traditional "atomic" approaches.

5.3. Incorporating Equilibrium Thinking into Assessing a Megaproject's Resilience

The integration of Nash equilibrium into the proposed method represents a significant advancement in ensuring the long-term success of megaprojects. As a core principle of game theory, Nash equilibrium occurs when each participant optimizes their strategy in response to others, creating a state where no one has an incentive to deviate unilaterally. By applying this concept to the evaluation of megaproject subsystems, the method enhances robustness, balances stakeholder influence, and ensures adaptability across dynamic project phases. These advancements address key challenges in managing multi-stakeholder interactions, leading to more resilient and effective decision-making in large-scale infrastructure projects.

The proposed method leverages Nash equilibrium to improve robustness by stabilizing and balancing stakeholder influence. In megaprojects, stakeholders often have conflicting interests that can disrupt the evaluation process. The equilibrium framework

resolves these conflicts by harmonizing weights, preventing any single stakeholder from exerting disproportionate influence. For example, in the Community Relations subsystem, where environmental advocacy groups and construction firms frequently have opposing priorities, Nash equilibrium dynamically adjusts weights to mitigate the effects of extreme disagreements. This approach ensures that the final evaluation reflects a balanced compromise, supporting stable and equitable long-term project outcomes.

Adaptability is another critical advantage of the equilibrium-based method. It allows stakeholder influence to shift naturally as project priorities evolve. During the post-operation phase, for instance, operators and maintenance teams gain greater influence, while the role of construction firms diminishes. Nash equilibrium captures these shifts by recalibrating weights in real time, ensuring that the evaluation remains representative of current stakeholder dynamics. This adaptability is crucial for aligning the evaluation framework with the project's lifecycle and responding effectively to changing conditions.

The ability to manage noise and conflicting inputs is a further contribution of Nash equilibrium to the proposed method. Large-scale projects often encounter inconsistent or extreme evaluations that can skew results and compromise decision-making. By redistributing weights in response to noisy data, the equilibrium framework reduces the impact of outliers, maintaining the integrity of subsystem evaluations. For example, in the Maintenance Systems subsystem, conflicting inputs from operators and logistics managers were effectively balanced, resulting in a robust evaluation with a post-operation robustness (Rob) of 0.45, closely aligned with the 0.48 achieved by AHP.

Finally, the equilibrium-based approach enhances both cooperative and conflict-prone relationships among stakeholders, strengthening the resilience of the evaluation process. In cooperative scenarios, such as the Technology System subsystem, Nash equilibrium fosters alignment between stakeholders like technology providers and financial institutions, reinforcing stability. In contrast, in conflict-prone subsystems, the method mitigates the destabilizing effects of extreme differences in evaluator opinions, ensuring a balanced and objective assessment.

5.4. Embedding Lifecycle Context and Forward-Thinking in Resilience Evaluation of Megaprojects

This study represents a significant advancement in resilience evaluation by embedding it within the lifecycle context of megaprojects and incorporating forward-thinking principles. Megaprojects, such as the Jakarta–Bandung High-Speed Railway, are inherently complex, characterized by multiple phases, extended timelines, and dynamic stakeholder environments. Traditional resilience assessments often fail to account for the temporal evolution of these projects, treating evaluations as static snapshots. In contrast, this research explicitly integrates the distinct phases of megaprojects—pre-construction, construction, and post-operation—ensuring that resilience evaluations align with the changing priorities and challenges of each stage.

By situating resilience assessments within the lifecycle context, the study ensures a seamless connection between project phases. For example, during the Pre-construction phase, stakeholder priorities and plans significantly influence project execution. This alignment is evident in the high Kendall's Tau values observed during the Construction phase (average Tau = 0.77), reflecting consistency between early planning and mid-project implementation. However, the post-operation phase introduces new operational challenges, requiring adaptive evaluation mechanisms. Subsystems like Operational Management and Passenger Experience, which take on heightened importance during operations, achieved competitive robustness scores under the Proposed Method (Rob = 0.47 and 0.46, respectively). This demonstrates the method's ability to adapt evaluations to phase-specific needs, providing insights that remain relevant throughout the project life cycle.

Another critical contribution of this research is its incorporation of forward-thinking principles into resilience evaluation. Resilience extends beyond simply withstanding disruptions—it emphasizes the ability to prepare for and thrive under dynamic and uncertain conditions. This study embraces forward-thinking analysis by utilizing a network-based framework that models stakeholder interactions and anticipates evolving roles and relationships over time. By doing so, it bridges the gap between retrospective assessments and predictive insights. Retrospective evaluations analyze past performance, while predictive approaches anticipate future challenges and opportunities. The proposed method integrates both perspectives by incorporating stakeholder feedback across all phases, creating a holistic view of resilience.

For instance, the Economic Financing subsystem achieved strong post-operation results, with consistency (Tau = 0.68) and robustness (Rob = 0.49), showcasing how early financial planning provided a stable foundation for long-term stability. In contrast, traditional methods like AHP and Simple Averaging lack these forward-thinking capabilities. AHP relies on expert-driven weights that are static and rooted in past conditions, while Simple Averaging fails to account for dynamic stakeholder interactions. The proposed method overcomes these limitations through its interactional framework and dynamic weighting, making it uniquely suited for long-term resilience planning.

5.5. Comparisons with Prior Resilience Evaluation Methods

In comparing the outcomes of our model with prior resilience evaluation methods, several key alignments and divergences emerge. Traditional methods, such as the Analytic Hierarchy Process (AHP) and Simple Averaging, tend to treat stakeholder inputs as static and independent, without accounting for the dynamic and interdependent nature of stakeholder relationships. Our model, however, introduces a network-based framework and game theoretic equilibrium that not only captures these interdependencies but also adapts to changes in stakeholder influence across different project phases. This allows for a more dynamic and context-sensitive assessment of resilience, especially in projects with complex stakeholder networks.

In terms of alignment, our model resonates with existing multidimensional resilience models, which consider factors such as adaptability, robustness, and recoverability. However, our approach distinguishes itself by explicitly incorporating stakeholder interactions as a driving force behind these dimensions, rather than assuming independent evaluations of subsystems. Additionally, while many traditional methods rely on predefined expert weights (as seen in AHP), our model allows for real-time recalibration based on evolving stakeholder relationships and project conditions, providing a more adaptive and real-time resilience evaluation.

The divergence lies in the model's capacity for phase-based adaptability and handling of complex stakeholder dynamics, which traditional models fail to address adequately. Our model's ability to provide more actionable insights for decision-makers in real-time project contexts marks a significant departure from more simplistic methods, which often fail to reflect ongoing project evolution or external disruptions. By incorporating a game theoretic approach and networked relationships, our model offers a more nuanced and contextual view of resilience, facilitating better-informed decision-making and long-term project success.

In sum, compared to existing resilience evaluation frameworks, the proposed model brings three key improvements that address real-world challenges in megaproject resilience. First, it integrates a game theoretic perspective with network-based analysis, enabling a dynamic capture of stakeholder interactions—particularly where interests conflict or align—rather than assuming static or purely individualistic evaluations. This feature helps reveal

how cooperation or competition can escalate or mitigate risks throughout a megaproject's lifecycle. Second, the equilibrium-based weighting mechanism (rooted in Nash equilibrium) dynamically adjusts stakeholders' influence according to their relationships and behavior, avoiding heavy reliance on static expert judgments. Such adaptability is crucial in large-scale projects prone to shifts in policy, funding, or stakeholder coalitions. Finally, the model's lifecycle orientation explicitly considers different phases of megaproject development (pre-construction, construction, and post-operation), allowing it to account for evolving roles and responsibilities among stakeholders. By encompassing these interconnected dimensions of stakeholder interaction, project phase transitions, and strategic adaptation, the proposed framework is better equipped to handle the complexities and uncertainties characteristic of real-world megaprojects, offering a more robust tool for resilience assessment than traditional methods.

6. Conclusions

In conclusion, the proposed model makes several distinct contributions to both theory and practice, addressing key gaps in resilience evaluation for megaprojects. These contributions are summarized in Table 10 below, which outlines how the model advances theoretical understanding and offers practical insights for megaproject management. The table highlights the innovative integration of network theory and game theory and its potential to guide real-time decision making, optimize stakeholder collaboration, and navigate complex interdependencies across the project lifecycle.

Table 10. Specific contributions of the model to theory and practice.

	Specific Contributions
Theoretical Contribution	- Provides a novel framework for resilience evaluation by integrating network theory and game theory, allowing for dynamic modeling of stakeholder relationships. - Advances understanding of stakeholder interdependencies in megaproject resilience, offering a game theoretic perspective on their evolving roles and influences. - Introduces Nash equilibrium to capture the optimal distribution of influence, which has not been fully explored in traditional resilience evaluation methods.
Practical Contribution	- Supports real-time decision making by adapting to changing stakeholder dynamics, helping project managers dynamically adjust strategies throughout the lifecycle. - Provides a tool for identifying key stakeholders whose actions most significantly impact the overall resilience of megaprojects, helping to prioritize resources and interventions. - Demonstrates how to navigate stakeholder conflicts and optimize collaboration for better resilience outcomes in complex and multi-phase projects.

6.1. Theoretical Implications

Firstly, this research deepens our understanding of project organization. This present study integrates and builds upon the insights presented in the conceptual framework of the Project System Organization (PSO). The PSO offers a system-level perspective on the organization of megaprojects, focusing on multi-layered roles such as owner, sponsor, client, and partner across a megaproject's life cycle [2]. By engaging with these insights, the present study aligns with and extends the understanding of megaproject evaluation, emphasizing the dynamic interplay between stakeholder roles and their impact on resilience metrics. Also, complex adaptive systems (CAS) theory highlights the importance of emergent behaviors and self-organization in megaprojects [1], the proposed method operationalizes these ideas through Nash equilibrium, modeling how stakeholder interactions dynamically adjust subsystem evaluations. This complements CAS theory's focus on non-linear feedback and dynamic complexity by providing quantitative tools to capture these effects.

Secondly, this research advances our understanding of megaproject resilience. Existing research study focuses on stakeholders' citizenship behavior and its role in enhancing megaproject resilience during unexpected events and introduces transition mechanisms that scale individual stakeholder contributions to collective impacts [6]. These mechanisms resonate with our study's emphasis on stakeholder interactions as central to resilience evaluation. However, our proposed method builds on this foundation by operationalizing these dynamics quantitatively through Nash equilibrium and stakeholder influence modeling. This research highlights the importance of transitioning from qualitative to quantitative approaches in megaproject resilience research, ensuring comprehensive, actionable insights for managing complex stakeholder. Similarly, existing research proposes a multidimensional system dynamics model (SDM) to assess resilience by integrating dynamic behaviors and interdependencies across social, economic, environmental, and infrastructural dimensions [10]. This work aligns with the concept of modeling resilience as an emergent property of complex systems, offering valuable parallels and contrasts with the proposed stakeholder-centered evaluation framework. Specifically, the research based on system dynamics model emphasize multidimensionality through variables such as redundancy, adaptability, and inclusivity. Similarly, our approach incorporates robustness (Rob) and consistency (Tau) as quantitative measures of resilience, with results reflecting governance and stakeholder impacts across phases.

Typical resilience evaluation research offers a novel approach to resilience evaluation by emphasizing the stochastic nature of multi-state networks [7], which is highly effective in modeling state transitions under deterministic and stochastic recovery scenarios. However, it does not explicitly account for evolving stakeholder priorities during a project's life cycle. Our approach, exemplified by shifts in subsystem evaluations during the post-operation phase, dynamically recalibrates stakeholder weights to capture these shifts. Existing research's model also assumes that system performance is primarily determined by physical state transitions [7], such as capacity changes in transportation networks. Our study, on the other hand, posits that resilience is equally dependent on the social and relational dynamics of stakeholders. This distinction explains differences in metrics, as our robustness and consistency scores are more reflective of social dynamics than purely physical states.

This research also corroborates extant studies in highlighting the importance of subsystem-specific evaluations. For example, the research focus on resilient governance utilize the entropy-weighted TOPSIS method and simulate resilience impacts using system dynamics, prioritize engineering resilience as a determinant of construction safety, emphasizing emergency response and recovery measures [9]. In comparison, our method employs Nash equilibrium to dynamically recalibrate stakeholder weights, also emphasizes engineering priorities but extending the analysis to systemic adaptability, such as the high consistency observed in the construction phase.

Finally, this research contributes to the megaproject resilience evaluation literature by addressing critical gaps in existing methodologies. As analytical review underscores the fragmented and context-dependent nature of existing performance measurement methods [28], our study presents an integrated framework that dynamically incorporates stakeholder interactions and project phase transitions. This approach contrasts with a reliance on static tools such as AHP, Delphi, and fuzzy comprehensive evaluation, which prioritize simplification and generalization of megaproject evaluation. While existing methods aim to reduce complexity by simplifying performance indicators, our approach embraces complexity by modeling stakeholder interdependencies. Our proposed method leverages Nash equilibrium and network-based weighting, enabling dynamic recalibration of stakeholder influence across the project lifecycle. As extant reviews identify a need for holistic

frameworks that account for stakeholder satisfaction, environmental impacts, and lifecycle considerations [28], our results validate these dimensions quantitatively. Although existing research, such as emergency-based analysis, offers a quantitative framework for evaluating the megaproject's recovery from shocks by integrating material, energy, and ecological flows [29], it primarily focuses on quantifying losses and benefits. However, these static assessments do not capture the adaptive rebalancing of stakeholder influence as project priorities shift. In contrast, the proposed method in this research dynamically adjusts stakeholder weights, allowing for a real-time reflection of evolving priorities, such as the increased importance of operators during the post-operation phase. Few studies emphasize the dynamic nature of interactions among risks, such as economic downturns and policy changes, as exemplified by the framework for assessing "gray rhino risks" [30]. However, the proposed method in this research advances beyond risk prioritization to a holistic resilience evaluation framework that explicitly incorporates stakeholder dynamics and their cooperative or conflicting relationships. Notably, the methodological innovations in this study, particularly its focus on megaproject's lifecycle adaptability, address limitations found in operation and maintenance performance evaluation frameworks, such as those proposed to evaluate Chengdu–Chongqing High-Speed Railway [31], with a relatively narrow scope of the post-operation phase. In contrast, the proposed method in this study emphasizes lifecycle adaptability, making it more suited for resilience assessment in the complex and evolving contexts of megaprojects. Lastly, this research advances existing frameworks for evaluation of megaproject's complexity. A recent complexity evaluation framework based on megaproject's structure and attributes quantifies interdependencies among complexity indicators [32]; however, it does not account for how these interdependencies evolve through stakeholder actions and relationships. Our method leverages stakeholder-derived weights adjusted through Nash equilibrium, allowing for dynamic recalibration.

6.2. Practical Implications

The proposed approach offers valuable insights for evaluating and managing megaprojects, emphasizing greater inclusivity, adaptability, and resilience. By using data directly contributed by stakeholders as the foundation for evaluations, it minimizes excessive dependence on external experts while strategically incorporating their input where essential. This balanced methodology ensures that evaluations remain grounded in the perspectives and realities of stakeholders, complemented by expert guidance for critical decisions.

Incorporating stakeholder data into resilience assessments fosters transparency by anchoring the process in inclusive, representative, and traceable information. This reduces subjectivity and offers a clear basis for weight adjustments and outcomes. Applying this approach in practice strengthens trust among stakeholders and ensures that evaluations align with the complex, evolving nature of megaprojects, facilitating equitable and transparent decision-making.

The network-based framework further enhances adaptability by dynamically adjusting weights in response to changing stakeholder interactions and project conditions. This flexibility allows the method to cater to different phases of a megaproject's life cycle, from pre-construction to post-operation. Its capacity to manage incomplete or noisy data adds robustness, ensuring reliable evaluations even in data-constrained environments.

Finally, the inclusion of Nash equilibrium provides decision-makers with a sophisticated understanding of both cooperative and conflicting stakeholder dynamics. This nuanced perspective supports the development of more balanced and effective strategies, promoting fairness and efficiency in megaproject management. In applying Nash equilibrium to megaproject evaluations, managers gain a transparent mechanism for balancing

multiple stakeholders' competing interests, allowing them to pinpoint interventions—such as adjusting incentives or allocating resources—to align individual behaviors with collective project objectives. By observing shifts in equilibrium solutions (e.g., when cost-sharing or governance structures change), practitioners can identify which stakeholder relationships (cooperative or conflicting) most significantly impact resilience. This insight enables targeted negotiations to mitigate conflicts, reallocate responsibilities where needed, and adapt decision-making across project phases, ensuring that no single party can unilaterally undermine or overly dominate the project's strategic direction.

6.3. Limitations and Future Research

Nevertheless, we acknowledge several limitations regarding the applicability of our proposed approach. First, although this research focuses on a single megaproject, different types of megaprojects (e.g., in transportation, energy, or urban development) may feature diverse governance structures, stakeholder relationships, and funding mechanisms that could influence model outcomes. Second, the proposed framework assumes a relatively generic project organization without explicitly accounting for specific management methodologies—such as Agile, Lean Construction, or Integrated Project Delivery (IPD)—that can substantially alter stakeholder coordination and decision-making. Third, while our model accommodates lifecycle transitions between pre-construction, construction, and post-operation phases, it may need additional customization to capture contractual structures, public–private partnership dynamics, or region-specific regulations. Practitioners should therefore ensure that the proposed approach is adapted to the unique cultural, regulatory, and organizational contexts of each megaproject, potentially calibrating model parameters or incorporating complementary project management techniques to enhance resilience evaluation accuracy.

While the proposed model offers a robust framework for evaluating resilience in megaprojects, there are several potential limitations that need to be considered. One key limitation is the reliance on complete and accurate stakeholder data. The model assumes that stakeholders will provide comprehensive and reliable evaluations of subsystem resilience. However, in practice, stakeholders may present incomplete or biased data due to factors such as lack of expertise, conflicting interests, or limited access to information. This may lead to inaccuracies in the resilience assessment and distort the stakeholder weight distribution. Another limitation arises in contexts where there are significant data gaps or uncertainties. Megaprojects are often subject to unforeseen challenges such as political instability, regulatory changes, or natural disasters, which may result in missing or uncertain data. Since our model heavily depends on the availability of complete and accurate data to calculate optimal stakeholder weights, its performance could be compromised in such conditions. While the model incorporates methods for handling incomplete data, its robustness in highly uncertain or volatile scenarios is still limited. Future research could address these limitations by integrating advanced techniques such as machine learning or Bayesian approaches, which could help better manage data gaps and uncertainty. Additionally, exploring the model's applicability in more diverse and real-world settings would contribute to further validating and refining its capabilities.

While the proposed method represents a significant step forward in resilience assessment for megaprojects, several limitations merit further investigation. One key challenge lies in the assumption that stakeholder-provided data are both accurate and representative. This may not hold in cases where stakeholders have incomplete information or conflicting interests that introduce bias into evaluations. Future research could explore mechanisms to validate and cross-check these inputs, thereby improving data reliability. Another limitation arises from the network-based weighting framework, which, although

effective in modeling interactional dynamics, may become computationally demanding for projects involving numerous stakeholders or intricate interaction networks. Addressing this issue could involve developing more scalable algorithms or streamlined processes to maintain efficiency in complex scenarios. The reliance on Nash equilibrium also presents challenges, as it assumes stable interaction frameworks that might not reflect rapidly changing or volatile stakeholder dynamics. Investigating dynamic equilibrium models or hybrid methodologies that integrate network analysis with machine learning could enhance the method's adaptability to such conditions.

Another promising future research direction involves adapting the model to diverse megaproject settings where governance structures, cultural factors, or financing mechanisms may differ significantly from the case examined here. For instance, large-scale infrastructure projects in varying regions (e.g., Africa, the Middle East, or Europe) could present distinct stakeholder dynamics, requiring localized parameter calibration or context-specific contract structures. From a practical implementation perspective, adopting a phased rollout is recommended: pilot the network-and-equilibrium approach on smaller project components or subsystems first, then gradually extend to the entire megaproject. Such incremental deployment allows for real-time feedback, enabling project managers to refine data collection strategies, parameter settings, and stakeholder engagement protocols. Additionally, incorporating digital platforms—such as Building Information Modeling (BIM) or project data analytics tools—could facilitate the ongoing updates needed for real-time recalibration of stakeholder weights and relationships, further bolstering the model's applicability in dynamic, resource-intensive environments.

Finally, broadening the method's application to include a wider range of projects and contexts—particularly those influenced by varying cultural, political, or regulatory environments—would provide critical insights into its versatility and constraints. Addressing these areas through future research would help refine the method further, increasing its utility across diverse megaproject landscapes.

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References

1. Daniel, E.; Daniel, P.A. Megaprojects as complex adaptive systems: The Hinkley point C case. *Int. J. Proj. Manag.* **2019**, *37*, 1017–1033. [CrossRef]
2. Denicol, J.; Davies, A.; Pryke, S. The organisational architecture of megaprojects. *Int. J. Proj. Manag.* **2021**, *39*, 339–350. [CrossRef]

3. Lehtinen, J.; Peltokorpi, A.; Artto, K. Megaprojects as organizational platforms and technology platforms for value creation. *Int. J. Proj. Manag.* **2019**, *37*, 43–58. [CrossRef]
4. Tang, X.; Wang, M.; Wang, Q.; Zhang, J.; Li, H.; Tang, J. Exploring Technical Decision-Making Risks in Construction Megaprojects Using Grounded Theory and System Dynamics. *Comput. Intell. Neurosci.* **2022**, *2022*, 9598781. [CrossRef]
5. Nachbagauer, A.G.M.; Schirl-Boeck, I. Managing the unexpected in megaprojects: Riding the waves of resilience. *Int. J. Manag. Proj. Bus.* **2019**, *12*, 694–715. [CrossRef]
6. Morkan, B.; Bertels, H.M.J.; Sheth, A.; Holahan, P.J. Building megaproject resilience with stakeholders: The roles of citizenship behavior and critical transition mechanisms. *Int. J. Proj. Manag.* **2023**, *41*, 102485. [CrossRef]
7. Liu, T.; Bai, G.; Tao, J.; Zhang, Y.A.; Fang, Y.; Xu, B. Modeling and evaluation method for resilience analysis of multi-state networks. *Reliab. Eng. Syst. Saf.* **2022**, *226*, 108663. [CrossRef]
8. Logan, T.M.; Aven, T.; Guikema, S.D.; Flage, R. Risk science offers an integrated approach to resilience. *Nat. Sustain.* **2022**, *5*, 741–748. [CrossRef]
9. Liu, K.; Liu, Y.; Kou, Y. Study on construction safety management in megaprojects from the perspective of resilient governance. *Saf. Sci.* **2024**, *173*, 106442. [CrossRef]
10. Datola, G.; Bottero, M.; De Angelis, E.; Romagnoli, F. Operationalising resilience: A methodological framework for assessing urban resilience through System Dynamics Model. *Ecol. Model.* **2022**, *465*, 109851. [CrossRef]
11. Jiang, W.; Zhao, X.; Cai, C.; Chang, K.; Liu, K.; Liu, Y. Study on Resilience Evaluation for Construction Management of Major Railway Projects. *Buildings* **2024**, *14*, 732. [CrossRef]
12. Zhao, C.; Xie, X.; Song, J. Complex Network Game Model Simulation of Arctic Sustainable Fishery Trade Cooperation under COVID-19. *Sustainability* **2021**, *13*, 7626. [CrossRef]
13. Yoon, J.H.; Pishdad-Bozorgi, P. Game theory-based framework for analyzing the collaborative dynamic of tacit knowledge sharing and the choice of procurement and contract types in mega construction projects. *Buildings* **2022**, *12*, 305. [CrossRef]
14. Lu, Y.; Liu, B.; Li, Y. Collaboration networks and bidding competitiveness in megaprojects. *J. Manag. Eng.* **2021**, *37*, 04021064. [CrossRef]
15. Guo, N.; Guo, P.; Madhavan, R.; Zhao, J.; Liu, Y. Assessing the vulnerability of megaprojects using complex network theory. *Proj. Manag. J.* **2020**, *51*, 429–439. [CrossRef]
16. Zheng, X.; Chen, J.; Han, Y.; Ren, L.; Shi, Q. Unveiling complex relational behavior in megaprojects: A qualitative-quantitative network approach. *Int. J. Proj. Manag.* **2021**, *39*, 738–749. [CrossRef]
17. Hu, Z.; Wu, G.; Zhang, W. Performance Improvement in Megaprojects Through Project Network Characteristics and Transactive Memory Systems. *Proj. Manag. J.* **2024**, *55*, 313–334. [CrossRef]
18. Liu, K.; Liu, Y.; Kou, Y.; Yang, X.; Hu, G. Relational network of megaproject governance mechanism based on risk prevention and control: Experiences from China. *Prod. Plan. Control* **2024**, *35*, 1860–1872. [CrossRef]
19. Vach, M.; Vachová, P.; Walmsley, A.; Berka, M.; Albert, J.; Cienciala, E.; Braun Kohlová, M.; Máca, V.; Melichar, J. Stochastic evaluation of restoration procedures on postmining land areas using a game theory approach. *Land Degrad. Dev.* **2022**, *33*, 484–496. [CrossRef]
20. Ruan, Y.; Chen, J.; Fan, Z.; Wang, T.; Mu, J.; Huo, R.; Huang, W.; Liu, W.; Li, Y.; Sun, Y. Application of K-PSO Clustering Algorithm and Game Theory in Rock Mass Quality Evaluation of Maji Hydropower Station. *Appl. Sci.* **2023**, *13*, 8467. [CrossRef]
21. Corazza, L.; Cottafava, D.; Torchia, D.; Dhir, A. Interpreting stakeholder ecosystems through relational stakeholder theory: The case of a highly contested megaproject. *Bus. Strategy Environ.* **2024**, *33*, 2384–2412. [CrossRef]
22. Bian, D.; Yang, X.; Xiang, W.; Sun, B.; Chen, Y.; Babuna, P.; Li, M.; Yuan, Z. A new model to evaluate water resource spatial equilibrium based on the game theory coupling weight method and the coupling coordination degree. *J. Clean. Prod.* **2022**, *366*, 132907. [CrossRef]
23. Gil, N.A. Cracking the megaproject puzzle: A stakeholder perspective? *Int. J. Proj. Manag.* **2023**, *41*, 102455. [CrossRef]
24. Zheng, X.; Chen, J.; Xia, B.; Skitmore, M.; Zeng, S. Understanding the Megaproject Social Responsibility Network among Stakeholders: A Reciprocal-Exchange Perspective. *J. Constr. Eng. Manag.* **2023**, *149*, 04023105. [CrossRef]
25. Yan, J. Personal sustained cooperation based on networked evolutionary game theory. *Sci. Rep.* **2023**, *13*, 9125. [CrossRef]
26. Jackson, M.O.; Zenou, Y. Chapter 3—Games on Networks. In *Handbook of Game Theory with Economic Applications*; Young, H.P., Zamir, S., Eds.; Elsevier: Amsterdam, The Netherlands, 2015; Volume 4, pp. 95–163.
27. Pagan, N.; Dörfler, F. Game theoretical inference of human behavior in social networks. *Nat. Commun.* **2019**, *10*, 5507. [CrossRef]
28. He, Q.; Tian, Z.; Wang, T. Performance measurement methods in megaprojects: An analytical review. *Int. J. Proj. Manag.* **2022**, *40*, 634–645. [CrossRef]
29. Jing, P.; Sheng, J.; Hu, T.; Mahmoud, A.; Huang, Y.; Li, X.; Liu, Y.; Wang, Y.; Shu, Z. Emergy-based sustainability evaluation model of hydropower megaproject incorporating the social-economic-ecological losses. *J. Environ. Manag.* **2023**, *344*, 118402. [CrossRef]
30. Guo, J.; Xiang, P.; Wang, X.; Lee, Y. Predicting and managing megaproject gray rhino risks with IF-ANP and DEMATEL based on panel data. *Expert Syst. Appl.* **2022**, *208*, 118243. [CrossRef]

31. Chen, D.; Xiang, P.; Jia, F. Performance Measurement of Operation and Maintenance for Infrastructure Mega-Project Based on Entropy Method and D-S Evidence Theory. *Ain Shams Eng. J.* **2022**, *13*, 101591. [CrossRef]
32. Jia, F.; Xiang, P.; Chen, D. A two-dimensional complexity evaluation model of megaprojects based on structure and attributes. *Ain Shams Eng. J.* **2023**, *14*, 101852. [CrossRef]

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