Computers & Industrial Engineering 218 (2026) 112108

Contents lists available at ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

A motivation-focused approach to co-investment in enhancing joint venture project quality‘

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ARTICLE INFO

Keywords:
Joint Venture Projects
Quality investment
Game theory
Hierarchical approach

ABSTRACT

Joint venture alliances have emerged as an effective approach for acquiring advanced technologies by allowing organizations to pool resources, knowledge, and competitive advantages. Large-scale projects are often assigned to multiple companies as non-integrated joint ventures, sometimes involving companies from different countries, each exhibiting different levels of expertise and quality standards. Disparities in deliverable quality among these partners can increase project duration, generate idle resources, and raise overall costs. This study proposes investing in quality enhancement programs for selected partners to mitigate these challenges. A novel hybrid multi-step framework is developed, integrating a non-cooperative game for delay cost allocation, an optimal control model for planning quality improvements, and cooperative game formulations to fairly distribute costs and benefits among partners. Results indicate that the proposed approach effectively reduces both total project costs and individual partners' costs. Sensitivity analysis further reveals that higher quality-conversion coefficients and increased partner idleness costs enhance the effectiveness of the cooperative strategy, increasing the cost advantage of the cooperative strategy over the non-cooperative one.

1. Introduction

A joint venture (JV) is a strategic business arrangement where two or more independent organizations enter into a contractual agreement to collaborate by sharing resources, like equipment and expertise. This partnership is usually temporary and aims to secure mutual benefits from the combined effort. Joint ventures can be divided into integrated and non-integrated categories based on their ownership, control, and decision-making structures. In the integrated category, ownership, responsibilities, and decision-making are shared according to the stipulated obligations, but in the non-integrated, each of the partners undertakes a part of a project without the intervention of the other. This is often necessary when the different parts of the project require expertise unique to each partner (Garb, 1988; Norwood & Mansfield, 1999). In a non-integrated joint venture, often associated with technology-focused projects, the partners' individual work packages are eventually combined to produce the final project outcome. Hence, despite their contractually independent nature, there is an inherent interdependence between the partners' activities and their planned execution which makes the coordination and partnership of the partners inevitable. This research examines a non-integrated joint venture alliance and suggests an incentive mechanism to address challenges that collectively impact project outcomes. The process of establishing a JV strategic alliance involves five key stages, as outlined by (Rumpunen, 2011). Initially, there is a preparation phase to set everything in motion. Next, potential partners are identified. Then, partners are chosen based on specific criteria. After that, the partners engage in negotiations, a crucial stage for aligning obligations and drafting a contract. The more detailed the agreement provisions, the stronger the partnership becomes. This paves the way for the final stage, where the JV is implemented, managed, and controlled. The current research model emphasizes the fourth stage where partners negotiate and draft a contract. A well-crafted contract with thorough provisions helps establish a robust partnership and minimizes the risk of conflicts.

Local governments often support high-tech projects through non-integrated joint ventures involving local and foreign companies. This partnership allows local companies to utilize their skills (Ling & Gui, 2009) and contributes to macroeconomic indicators, such as employment, gross national product (GNP), as well as national growth and development programs. Foreign companies also benefit from this

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https://doi.org/10.1016/j.cie.2026.112108
Received 12 August 2025; Received in revised form 7 March 2026; Accepted 6 May 2026
Available online 9 May 2026

strategic alliance, as it enables them to obtain authorizations to operate in local countries more easily, thereby expanding their market (Raftery et al., 1998). But despite the opportunities that this strategic alliance provides for partners, the differences in business environments, performance standards, and even management and leadership styles of foreign and local companies pose many challenges to JVs (Momeni, Yaghoubi, & Aliha, 2019; Scaringella & Burtschell, 2017). The current research explores the issue of varying quality standards among partners in international JV projects and analyses how these differences impact the project's cost, time, and quality outcomes. It further investigates the participation of partners in quality improvement programs as a complementary strategy to address this challenge within the JV project.

If the deliverables provided by the partners do not meet the required quality standards, they will be rejected, leading to rework and extending the duration of the relevant work package (Momeni, Yaghoubi, & Aliha, 2019). Conversely, in a project network, if one work package is delayed due to its precedence relations, it results in the idleness of resources for other work packages and causes delays in the entire project, along with increased costs. The proposed strategy in this research can address these challenges by utilizing different evaluation models. These include models to assess the impact of quality on work package completion time, measure project delay costs and partners' share of those costs and encourage participation in quality improvement programs through incentives. By integrating these models, we employ a hierarchical approach, meaning each model uses the output of others in a specific order. This approach is well-suited for problems with considerable computational and analytical complexity when tackled within a single model (Hans et al., 2007).

Poor quality of work packages is a major factor in project failure and inefficiency, potentially leading to increased costs, delays, and even contractor bankruptcy. According to Scaringella & Burtschell (2017), differences in the quality levels among partners have been identified as a primary cause of failure in joint venture projects. These differences may arise due to the novelty of collaboration, the absence of shared standards, or the involvement of partners from diverse industries or countries. Such discrepancies can occur regardless of whether a partner is local or foreign, depending on firm-specific capabilities and contextual factors. This results in significant deviations in time and cost from the original plan. Similar findings have been reported in other studies. For instance, (Chen et al., 2019) identify mismatched partner priorities in cost–quality trade-offs and lack of unified quality standards as major factors contributing to inefficiencies in construction joint ventures. Likewise, (Bamford et al., 2022) highlights that contractual mechanisms such as *sole risk* or *nonconsent* provisions are often used to address divergences in partners’ quality expectations and investment commitments. Furthermore, evidence from the South African construction industry (Seiso, Ogunbayo, & Aigbavboa, 2023) suggests that unclear distribution of responsibilities and insufficient commitment to quality requirements frequently result in project delays and cost overruns.

These studies collectively reinforce the empirical observation of discrepancies in quality standards and management practices among partners across different contexts, emphasizing the practical significance of modeling investment in quality improvement within joint ventures.

The relationship between quality and cost is typically examined within manufacturing systems and the models that relate quality and cost factors are known as quality-cost models. In these models, the cost of quality is examined by considering different aspects of quality on cost components such as market share, inspection cost, maintenance and repair costs, etc. (Schiffauerova & Thomson, 2006). The optimal control-based model of (Momeni, Yaghoubi, & Aliha, 2019) is utilized as the quality-cost model of the present research. This model measures the relationship between quality, cost, and time in the context of project management, determining the optimal time and amount of investment in quality.

It should also be noted that while contractual quality requirements, penalties, and inspection mechanisms are commonly employed in most construction and engineering projects, they are often insufficient in joint ventures due to the decentralized control structure and heterogeneous quality management systems among partners (Momeni, Yaghoubi, & Aliha, 2019; Rumpunen, 2011; Scaringella & Burtschell, 2017). In non-integrated JV projects, each partner is responsible for its own work package, and contractual inspections usually occur after task completion rather than during execution. This reactive nature of standard mechanisms fails to prevent quality deviations that propagate through interdependent work packages (Estévez-Fernández, 2012). Moreover, enforcing penalties may damage long-term collaboration and trust, while inspections alone cannot ensure alignment of quality expectations or investment efforts among partners (Huynh, Trinh, & Nguyen, 2019). Therefore, a cooperative framework that jointly optimizes quality investment and cost sharing is required to complement conventional contractual mechanisms and enhance project-wide efficiency.

Overall, the findings of this research demonstrate that the proposed hybrid multi-step model combining optimal control theory with both cooperative and non-cooperative game-theoretical approaches provides a comprehensive and effective framework for addressing the challenges of quality inconsistency and cost overruns in non-integrated joint venture projects. The results obtained from the real case study confirm that integrating quality investment decisions with cost-sharing and delay-penalty allocation mechanisms leads to a substantial reduction in total project costs, enhanced fairness in the distribution of costs and benefits, and improved synchronization among partners. In particular, the optimal control component identifies efficient investment paths for quality improvement, while the game-theoretical mechanisms ensure the equitable allocation of delay and idleness costs, promoting collaboration rather than conflict among partners. Moreover, the cooperative investment in quality enhancement contributes to minimizing rework, improving time performance, and increasing the overall efficiency of the project network. These outcomes collectively show that the proposed hybrid framework not only achieves the objectives of cost reduction and fairness but also provides a practical and theoretically sound tool for managers and policymakers to foster sustainable collaboration in complex multi-partner projects.

The term “motivation-focused approach” in this study refers to a framework that explicitly integrates motivational incentives into the mechanisms of quality improvement and collaboration among partners. Unlike traditional quality management frameworks that primarily rely on control, inspection, and compliance mechanisms, the motivation-focused approach emphasizes partners’ behavioral and incentive-driven engagement in achieving collective quality goals. In non-integrated joint venture projects, where partners retain independent decision-making authority, the success of quality enhancement programs depends not only on technical investments but also on the willingness of partners to align their actions toward shared objectives. Therefore, the proposed framework operationalizes motivation by employing game-theoretical models that translate cooperative benefits and delay penalties into quantifiable incentives. Through this structure, partners are encouraged to participate voluntarily in joint quality improvement efforts because they perceive fair and measurable rewards for collaboration and cost-sharing. In essence, the “motivation-focused approach” captures the dynamic interplay between economic motivation, cooperative behavior, and technical quality management, thereby distinguishing it from conventional quality assurance systems that are primarily enforcement-oriented.

The remainder of the paper is organized as follows: the next section reviews related studies to identify the gaps that the present research addresses. In section 3, we clarify the research models. Section 4 presents the results of the proposed models in a real case study. Section 5 highlights insights derived from the results. Section 6 discusses the model's applicability. Finally, section 7 concludes the paper.

2. Literature review

International joint venture research has primarily focused on strategic issues such as partner selection, risk management and evaluation, governance mechanisms, economic and managerial theories underpinning JVs, performance measurement, key performance indicators, JV learning, and JV instability (Child et al., 2005; Hong et al., 2014; Lin & Li, 2024). Most of these studies rely on qualitative and subjective evaluations, whereas there is relatively little quantitative research using mathematical modelling to support tactical and operational decisions, predominantly emerging in recent years (Girmscheid & Brockmann, 2010; Hong & WM Chan, 2014). The research work done in (Moiseenko & Gorelova, 2021) analyzed the criteria for selecting investment programs for existing facilities reconstruction. In the review paper of (Liu et al., 2024), knowledge transfer was identified as the most researched topic of IJV studies between 2012 and 2021. "Value creation" and "product innovation" were considered the main results of learning and knowledge transfer in the JV. This paper aligns with JV learning studies and focuses on developing mathematical models to address JV problems. It takes a quantitative approach and utilizes a hybrid method due to the complexity of the problem being studied.

Some papers explored the triple constraints of project management, namely cost, time, and quality, in the context of JV projects. For example, the work done by (Razzaq et al., 2018) investigated the effects of risk factors on the cost, time, and quality of JV projects using an analytical hierarchical process (AHP) and determined economic, legal, social, and environmental risks as the most influential external risks. In another research by (Akhund et al., 2018), unclear and undefined goals, language differences, price fluctuations, and lack of appropriate rules using the Average Index method were the risks that had the greatest effect on the cost, time, and quality criteria of JV construction projects. Quality and other process variables are not necessarily linearly related and (Zhao et al., 2020) investigated this relationship using kernel ridge regression (KRR)-based methods. (Mahdiraji et al., 2021) proposed a multi-objective linear programming model to optimize time, cost, quality, and risk simultaneously. Their proposed approach benefits hesitant fuzzy linguistic term sets and helps to identify the best implementation situation of activities under uncertain circumstances. This is when time, cost, quality, and risk criteria are relevant in the project planning and scheduling. The work by (Momeni, Yaghoubi, & Aliha, 2019) measured the relationship between investment in quality improvement and the cost and execution time of a work package by using an optimal control model. Their proposed model was one of the few models that provided a mathematical relationship between these three dimensions. However, it concentrated on a single work package within the project. This research extends (Momeni, Yaghoubi, & Aliha, 2019) by generalizing the relationships among the three dimensions across the entire project. It considers the interactions between work packages in the project network and how their completion times impact project delays and resource idleness.

When there is some kind of interrelation between the quality of work or products of one company and another, joint investment in the quality of partners has emerged as a cooperative strategy. To induce quality improvement efforts, contractual agreements between a manufacturer and a supplier were developed by (Chao, Iravani, & Savaskan, 2009) using insights from super modular game theory. In a market where demand is dependent on the retail price and the consumer reference-quality effect, (Qiu, Yu, & Sun, 2022) presented a Stackelberg game in which a retailer follows a supplier, and some contract types are employed to coordinate their actions. In that model, the supplier sets the quality level of the product while the retailer specifies the retail price. An optimal control model is also used to determine the quality level over time. In a similar study, (Cao et al., 2022) provided several schemes for joint quality investment to reach the optimal supply chain profit. Quality improvement was introduced as a competitive strategy for dual-channel retailers by (Xu et al., 2022), and a game-theoretical model was employed to investigate the trade-off between quality improvement and price-matching in competition. (Zhang et al., 2022) studied shared manufacturing quality synergistic improvement. Using a co-evolutionary game model, they examined the effects of interrelated factors on the effectiveness of the mechanism. They indicated that the most effective and reliable mechanism is one that varies the intensity of rewards and penalties. For interfirm innovation projects where success depends on all firms generating high-quality outputs, (Beer & Qi, 2024) investigated the decisions of firms' decisions to communicate their quality output progress using game theory. Despite the valuable insights of the mentioned studies, none of them are in the field of project management, and defining the quality and quality dependence of work packages is one of the innovations of the present research. According to (Gil, Mataveli, & García Alcaraz, 2021), quality management measures are essential to the success of projects.

Conflict management is one of the key topics in collaborative projects (in the form of JV or other forms). Some researchers have proposed analytical and descriptive models to manage contradictions by identifying the reasons and motivations for creating contradictions and differences. (Lee et al., 2017) identified reasons for conflicts in South Korean collaborative projects and presented scenarios to avoid them during the projects. (Zarei, Sharifi, & Chaghouee, 2018) conducted a comprehensive study on oil and gas project delays in Iran. They utilized Semantic Network Analysis to identify the root causes of these delays and prioritize them. One of the most significant conflicts in projects is the delay of the project due to the deficiencies of each of the project partners. Avoiding delays and assigning penalties to partners in case of delays are among the main concerns of project managers and planners. This topic has been extensively analyzed in academic research, often employing game theory. In (Bergantiños & Lorenzo, 2019), the design of a central mechanism for assigning delay penalties to partners was assessed using game theory. Notably, they evaluated the delay consequences of losing opportunities in future projects. Therefore, their functionality mechanisms differ from those proposed in the present paper, which relate the delayed costs of quality defects to contractual commitments. One of the most thorough investigations of delayed assignment in projects is the work of (Estévez-Fernández, 2012). They used bankruptcy and taxation games to assign the penalty for delay directly to the partner who was responsible for the work packages. This was instead of assigning them to coalitions or routes in the project relationship network. Due to the widespread application of their model and its compatibility with profit and loss sharing between partners of a JV project, we will also utilize it in the present paper.

Researchers also examined other problems that required the cooperation of partners in projects. (Zarei, Sharifi, & Chaghouee, 2018) examined various sharing mechanisms based on cooperative game theory, such as the core, the nucleolus, and the Shapley value, to allocate excess benefits or costs of public–private partnership (PPP) projects among stakeholders. The multiple project scheduling and resource allocation problem subject to a globally available budget is investigated by (Liu et al., 2024) using a multi-agent-based cooperative approach. They assumed that such project managers are autonomous and employ a negotiation protocol to resolve resource conflicts. This problem with multi-skilled staff shared between projects was also studied by (You, Xu, & Zhao, 2024), who developed a two-layer approach to solve the problem: a local scheduling layer to determine the scheduling of single projects and a global coordination decision-making layer with a greedy assignment strategy to resolve global resource conflicts while minimizing the multi-project total tardiness cost. (Jia, Zhang, & Wang, 2023) explored cooperative behavior among social capital regarding different parameters such as network density and initial cooperation probability. (Fernandes & O'sullivan, 2023) listed project management practices that have positive effects on university-industry R&D collaboration programs. These practices were linked to various project phases: project initiation, project planning, project execution, and project closure. This research examined the issue of qualitative participation, which is crucial and challenging in JV projects (Scaringella & Burtschell, 2017), but has been less emphasized in previous studies.

As such, game theory has also had a growing application in achieving equilibrium and cooperative solutions in projects. This is especially true for projects that are carried out in collaboration with several companies, such as JVs. The work by (Huynh, Trinh, & Nguyen, 2019) addressed three challenging issues that can lead to conflicts among project stakeholders: 1) scheduling of payments by the employer, 2) scheduling of project item deliveries by contractors, and 3) procurement of necessary items by suppliers. For this purpose, they considered strategies to reduce bidding risk and used the Nash equilibrium to identify the final strategy. The work by (Müller & Zaby, 2019) used game theory and Nash solutions to determine optimal participation scenarios for JV research projects, including non-participation with only competition, non-participation with only technology sharing, and full participation. Efficient information sharing across Modular Integrated Construction (MiC) stakeholders was mentioned as a critical requirement that could be facilitated using blockchain technology by (Song et al., 2022) and (Zhang et al., 2023). Moreover, to evaluate blockchain deployment among stakeholders, the paper used the game theory approach. They demonstrated that adoption depends on functional factors such as the green level, equipment deployment cost, technology operation cost, benefits of blockchain adoption, and government subsidies. Joint resource procurement was introduced as a cooperative strategy in construction projects to reduce the cost of acquiring capital equipment by several independent firms (Rouhparvar, Babaei, & Navidi, 2024). They also employed a cooperative game theory approach to allocate the benefits of cooperation between them in a fair and efficient manner for this purpose. The environmental responsibility of firms is also outlined as a sustainable goal that requires the participation of partners in each other's plans. The application of game theory in bidding processes (Ahmed & El-adaway, 2023), construction safety supervisory mechanisms in projects (Jiang et al., 2023), the cooperation of the private sector to invest in oil companies (Safarii et al., 2023), and the evaluation for prioritizing sustainable power supply investment projects in (Lin & Li, 2024) are other researchers who used game theory to explore cooperation in the context of project management. While the reviewed studies frequently employed competitive and cooperative games, this research simultaneously utilizes both approaches to encompass different modes of participation and non-participation in evaluating results.

Table 1 presents a comparison between the reviewed studies and current research. In this table, "Collaborative Strategy" refers to studies that not only analyze current conditions and identify factors but also propose solutions for partner integration. "Cooperative" and "Non-Cooperative" game theories are classified according to (Asghari et al., 2022). The first includes games that use solution concepts of cooperative games, such as Shapley value or core, while the other contains those that use Nash or Stackelberg solutions, as well as coordination contracts, such as cost-sharing. Studies that focus on partners' disagreements and their solutions are placed under "Conflict Management". Finally, investigations that use dynamic programming, optimal control models, and evolutionary games to measure the effect of decisions over time are labeled as "Dynamic Evaluation".

Table 1 demonstrates that the current research addresses broader issues than prior studies. These include an integrated analysis of cost, time, and quality as the triple constraints of projects; a collaborative approach to quality improvement that mitigates problems in JV projects caused by negligence and enhances overall performance; solutions for resolving partner conflicts fairly; and a dynamic evaluation of cooperative strategy decisions that align with the objectives of learning and knowledge transfer in JV projects. The introduction and literature review highlight the significance of the problem from various previous research perspectives. Due to the project's numerous dependencies and complex problems, proposing a framework to address these issues offers significant practical value. Moreover, the framework's fairness levels further enhance its merit.

The definition of quality and the collaborative strategy to improve it, initially proposed in (Momeni, Yaghoubi, & Aliha, 2019) and expanded in this research, represents an emerging and innovative approach in project management. It draws insights from other fields like supply chain management. The application of game theory, in both cooperative and non-cooperative forms, is likely the most efficient method for resolving conflicts and evaluating the benefits of partnerships.

Although this paper builds on prior studies that allocate lateness penalties to partners, the method of displaying and evaluating other game forms makes a significant contribution to project management and

Table 1
The comparison of the current research with the reviewed ones.

Paper	JV Projects	Triple Project Constraints			Collaborative Strategy	Game Theory		Quality improvement	Conflict Management	Dynamic Evaluation
		Cost	Time	Quality		Cooperative	Non-Cooperative			
Estévez and Fernández (2012)						*	*		*	
Scaringella and Burtschell (2017)	*		*	*				*	*	
Lee et al. (2017)	*								*	
Sharafi et al. (2018)	*	*				*			*	
Akhund et al. (2018)	*	*	*	*					*	
Momeni et al. (2019)	*	*	*	*				*		*
Müller and Zaby (2019)	*				*		*		*	
Zhao et al. (2020)	*	*	*	*				*		
Mahdiraji et al. (2021)		*	*	*						
Qiu et al. (2022)					*		*	*		*
Cao et al. (2022)					*		*	*	*	
Srikanth et al. (2022)					*		*	*		
Zhang et al. (2022)					*		*	*		*
Zhang et al. (2023)					*		*		*	
Beer and Qi (2024)	*	*		*	*		*	*		
Liu et al (2024)	*				*				*	
You et al. (2024)		*	*		*				*	
Rouhparvar et al. (2024)					*	*			*	
Present Research	*	*	*	*	*	*	*	*	*	*

can be extended to future research. The proposed framework offers a precise assessment of the values of different coalitions of project partners, enabling collaboration within coalitions while competing against others, without assuming external information. It also provides a comprehensive explanation of handling common project data to meet research needs, offering project managers a complete tool for problem-solving.

3. Model description

This research focuses on a large project with multiple work packages, each undertaken by an independent partner, forming a non-integrated JV as a temporary strategic alliance. Such alliances are typical in technology-based projects with a broad scope, involving partners with unique skills and knowledge. Although the work packages appear independent, each partner is solely responsible for implementing, managing, and controlling their assigned work packages. If some deliverables are judged to be of low quality, rework becomes inevitable, extending the work package's timeline, delaying successors, and reducing resource productivity. Consequently, this quality issue impacts the project's time and cost, necessitating an integrated assessment. Quality differences are common in JV projects, especially when partners come from countries with varying standards. As quality defects affect all partners, it's crucial to establish clear contractual obligations to hold each partner accountable. Partnership agreements that foster collaboration and support can effectively prevent problems and promote mutual growth and support. We refer to this approach as collaborative investment in JV project quality, and Fig. 1 presents the conceptual model designed to address it.

According to Fig. 1, the integrated conceptual framework of the study combines several complementary models to address the interrelated problems of quality inconsistency, project delay, and cost allocation in joint venture (JV) projects. The framework begins with an optimal control model that determines the optimal level and timing of quality investment for each work package, establishing the link between quality improvement, time reduction, and rework cost. The outcomes of this stage specifically the adjusted completion times and costs are then used as inputs to a delay cost allocation model based on bankruptcy and taxation games, which fairly distributes project delay penalties among partners according to their contributions to the overall delay. Subsequently, a resource non-utilization model estimates the cost of idle resources arising from interdependent delays within the project network. Finally, these results are integrated within a cooperative game-theoretical model that evaluates various coalition strategies and determines equitable cost and benefit allocations to encourage collaborative investment in quality improvement.

This multi-level integration provides a coherent analytical sequence, where each model's output serves as the input for the next, ensuring both computational feasibility and interpretive clarity. By linking decision layers through hierarchical logic, the framework captures the dynamic and interdependent nature of JV projects while offering an intuitive understanding of how quality investments propagate through cost, time, and cooperation mechanisms.

Given the application of multiple mathematical models in this research, all variables and parameters utilized in the formulations are systematically listed and described in Appendix **1** to facilitate better understanding and improve the readability of the paper.

1. The quality investment model in work packages of JV projects

In this paper, the meaning of quality in the context of project management is based on (Momeni, Yaghoubi, & Aliha, 2019). In this regard, $\lambda(t)$ as the quality of a work package is defined by the ratio of perfect deliverables to total deliverables at time t (Momeni, Yaghoubi, & Aliha, 2019). Next, assume that to complete the work package, n units of deliverables should be produced in the standard T_c units of time (when there is no quality defects), the completed time of the work package in the presence of quality failure will be T, and the reworking cost per unit of time is denoted by c. Considering this definitions of quality, the total reworking costs in the planning horizon is $\int_0^T c.(1-\lambda(t)).dt$[8].

However, by investing in the quality improvement plans, the rate of $\lambda(t)$ will be increased and doing so, the overtime costs will be decreased. Defining the investment rate in quality at time t by $\delta(t)$ and the discount rate by dr, the total investment costs will be as $\int_0^T e^{-dr.t}.\delta(t).dt$. Usually, the relationship between investment (δ) and quality level (q) is considered as the quadratic relationship of $\alpha.\delta = q^2$ where the constant α is a **quality-conversion coefficient** reflecting the effectiveness with which investment δ is transformed into quality improvements (Gavious &

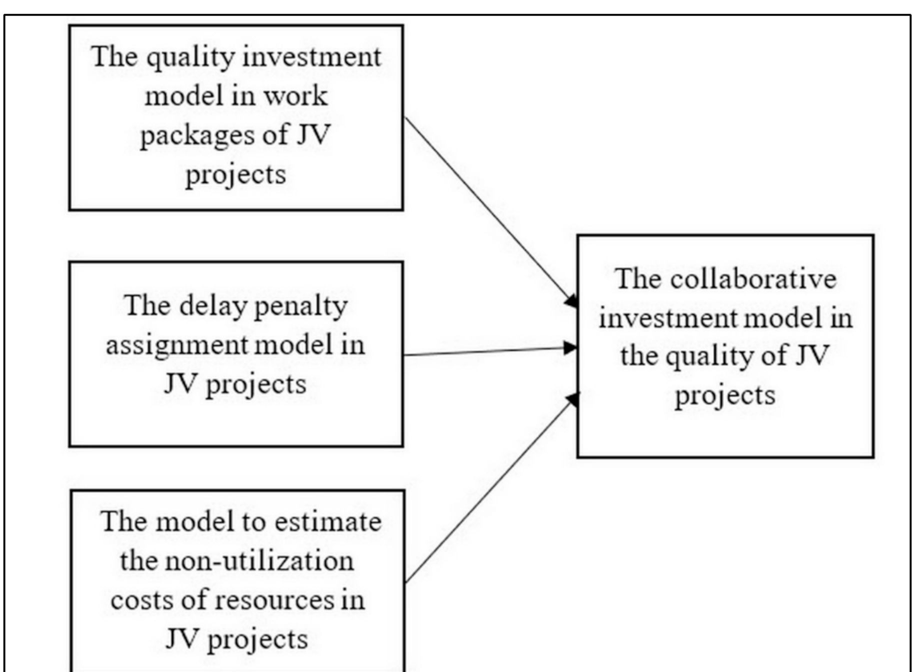

Fig. 1. The conceptual model for the quality assessment in JV projects.

Lowengart, 2012). A practical method for estimating this coefficient in real-world cases has also been presented in (Momeni, Yaghoubi, & Aliha, 2019). Assuming the same relationship in this study and denoting the initial quality level by λ_0, the differential equation $d\lambda(t)/dt = \alpha.\delta(t)/(2\lambda(t))$ and the boundary condition $\lambda(0) = \lambda_0$ will describe the effects of investment on the quality level improvement (Momeni, Yaghoubi, & Aliha, 2019). In practice, the initial quality level (λ_0) can be estimated through a brief preliminary quality assessment before project initiation. Such rapid evaluations—often completed within a single working day—are common in engineering and construction JVs to gauge partners' quality systems and prior performance. The resulting estimate provides a practical baseline for λ_0, which can later be refined as project data becomes available.

Also, a state variable is required to show the relationship between the completion time T and the quality level $\lambda(t)$. The state variable $\tau(t)$ which indicate how much of the required time T_c has been completed up to time t could be used for this purpose and as shown by (Momeni, Yaghoubi, & Aliha, 2019), the differential equation $d\tau(t)/dt = \lambda(t)$ and the boundary conditions $\tau(0) = 0$ and $\tau(t) = TC$ could establish this relationship.

Regarding the discussion above, the optimization model for investing in the quality of work package i is structured as follows. The index i distinguishes work package i from others Also, $\delta_i^{\max}$ is the maximum rate of investment in quality of work package i per unit of time that is dictated by the financial constraints on the project (Momeni, Yaghoubi, & Aliha, 2019):

Model 1: The optimization model of investment in the quality of a work package(Momeni, Yaghoubi, & Aliha, 2019):

$$\min \pi(\lambda_i(t), \delta_i(t), T) = \int_0^T c_i.(1-\lambda_i(t)).e^{-dr.t}.dt + \int_0^T e^{-dr.t}.\delta_i(t).dt \tag{1}$$

$s.t.$

$$\frac{d\lambda_i(t)}{dt} = \frac{\alpha_i.\delta_i(t)}{2\lambda_i(t)} \tag{2}$$

$$0 \leqslant \lambda_i(t) \leqslant 1 \tag{3}$$

$$\frac{d\tau_i(t)}{dt} = \lambda_i(t) \tag{4}$$

$$0 \leqslant \delta_i(t) \leqslant \delta_i^{\max} \tag{5}$$

$$\lambda_i(0) = \lambda_{i0} \tag{6}$$

$$\tau_i(0) = 0; \quad \tau_i(T) = TC_i \tag{7}$$

The above model is an optimal control model in which the control variable $s_i(t)$ should be specified to determine the state variables $\lambda_i(t)$,$\tau_i(t)$ and consequently, the cost function in Eq. (1). The detailed and thorough solution of this model in (Momeni, Yaghoubi, & Aliha, 2019) reveals several valuable points:

1) It is proved that in the optimal solution, there is at most one investment interval. Furthermore, considering that the Hamilton function for this optimal control model is linear with respect to the control variable $\delta_i(t)$, the investment at the maximum rate of $\delta_i^{\max}$ is optimal in this interval.
2) The optimal interval of the investment is determined by considering the first order conditions of the Hamilton function and the general minimum condition of the Hamilton function, and solving the resulting system of equations (For more information, refer to (Momeni, Yaghoubi, & Aliha, 2019)).
3) If the problem is regarded as a free final time optimal control model, the optimal final time T is reached by balancing between saving in reworking costs and the amount of investment. This time is the maximum time for completing the work package denoted by $T_i^{\min}$. Notably, when project managers have no plan to utilize the quality investment strategy, $\delta_{i,\max}$ will be equal to zero which leads to $\lambda_i(t) = \lambda_{i0}$, $\delta_i(t) = 0$ and $T_i^{\max} = TC_i/\lambda_{i0}$.
4) However, one might aim to compress the work package execution time as much as possible. This is achieved by investing the maximum amount of money until the quality level reaches its highest level. We denote this minimum time by $T_i^{\min}$.

Accordingly, the completion time of the work package place in the interval $[T_i^{\min}, T_i^{\max}]$ and as mentioned earlier, this time affects also the project delay and utilization rates of partners' resources. In this paper, the possible execution times of the work package are considered as discrete scenarios from this interval. Moreover, for each scenario, this model is solved by setting the final time T equal to the intended execution time and using the procedure suggested by (Momeni, Yaghoubi, & Aliha, 2019). Doing so, the quality related costs in Eq. (1) is determined. However, to identify costs related to project delays and the non-utilization of partners' resources, we need additional models, which are explained in the following section.

It should be noted that what makes problems in the field of project management and control particularly challenging is the presence of multiple work packages and the complex network relationships among them. The problem under investigation in this study is no exception. Therefore, in order to analyze each aspect of the problem more precisely, several models and analytical tools have been developed, as discussed in the subsequent sections. The integration of their results, in line with realistic project conditions, enables them to obtain an appropriate and near-optimal solution.

However, there are also practical cases in which only a single work package in the project is affected by a quality violation. In such situations, the network relationships among work packages do not need to be jointly analyzed to improve the affected one. This case, which is not uncommon in real-world projects, can be effectively addressed using **Model 2**. Compared to the more complex multi-model framework required for interconnected work packages, **Model 2** provides a simpler yet optimal solution for this specific situation.

Accordingly, Model 2 is relevant in situations where a project involves a single phase or primary work package executed by one partner, or when the quality defect and its resulting costs can be solely attributed to one partner—such as in the last work package of a JV project, the responsible partner bears the delay and non-utilization costs of resources. This simplifies the scenario, as there's no need to consider complex network relationships with multiple work packages and partners. Thus, the optimal control model can be adjusted by incorporating delay costs without the necessity to explore the detailed network models. Thus, **Model 2** is introduced to address the whole quality defect problems in the mentioned cases as follows:

Model 2: The modified quality investment model when the quality defects only affect one work package in a JV project

$$\min \pi(\lambda(t), \delta(t), T) = c_D.(T - TC) + \int_0^T c.(1 - \lambda(t)).e^{-dr.t}.dt + \int_0^T e^{-dr.t}.\delta(t).dt \tag{8}$$

$s.t.$

$$\frac{d\lambda(t)}{dt} = \frac{\alpha.\delta(t)}{2\lambda(t)} \tag{9}$$

$$0 \leqslant \lambda(t) \leqslant 1 \tag{10}$$

$$\frac{d\tau(t)}{dt} = \lambda(t) \tag{11}$$

$$0\leqslant\delta(t)\leqslant\delta^{\max} \quad (12)$$

$$\lambda(0)=\lambda_0 \quad (13)$$

$$\tau(0)=0;\quad \tau(T)=TC \quad (14)$$

In Model 2, the parameter c_D denotes the unit delay cost of the project, which includes both the contractual delay cost and the non-utilization cost of resources per unit of time. Except for the first term in the objective function of **Model 2**, the other terms are the same as in **Model 1**. Therefore, the first-order conditions and proof of convergence of **Model 2** are similar to those of **Model 1**. The only difference between these models is the boundary condition in the form of Eq. (15), which must be established according to Pontryagin's Maximum Principle. Taking into account the boundary conditions in the form of Eq. (15), the method used to solve **Model 1** can also be applied to solve **Model 2**.

$$H(\lambda(T),T,\delta(T)))+\frac{\partial(c_D(T-TC))}{\partial T}(T)=0\rightarrow H(\lambda(T),T,\delta(T)))+c_D=0 \quad (15)$$

2. The delay penalty assignment model in JV projects

In joint venture projects, delays resulting from issues such as quality defects can lead to penalties being imposed by clients. To fairly distribute responsibility among partners, it's essential to allocate these delay penalties based on each partner's contribution to the delay. However, assessing each work package's contribution to the project delay is challenging due to the interdependence between work packages in the project network. This paper utilizes the models proposed in (Estévez-Fernández, 2012) to assign delay penalties to JV partners.

To better understand the model, let's look at the project network illustrated in Fig. 2. This network comprises five work packages, namely A through E. It is worth noting that the nodes S and F do not represent work packages; rather, they indicate the start and finish time of the project, respectively. In the network of this project, there are four routes S-B-D-F, S-A-D-F, S-A-E-F, and S-C-E-F. The total time to complete the work packages in each path will be the project completion time in each path, and the path with the longest time will be the critical path of the project, which determines the project completion time. It becomes unavoidable to delay the project if the completion time of the work packages changes, as this results in a change in the critical path time. Hence, determining a package's contribution to project delay should be done by considering project paths, each becoming a critical path.

According to (Estévez-Fernández, 2012), each project could be presented by the notation $(\{N_1,\ldots,N_m\},p,r,R)$ where $\{N_1,\ldots,N_m\}$ denotes m paths of the project, p is a vector contains the scheduled duration of work packages, r is the vector of actual duration of work packages, and R is a function which identify the penalty delay as a function of the delay amount. In this project, the delay of work package i for a given r is determined by $d_i(r)=\max\{0,r_i-p_i\}$ and for its earliness $e_i(r)$, the relation $e_i(r)=\max\{0,p_i-r_i\}$ is employed. In this research, it is assumed that some work packages are delayed due to quality failure. Also, a firm's capability may allow it to complete its work package ahead of schedule or develop this capability through investment in quality. To determine a work package's contribution to project delay, as outlined in the delay assignment mechanism of (Estévez-Fernández, 2012), you first identify its role in delaying project paths using a cost-sharing mechanism. Then, by considering each work package's contribution to delays within various coalitions, the Shapley value can be employed to allocate the delay costs to individual work packages effectively.

A cost-sharing mechanism could be expressed by the notation (N,q,c) in which, $N=\{1,\ldots,n\}$ is the set of players and $q\in\mathbb{R}_+^N$ is a non-negative vector whose i-th element (q_i) indicate the demand for player i. Also, $c:\mathbb{R}\rightarrow\mathbb{R}_+$ is a non-decreasing cost function such that for $t\leqslant0$, $c(t)=0$. A cost sharing mechanism is a mapping to (N,q,c) as the vector $y(N,q,c)\in\mathbb{R}_N^+$ where $\sum_{i\in N}y_i(N,q,c)=c\left(\sum_{i\in N}q_i\right)$ and if $q_i=0$, then $y_i(N,q,c)=0$. So far, many cost-sharing mechanisms have been developed in the literature (Koster, 1999; Moulin, 1987; Society, 1955) among which, the serial cost-sharing mechanism (y^s) is employed in this paper (Estévez-Fernández, 2012). In this mechanism, without loss of generality, first, the players are sorted based on their demand vector such that $q_1\leqslant q_2\leqslant\ldots\leqslant q_n$. Next, the costs are assigned to partners using Eqs. (16) and (17):

$$y_1(N,q,c)=\frac{c(nq_1)}{n} \quad (16)$$

$$y_i(N,q,c)=\frac{c(nq_1)}{n}+\sum_{k=2}^{i}\frac{c\left(\sum_{j=1}^{k-1}q_j+(n-k+1)q_k\right)-c\left(\sum_{j=1}^{k-2}q_j+(n-k+2)q_{k-1}\right)}{n-k+1}\quad\forall i\geqslant2 \quad (17)$$

In the cost-sharing mechanism for assigning the delay cost to project paths, c will be the same as R which is a non-decreasing function of the project delay (Estévez-Fernández, 2012). Now, if $\mathrm{P}\in\{1,\ldots,m\}$ will be a path in the project, N_P represents the set of work packages in this path, and for the demand vector of path P, i.e., q^P, $q_i^\mathrm{P}=d_i(r)$ is considered. As will be seen later, quality investment strategies affect the actual duration of work package execution, i.e., vector r. On the other hand, the demand vector q^P was defined as a function of vector d, which is itself a function of vector r, assuming vector p is fixed. So, the cost-sharing mechanism for path P will be in the form of $y^\mathrm{P}(r)=y\left(N_\mathrm{P},q^\mathrm{P}(r),R\right)$ and R is the penalty cost of the project as a function of project delay.

To evaluate the joint effects of work packages on project delay, it's crucial to consider different coalitions of work packages. When work packages form a coalition, delays in one can be offset by expediting others within the same coalition. However, this compensation does not apply to work packages outside the coalition. Therefore, when calculating a coalition's share in the project delay cost, if a work package outside the coalition finishes earlier than planned, its execution time is set to the planned duration. Meanwhile, the execution times of delayed work packages, both within and outside the coalition, are recorded as their actual durations.

For this purpose, first, $\varepsilon=\{i\in N|e(i)\geqslant0\}$ is regarded as the set of work packages completed earlier than schedule. Then, if coalition g is defined as a subset of the work packages, the vector $(p|\varepsilon\backslash g,r|N\backslash(\varepsilon\backslash g))$ contain the planned duration of work packages in ε and outside the

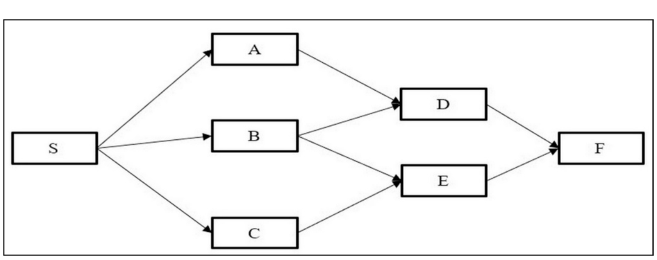

Fig. 2. A project network of several work packages.

coalition, and the real time for other work packages as explained. Accordingly, the completion time specific to path P will be as $D_P(p|\varepsilon\backslash g, r|N\backslash(\varepsilon\backslash g))$. By these notations and further denoting the set of paths that contain at least one work package from coalition g by $\rho(g)$, Eq. (18) determines the cost associated to coalition g in the cost-sharing mechanism (Estévez-Fernández, 2012). This relationship implies that each coalition's work packages are responsible for no more cost than what is allocated to them according to the cost-sharing mechanism and no more than the delay penalty for the paths they are on.

$$c_g(r) = \max_{P\in\rho(g)}\left\{ \min\left\{ \sum_{i\in N_P\cap g} y_i^P, R(D_P(p|\varepsilon\backslash S, r|N\backslash(\varepsilon\backslash S)) - D(P)) \right\}\right\} \tag{18}$$

Given the costs associated with different coalitions, cooperative game theory mechanisms, such as the Shapley value, can be applied to allocate costs to individual work packages. In this research, the Shapley value is employed to ensure consistency throughout the paper. The Shapley value is particularly suitable in this context because it ensures fair and equitable distribution of costs based on each partner's marginal contribution to all possible coalitions. This method satisfies key properties, such as efficiency (the total cost is fully distributed), symmetry (partners with equal contributions receive equal allocations), the dummy player property (partners with no contribution incur no cost), and additivity, which are critical for maintaining cooperation and fairness among partners. Compared to other cooperative game solutions, the Shapley value provides a theoretically grounded and widely accepted approach that balances incentives, ensures individual rationality, and facilitates practical implementation in multi-partner joint ventures. In this research, the Shapley value is employed to ensure consistency throughout the paper.

For this purpose, we first introduce the value of coalition g by the notation $v_g(r)$ which is the negative of $c_g(r)$, that is $v_g(r) = -c_g(r)$. Next, applying Eq. (19), the share of work package i from the delay costs for a given r, i.e., $cs_i(r)$ is determined by Eq. (20):

$$\phi_i(r) = \sum_{\substack{g\subset N \\ i\in g}} \frac{(|g|-1)!\,(n-|g|)!}{n!}\left[v_g(r) - v_{g-\{i\}}(r)\right] \tag{19}$$

$$cs_i(r) = -\phi_i(r) \tag{20}$$

3. The model to estimate the non-utilization costs of resources in JV projects

Since partners must prepare project resources in advance, adjusting their access schedules on short notice may be unfeasible. Consequently, a delay in one work package not only elevates its resource costs but also impacts those of succeeding work packages. Additionally, it's assumed that the location intended for executing a work package is equipped with the necessary resources according to the schedule. Thus, if its proceeding work packages face a delay, those resources will have to wait until the delays are resolved. Defining P_P^i as the set of work packages in path P that should be executed before work package i, the idleness time of work package i for a given r denoting by $nut_i(r)$ will be as Eq. (21). Based on this concept, the idleness of a work package can be attributed to the delay of the work package itself or to the additional waiting time required to complete its prerequisites in various project paths. It is worth noting that completing prerequisite work packages earlier can reduce the waiting time-related idleness.

$$ntu_i(r) = d_i(r) + \max\left(0, \max_{P|i'\in N_P}\left(\sum_{i'\in P_P^i}(d_{i'}(r) - e_{i'}(r))\right)\right) \tag{21}$$

Hence, if the unit idleness cost of work package i is $unuc_i$, its overall non-utilization cost will be as Eq. (22):

$$nuc_i(r) = unuc_i \times ntu_i(r) \tag{22}$$

When calculating the idleness cost of resources per unit of time, it's crucial to consider only the opportunity cost of utilizing non-consumable or renewable resources, such as equipment and human resources. Surplus consumable resource costs due to quality failure are already included in the overtime costs of model 1. This differentiation prevents duplication in calculating resource non-utilization and overtime costs.

4. The collaborative investment model in the quality of JV projects

Regarding the initial quality level of each work package, partners have the option to implement their work packages without improving the quality or to enhance the quality to reduce costs related to quality defects and the overall project. Since the quality of work packages affects project completion time, a collaborative investment in quality improvement can yield better results than individual efforts.

This argument is consistent with practical evidence reported in Scaringella and Burtschell (2017), which originally inspired the present study. In that case, a joint venture project encountered a critical coordination problem when the company responsible for assembling the main structure was unable to utilize certain components manufactured by a local supplier due to their poor quality and inaccurate tolerances. The issue was only resolved once the assembling company became directly involved in the supplier's quality control activities, thereby improving component compatibility and reducing rework delays. This case highlights the practical necessity of collaborative quality investment to ensure consistent standards and synchronized progress across interdependent work packages.

The positive implications of such collaboration are also reflected in the proposed models, which capture the complex interdependencies between work package quality and project performance. Specifically, when a work package suffers from low quality and subsequent delays, it not only increases its own rework costs but also causes idleness of resources in successor tasks and leads to cost propagation throughout the project network. Moreover, the resulting delays complicate the distribution of penalties and incentives among project partners. Therefore, as project complexity amplifies these interrelations, addressing quality-related challenges requires both cooperative and non-cooperative investment evaluation models and strategies that minimize the adverse effects of non-collaboration.

This collaborative investment problem in JV project quality is modelled as a cooperative game theory model. In this game, the key elements are the various strategies of the partners and the significance of coalitions that encourage cooperation over competition. Once these factors are identified, cooperative game solution concepts can be used to fairly allocate the cost of investing in quality among partners or even to incentivise their participation in quality improvement programs.

In the cooperative game, each work package is assumed to be assigned to one of the partners. Therefore, the respective work package or partner is considered one of the players. In this game, a set of durations is considered for executing each work package as the strategies of the respective player. The combination of these durations for all work packages determines the possible strategies of the cooperative game.

Assume that X_i is the set of possible execution times of work package i, which is defined as $X_i = \{T_{i,1}, T_{i,2}, \ldots, T_{i,m_i}\}$. In this definition, T_{ij} is the j'th duration considered for work package i. The n-player cooperative game is then presented in the strategic form of $(X_1, \ldots, X_n, u_1, \ldots, u_n)$ such that u_i is the output function for player i. Also, the set of possible strategies for the players in the n-player cooperative game is as $S = \{(x_1, x_2, \ldots, x_n)|x_1 \in X_1, x_2 \in X_2, \ldots, x_n \in X_n\}$. For $s = (x_1, x_2, \ldots, x_n) \in S$, $u_i(s)$ as the payoff of player i is determined using Eq. (23):

$$u_i(s) = \pi(\lambda_i(t), \delta_i(t), x_i) + cs_i(s) + nuc_i(s) \tag{23}$$

Again, the set of $N = \{1, \ldots, n\}$,which includes all players, is considered. Each coalition is a subset of N, and G is defined as the set of all coalitions, i.e., $G = \{g|g\subset N\}$. The payoff for coalition g in strategy s remembering the individual outputs as Eq. (23) will be according to Eq. (24):

$$U_g(s) = \sum_{i \in g} u_i(s) \tag{24}$$

Clearly, coalition g plays its dominant strategy in equilibrium. The dominant strategy is the one that yields the best payoff for g, regardless of the possible responses of other players, and thus it is the best response strategy. In cooperative games, determining whether such a strategy is pure or mixed has its own computational and practical complexities. Hence, many methods have focused their attention on finding an approximation of this strategy and its payoff. In this regard, the conservative and robust solution is a good representation of the dominant strategy for n-player cooperative games. This solution is obtained by converting the cooperative game in the strategic form to a Zero-Sum Game (Ferguson, 2020). In this approximation, each coalition g is considered as one player, and its complementary coalition, N-g, will be the competing player. This yields the value of coalition g according to Eq. (25).

$$V_g = Val\left(\sum_{i \in g} u_i(S)\right) \tag{25}$$

To identify $Val\left(\sum_{i \in g} u_i(S)\right)$, matrix A should be constructed wherein, rows correspond with all combinations of strategies for alliance g while, columns stand that of other players acting as the opponent. Assume the players in alliance g are numbered from 1 to m and others from $m+1$ to n. Also, denote the strategy of the alliance in row i by $\left(x_1^i, \ldots, x_m^i\right)$ and the strategy of the opponent in column j by $\left(x_{m+1}^j, \ldots, x_n^j\right)$. Now, A_{ij} is set to the payoff of alliance g in the strategy formed by the combinations of individual strategies in row i and column j, that is $A_{ij} = u_g\left(x_1^i, \ldots, x_m^i, x_{m+1}^j, \ldots, x_n^j\right)$. Finding the dominant strategy and the value of the zero-sum game given matrix A is straightforward in many cases. However, for general cases, especially when the dominant strategy is mixed, the following optimization problem could be solved to calculate V_g (Society, 1955) where p_{ij} is the probability to play strategy in row i by the player and strategy in column j by its opponent.

$$V_g = \max_i \min_j \sum_{i=1}^{m} p_{ij} \times A_{ij} \mid \sum_{i=1}^{m} p_{ij} = 1, p_{ij} \geqslant 0 \tag{26}$$

The above model is easily converted into a linear programming model that can be solved with commercial software such as GAMS. By determining the value of each coalition V_g, the Shapley value can be used to share the costs of the best strategy between work packages.

In summary, the optimal strategy for investing in network quality is one that minimizes the total costs across all work packages. Once each partner's share of these costs is determined, if a partner's actual costs (including delay, investment, overtime, and resource idleness) exceed the amount derived from the Shapley value, the difference should be compensated by lateral transfers from other partners. This difference arises from their greater investment in quality, benefiting the entire project. Thus, lateral transfers from other partners represent their share in these quality improvement investments. Conversely, if the Shapley value cost exceeds a partner's actual costs, the surplus should be redistributed to the other partners as lateral transfers. To ensure that these transfers are effectively negotiated and implemented, contractual clauses specifying transfer conditions, monitoring mechanisms, and verification procedures can be included in the project agreement. Alternatively, partners may rely on relational governance mechanisms, such as reputation-based trust or long-term collaboration incentives, to facilitate compliance and fairness in these exchanges.

From a practical standpoint, the purpose of introducing lateral transfers is not limited to financial compensation; rather, it aims to encourage balanced participation among partners. These transfers may also take the form of technical support, shared quality control resources, or joint process improvements that help maintain consistent performance standards across the network. In this way, the mechanism fosters cooperative behavior and mutual accountability beyond purely monetary interactions.

4. Numerical results from a real case study

In this section, we apply the proposed framework to a real-life sample problem within a bridge construction project, featuring a unique design and completed by multiple independent teams as part of a joint venture. This project includes several phases where quality defects can emerge in any phase or work package. We begin by detailing the sample problem and demonstrating how the presented models can be utilised to assess decisions related to collaborative quality investment. We also discuss methods for managing the collected data relevant to this problem and explore different conditions that may influence the results. Furthermore, the paper examines specific strategies for quality improvement that can provide valuable insights for managers and practitioners in this field.

1. Case study description

The case study focuses on a bridge construction project in Iran, comprising four main phases: design, pipe preparation, roof covering preparation, and the installation of structures and bridge roofs. Structures can be installed after a designated period following pipe and roof covering production. Pipe production and installation start after completing the design phase. The roof covering production can proceed concurrently with pipe production, allowing half of the roof to be completed alongside structure installation, culminating in the project's overall completion. The project network is depicted in Fig. 3.

According to the contract between the client and the project team, which has formed a joint venture to execute the project, the estimated completion time is 4 years. The JV project management team has allocated 1 year for the design phase and 3 years for the production of pipes and roofing, as well as the installation of structures. The planned execution time for each work package, including their start and end times, is detailed in Table 2. The penalty for the project delay is $74.78 per day or $19,444.40 per year. Notably, the discount rate for this project is $dr = 0.1$.

In this project, the design phase includes the preparation of engineering drawings of the bridge after evaluations about the type of materials, analysis of the resistance of the bridge over time, against earthquakes, and other technical aspects. In the production phase of the structures, the pipes are produced as the basic structures of the bridge and cut into appropriate dimensions. A firm active in the field of cutting is responsible for cutting pipes using plasma cutting machines. The roof covering is also produced by another contractor and used appropriately in the operation of the bridge. Finally, the welding and bolting of steel structures, as well as the bridge roof and other equipment related to bridge architecture, are done in the installation phase. In the following, for the sake of simplicity, we introduce the companies responsible for work packages A, B, C, and D with the titles of Firm A, Firm B, Firm C, and Firm D, respectively.

It is worth noting that readers might wonder why some activities in Table 2 appear to be delayed from the outset and why given such anticipated delays the project completion time was not set later in the initial contract. This observation, however, reflects the typical structure of large-scale project planning. In most cases, the total project duration is predetermined by the client in the initial Request for Proposal (RFP). The project teams then develop their proposals and preliminary schedules for each phase based on this fixed timeframe. Naturally, these initial schedules are not perfectly accurate, as each project contains unique elements and unforeseen challenges compared with prior experiences.

Consequently, deviations and delays are common in practice. Indeed, numerous studies have shown that project delays are a widespread global phenomenon across various industries (Al-Wadei, 2020; Love, Ahiaga-Dagbui, & Irani, 2016). Therefore, the times listed in Table 2

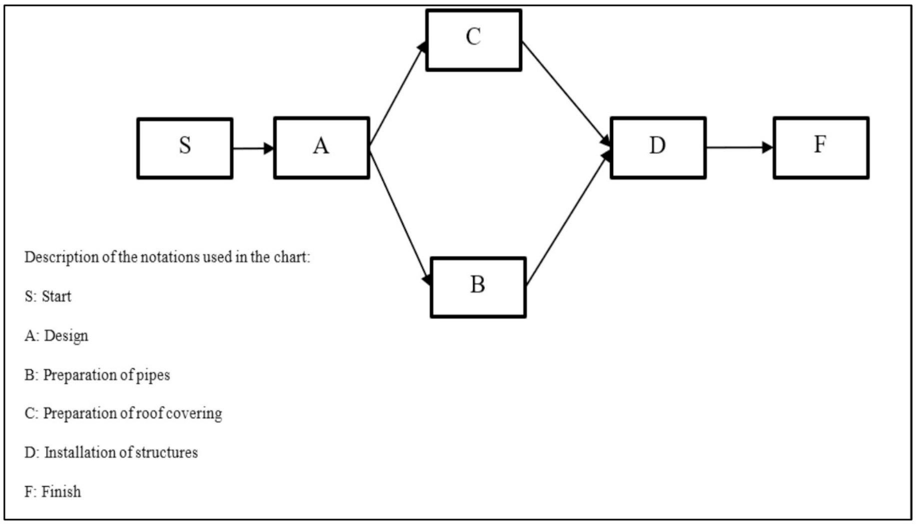

Fig. 3. The bridge construction project network.

Table 2
The initial scheduling of work packages.

Work package	Execution time (year)	Start time (year)	Finish time (year)
A	1	0	1
B	3	1	4
C	3	1	4
D	3	After the start of B and C	After the finish of B and C

should be interpreted as the *initial estimates* proposed in the early project phase. Later, after risk management meetings and further collaboration among the joint venture (JV) partners, these estimates are refined and adjusted based on a more realistic understanding of quality considerations and potential risks once the project contract has been secured.

Another point is about the rationality of data selection in this paper. In this regard, the numerical values and initial estimates used in this case study are based on a combination of contractual agreements, project proposals, and technical calculations performed by the joint venture (JV) project team, reflecting standard practices in large-scale construction projects. Specifically:

Execution times and schedules: The planned start and finish times for each work package (Table 2) are derived from the initial allocation made by the JV project management team, following the total project duration predetermined by the client in the Request for Proposal (RFP). These estimates represent early-stage projections and are consistent with typical planning procedures, where preliminary schedules are refined following risk assessment and coordination among partners.
Welding capacity and costs: Calculations for the installation of structures consider the physical characteristics of the bridge (total weight of 1800 tons), the daily assembly capacity of the assigned firm (2600 kg/day), standard working days, and the unit welding cost ($1/30 per kg). Based on these parameters, the standard welding time (TC) is determined to guide scheduling and cost allocation.
Quality parameters: Initial inspection results indicate that only 75% of welded parts meet the required quality standard ($\lambda_0 = 0.750$). These values reflect realistic performance levels observed in similar projects and are used to capture the potential impact of quality defects on project outcomes.

Moreover, it should be noted that one of the authors has employed similar data selection and estimation procedures in a previous study (Momeni, Yaghoubi, & Aliha, 2019) which further validates the practical relevance and consistency of these numerical choices in modeling quality investment in project management.

2. Quality defects in the process of installing structures (D)

The process of installing structures is usually done by welding and bolting connections. If the relevant firm lacks the necessary skills in this field, this process cannot be error-free. The bridge structure under study weighs about 1800 tons, with a welding cost of $1/30 per kilogram. The FF company has the capacity to assemble 2600 kg of structures per day, equivalent to 676,000 kg per year, considering 260 working days. Assuming no errors in the process, the standard welding time is calculated as $TC = 1800/676 = 2.663$ years, which is less than the project's desired completion time. However, initial inspection indicates that 75% of the welded parts meet the required quality, that is $\lambda_0 = 0.750$.

To calculate the completion time of the project if there is no investment in quality of D, Eqs. (4) and (7) are utilized, and in them, the quality level over time is set equal to its initial value, i.e., $\lambda(t) = \lambda_0$ 1. Therefore, the project completion time in this case is calculated as $d\tau(t)/dt = \lambda(t) = \lambda_0 \rightarrow \int_0^T \lambda_0 .dt = \tau(T) - \tau(0) \rightarrow \lambda_0 .T = TC \rightarrow T = TC/\lambda_0 = 2.66/0.75 = 3.546$. This time exceeds $T = 3$, indicating that measures should be taken to improve the quality level.

The value of T = 3.546 for work package D, which exceeds the initial execution time estimate of 3 years, demonstrates that initial project estimates—often formulated during the proposal and contractual agreement phase—may be updated several times once project execution begins and partners start collaborating. Observed data on parameters such as output quality, idle time, and coordination efficiency provide empirical ground truth. This allows for a shift from the initial, often subjective "inside view" to a more realistic "outside view" based on actual performance. Such a trend is not unexpected and is prone to systematic optimism and information asymmetry.

In this regard, a substantial body of empirical research on major projects consistently reveals a significant discrepancy between initial forecasts and actual outcomes. For instance, Flyvbjerg et al. (2002) found that 90% of transportation projects exceeded their initial budgets, with an average cost overrun of 28%. This phenomenon is often attributed to cognitive biases, such as the "inside view" (Lovallo & Kahneman, 2003), where planners focus on the specifics of their plan rather than the statistical record of similar past projects. In the context of joint ventures, this initial optimism is further compounded by the partners' limited direct experience with each other's operational capabilities (Reuer & Koza, 2000).

A 6-month quality improvement program ensures that the maximum quality level is achieved at a cost of \$5,000, which equivalently means \$10,000 per year. The maximum amount of investment in quality is not less than the budget of the firm responsible, and therefore, $\delta^{\max} =$ \$10,000. Hence, by setting $\delta(u) = 10000$, $t = 0.500$, $\lambda(t = 0.500) = 1$, and $\alpha.\delta_0 = \lambda_0^2 = (0.750)^2$, in the relation $\alpha.\left(\int_0^t \delta(u).du + \delta_0\right) = \lambda(t)^2$; which is stemmed from relations $d\lambda(t)/dt = \alpha.\delta(t)/(2\lambda(t))$ and $\lambda(0) = \lambda_0$; the quality coefficient will be $\alpha = 8.750 \times 10^{-5}$. Moreover, each kilogram of defective structures caused by welding operations will have a cost of $c_{f=}$ \$1/30, and therefore, the cost of failure per year using the relation $c = c_f.n/T_c$ is estimated to be \$22,556 per year where n is the total number of deliverables for D ($n = 1800{,}000$ kg).

On the other hand, considering the profit of \$0.02 per kilogram of welding operation and the ability of company D to weld 2600 kg of structures per day, the non-utilization cost of resources for D is equal to \$52 per day or \$13,520 per year. By adding the delay penalty of 19,444.400 per year to the non-utilization cost of resources, the delay cost of D in Model (2) will be $c_d = 32,964.400$ per year.

As can be seen from the model data, the cost of welding defects is very high and significant. Subsequently, the solution of Model (2) results in the optimal plan of investment in quality from the beginning of this phase, which should continue for 6 months. The investment path illustrated in Fig. 4 corresponds to a total cost of \$8,817.061, which represents the value of the objective function in Eq. (8) for firm D. Following this optimal plan allows for the completion of this phase within the time horizon T = 3.060 years.

3. Quality defects in all work packages

In the previous section, we explained how to convert the collected raw data into parameters used in the model. By collecting real data and using the same procedure as work package D, we estimate the quality parameters and the program specifications related to work packages B and C. This information, along with the previous one of D, is summarized in Table 3.

3.1. The quality improvement costs

First, for each work package, several completion times are considered as the work package strategies, and then by using **Model 1**, the costs related to overtime and investment in quality are determined for each strategy. In Table 4, the results in this regard are shown for each work package. Notably, $T_i^{\min}$ and $T_i^{\max}$ will be the same for work package D, meaning that we have just one number in the interval [$T_i^{\min}$,$T_i^{\max}$] to choose from. So, this number and the one denoting the no-investment solution are regarded for D. This is because the costs of quality defects in this work package are large enough, so if the problem is solved as a free final time optimal control problem to determine $T_i^{\max}$, the solution is to invest in quality from the start time of the work this time is the minimum possible time according to the definition of $T_i^{\min}$. This implies that early investment in quality prevents the occurrence of defective outputs and rework, which in turn avoids delays and additional costs. Therefore, postponing quality investment is not economically efficient and initiating it from the beginning of the work package leads to both the optimal cost and the minimum completion time.

3.2. Generate strategies and assign delay costs to the work packages in them

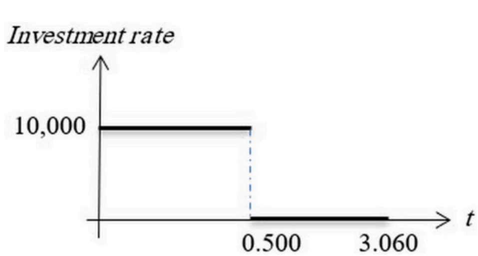

Fig. 4. The optimal investment path for improving the quality of installing structures phase.

Next, the share of delay costs for the work packages in each strategy should be determined. We denote strategy k in the form of $s_k = (x_1^k, x_2^k, x_3^k)$, where x_1^k, x_2^k and x_3^k are the execution times for work packages B, C, and D, respectively. As mentioned in Section 3.1, the completion time of work package i, which is denoted by x_i^t in generating the game strategies is considered to lie within the range [$T_i^{\min}$, $T_i^{\max}$]. The procedure used to determine $T_i^{\min}$ and $T_{\max}^i$ is also explained in that section. By considering three possible completion times for each of the work packages B and C (as explained earlier, only one completion time can be assumed for work package D), 9 project strategies are developed. The best strategy among them is then selected according to the method proposed in this study. These strategies are presented in the first column of Table 5.

Here, the delay assignment to one of the strategies according to (Estévez-Fernández, 2012) are explained. This strategy is $s_9 = (3.200, 3.300, 3.060)$ in which all work packages are completed with delay. There are two paths of $N_1 : B - D$ and $N_2 : C - D$ in this project. In path N_1, both work packages B and D are performed with a delay, and given that the delay of D is less than that of B, $q^1 = q^D = 0.06$ and $q^2 = q^B = 0.200$ in the cost-sharing mechanism. The penalty function in this project is also as $c(t) = R(t) = 19444.400 \times t$. Using Eqs. (16) and (17), the assigned delay costs to B and D in path N_1 are specified as $y_D^{N_1}(s_9) = R(0.060)/1 = 1166.664$ and $y_B^{N_1}(s_9) = R\ (0.060) + R\ (0.200 + 0.060)\text{-}R\ (2(0.06))/1 = 1166.664 + 5055.544–2333.328 = 3888.880$. As such, for path N_2, $q^1 = q^D = 0.060$ and $q^2 = q^C = 0.300$. Accordingly, applying Eqs. (16) and (17) results in$y_D^{N_2}(s_9) = R\ (0.06)/1 = 1166.664$ and$y_C^{N_2}(s_9) = R\ (0.060) + R\ (0.300 + 0.060)\text{-}R\ (2(0.060))/1 = 5833.320$.

In the next step, the value of different coalitions is identified using Eq. (18). The results of this evaluation for coalitions {B}, {C}, {D}, {BC}, {BD}, (OECD) and {ABC} are as follows:

$c_{\{B\}}(s_9) = \max\left(\min\left(y_B^{N_1}, R(3.260 - 3.000)\right)\right) = \max(\min(3888.880, 5054.544)) = 3888.88$;$c_{\{C\}}(s_9) = \max(\min(y_C^{N_1}, R(0.360))) = 5833.320$;$c_{\{D\}}(s_1) = \max\left(\min\left(y_D^{N_1}, R(0.260)\right), \min\left(y_D^{N_2}, R(0.360)\right)\right) = 1166.664$;$c_{\{BC\}}(s_9) = \max\left(\min\left(y_B^{N_1}, R(0.260)\right), \min\left(y_C^{N_2}, R(0.360)\right)\right) = 5833.320$;
$c_{\{BD\}}(s_9) = \max(\min(y_B^{N_1} + y_D^{N_1}, R(0.260)), \min(y_D^{N_2}, R(0.360))) = 5055.544$;$c_{\{CD\}}(s_9) = \max(\min(y_D^{N_1}, R(0.260)), \min\left(y_C^{N_2} + y_D^{N_2}, R(0.360)\right)) = 6999.984$;$c_{\{BCD\}}(s_9) = \max\left(\min\left(y_B^{N_1} + y_D^{N_1}, R(0.260)\right), \min\left(y_C^{N_2} + y_D^{N_2}, R(0.360)\right)\right) = 6999.984$.

Next, using Eqs. (19) and (20), the cost share of each work package from the delay is obtained. Subsequently, the shares of work packages from the costs are $cs_B(s_9) = 1944.440$, $cs_C(s_9) = 3888.880$, and $cs_D(s_9) = 1166.664$, respectively. As can be observed, this method imposes a penalty on the work packages proportionate to their delay. For instance, work package B, which caused the greatest delay in the project, has been assigned the largest penalty, while work package D should incur a lesser penalty compared to B and C due to its shorter delay. Similarly, the assigned delay cost to the work packages in the paths for all other strategies are shown in Table 5 while the strategies penalties for the work packages regarding their contribution to the delay costs allocated to their coalitions have been reported in Table 6.

3.3. The non-utilization costs of resources in the strategies

To complete the evaluation of the costs in different strategies, the equations are introduced in section 3. 3 are employed to calculate the non-utilization costs of the work packages in the strategies. In doing so, first Eq. (21) is used to compute the idleness times of work packages, and then by multiplying these times by the corresponding unit idleness costs in Table 3, the non-utilization costs are obtained as shown in Table 7.

3.4. The overall cost of the work packages in the strategies

By adding up the costs of investment, reworking, delay, and resource non-utilization as inputs from the previous steps, the total cost of work packages in different strategies is determined as described in Fig. 5.

As shown in Fig. 5, it is revealed that strategy $s_4 = (3.000, 3.005, 3.060)$ has the least cost, so is the preferred strategy.

Table 3
The quality and scheduling information of the bridge construction network project.

Work package	T (Years)	TC (Years)	$\delta_i^{\max}$($/Year)	α_i	c_i ($)	$unuc_i$ ($)	λ_{i0}
B	3.000	2.690	32,000	4.270×10^{-5}	12,500	2600	0.480
C	3.000	2.710	25,000	6.250×10^{-5}	16,050	8706	0.620
D	3.000	2.660	10,000	8.750×10^{-5}	22,556	13,520	0.750
Data source	Project proposal, contract terms	JV team technical calculation, contract terms	JV team technical calculation	JV team technical calculation	JV team technical calculation, contract terms	JV team technical calculation, contract terms	JV team technical calculation

Table 4
The investment and reworking costs for different completion times of work packages.

Work package	T	Investment cost	Reworking cost	Sum
B	2.800	15607.000	5422.000	21029.000
	3.000	15420.000	5442.800	20862.800
	3.200	9516.000	5908.000	15462.000
	5.690	0.000	36985.000	36985.000
C	3.005	9658.000	1107.000	10765.600
	3.140	8197.830	1568.820	9766.650
	3.300	5229.650	4272.350	9502.000
	4.370	0.000	26653.000	26653.000
D	3.060	4877.000	1963.000	6840.000
	3.540	0.000	19962.000	19962.000

* The last row for each work package indicates the lack of investment in quality.

Table 5
The delay costs of the strategies for the work packages in different paths according to the cost sharing mechanism.

s_k	$y_i^{N_1}(s_k)\|i \in N$	$y_i^{N_2}(s_k)\|i \in N$
$s_1 = (2.800, 3.005, 3.060)$	$y_B^{N_1}(s_1) = 0$; $y_D^{N_1}(s_1)$=1166.664	$y_C^{N_2}(s_1) = 97.220$; $y_D^{N_2}(s_1)$=1166.664
$s_2 = (2.800, 3.140, 3.060)$	$y_B^{N_1}(s_2) = 0$; $y_D^{N_1}(s_2)$=1166.664	$y_C^{N_2}(s_2) = 2722.216$; $y_D^{N_2}(s_2)$=1166.664
$s_3 = (2.800, 3.300, 3.060)$	$y_B^{N_1}(s_3) = 0$; $y_D^{N_1}(s_3)$=1166.664	$y_C^{N_2}(s_3) = 5833.320$; $y_D^{N_2}(s_3)$=1166.664
$s_4 = (3.000, 3.005, 3.060)$	$y_B^{N_1}(s_4) = 0$; $y_D^{N_1}(s_4)$=1166.664	$y_C^{N_2}(s_4) = 97.220$; $y_D^{N_2}(s_4)$=1166.664
$s_5 = (3.000, 3.140, 3.060)$	$y_B^{N_1}(s_5) = 0$; $y_D^{N_1}(s_5)$=1166.664	$y_C^{N_2}(s_5) = 2722.210$; $y_D^{N_2}(s_5)$=1166.664
$s_6 = (3.000, 3.300, 3.060)$	$y_B^{N_1}(s_6) = 0$; $y_D^{N_1}(s_6)$=1166.664	$y_C^{N_2}(s_6) = 5833.320$; $y_D^{N_2}(s_6)$=1166.664
$s_7 = (3.200, 3.005, 3.060)$	$y_B^{N_1}(s_7) = 3888.880$; $y_D^{N_1}(s_7)$=1166.664	$y_C^{N_2}(s_7) = 97.220$; $y_D^{N_2}(s_7)$=1166.664
$s_8 = (3.200, 3.140, 3.060)$	$y_B^{N_1}(s_8) = 3888.880$; $y_D^{N_1}(s_8)$=1166.664	$y_C^{N_2}(s_8) = 2722.210$; $y_D^{N_2}(s_8)$=1166.664

However, not all work packages have the best cost performance in this strategy. For example, work package B has a much lower cost in strategy $s_7 = (3.200, 3.005, 3.060)$ than in s_4. Therefore, the collaborative investment model in section 3.4 is essential for fairly distributing the cost of s_4 among work packages. This is done by considering their performance in the potential coalitions they could form.

As shown in Fig. 5, the affordable costs of the work packages vary with changes in the execution times of the strategies. When the execution time of the work packages decreases, the total cost tends to increase due to higher quality investments that are required to avoid rework and quality defects. However, this relationship is not strictly linear, as the balance between time reduction and quality improvement introduces cost fluctuations across different strategies. In other words, strategies with earlier quality investment (e.g., s_3 and s_6) exhibit higher direct costs but result in shorter completion times and lower risks of quality-

Table 6
The ultimate delay costs assigned to the work packages.

s_k	$c_g(s_k)\|g \subset G$	$cs_i(s_k)\|i \in N$	s_k	$c_g(s_k)\|g \subset G$	$cs_i(s_k)\|i \in N$
s_1	$c_{\{B\}}(s_1) = 0.000$ $c_{\{C\}}(s_1) = 97.220$ $c_{\{D\}}(s_1) = 1166.664$ $c_{\{BC\}}(s_1) = 97.220$ $c_{\{BD\}}(s_1) = 1166.664$ $c_{\{CD\}}(s_1) = 1263.886$ $c_{\{BCD\}}(s_1) = 1263.886$	$cs_B(s_1) = 0.000$ $cs_C(s_1) = 97.220$ $cs_D(s_1) = 1166.664$	s_5	$c_{\{B\}}(s_5) = 0.000$ $c_{\{C\}}(s_5) = 2722.216$ $c_{\{D\}}(s_5) = 1166.664$ $c_{\{BC\}}(s_5) = 2722.216$ $c_{\{BD\}}(s_5) = 1166.664$ $c_{\{CD\}}(s_5) = 3888.880$ $c_{\{BCD\}}(s_5) = 3888.880$	$cs_B(s_5) = 0,000$ $cs_C(s_5) = 2722.216$ $cs_D(s_5) = 1166.664$
s_2	$c_{\{B\}}(s_2) = 0.000$ $c_{\{C\}}(s_2) = 2722.216$ $c_{\{D\}}(s_2) = 1166.664$ $c_{\{BC\}}(s_2) = 2722.216$ $c_{\{BD\}}(s_2) = 1166.664$ $c_{\{CD\}}(s_2) = 3888.880$ $c_{\{BCD\}}(s_2) = 3888.880$	$cs_B(s_2) = 0.000$ $cs_C(s_2) = 2722.216$ $cs_D(s_2) = 1166.664$	s_6	$c_{\{B\}}(s_6) = 0.000$ $c_{\{C\}}(s_6) = 5833.320$ $c_{\{D\}}(s_6) = 1166.664$ $c_{\{BC\}}(s_6) = 5833.320$ $c_{\{BD\}}(s_6) = 1166.664$ $c_{\{CD\}}(s_6) = 6999.980$ $c_{\{BCD\}}(s_6) = 6999.980$	$cs_B(s_6) = 0.000$ $cs_C(s_6) = 5833.320$ $cs_D(s_6) = 1166.664$
s_3	$c_{\{B\}}(s_3) = 0.000$ $c_{\{C\}}(s_3) = 5833.320$ $c_{\{D\}}(s_3) = 1166.664$ $c_{\{BC\}}(s_3) = 5833.320$ $c_{\{BD\}}(s_3) = 1166.664$ $c_{\{CD\}}(s_3) = 6999.984$ $c_{\{BCD\}}(s_3) = 6999.984$	$cs_B(s_3) = 0.000$ $cs_C(s_3) = 5833.320$ $cs_D(s_3) = 1166.664$	s_7	$c_{\{B\}}(s_7) = 3888.880$ $c_{\{C\}}(s_7) = 97.220$ $c_{\{D\}}(s_7) = 1166.664$ $c_{\{BC\}}(s_7) = 3888.880$ $c_{\{BD\}}(s_7) = 5055.544$ $c_{\{CD\}}(s_7) = 1263.886$ $c_{\{BCD\}}(s_7) = 5055.544$	$cs_B(s_7) = 3840.270$ $cs_C(s_7) = 48.613$ $cs_D(s_7) = 1166.664$
s_4	$c_{\{B\}}(s_4) = 0.000$ $c_{\{C\}}(s_4) = 97.220$ $c_{\{D\}}(s_4) = 1166.664$ $c_{\{BC\}}(s_4) = 97.220$ $c_{\{BD\}}(s_4) = 1166.664$ $c_{\{CD\}}(s_4) = 1263.886$ $c_{\{BCD\}}(s_4) = 1263.886$	$cs_B(s_4) = 0.000$ $cs_C(s_4) = 97.220$ $cs_D(s_4) = 1166.664$	s_8	$c_{\{B\}}(s_8) = 3888.880$ $c_{\{C\}}(s_8) = 2722.216$ $c_{\{D\}}(s_8) = 1166.664$ $c_{\{BC\}}(s_8) = 3888.880$ $c_{\{BD\}}(s_8) = 5055.544$ $c_{\{CD\}}(s_8) = 3888.880$ $c_{\{BCD\}}(s_8) = 5055.544$	$cs_B(s_8) = 2527.780$ $cs_C(s_8) = 1361.111$ $cs_D(s_8) = 1166.644$

Table 7
The non-utilization cost of work packages in different strategies.

s_k	Work package (i)	$ntu_i(s_k)$	$nuc_i(s_k)$
$s_1 = (2.800, 3.005, 3.060)$	B	0.000	0.000
	C	0.005	43.530
	D	0.065	878.800
$s_2 = (2.800, 3.140, 3.060)$	B	0.000	0.000
	C	0.140	1218.840
	D	0.200	2704.000
$s_3 = (2.800, 3.300, 3.060)$	B	0.000	0.000
	C	0.300	2611.800
	D	0.360	4867.200
$s_4 = (3.000, 3.005, 3.060)$	B	0.000	0.000
	C	0.005	43.530
	D	0.065	878.800
$s_5 = (3.000, 3.140, 3.060)$	B	0.000	0.000
	C	0.140	1218.840
	D	0.200	2704.000
$s_6 = (3.000, 3.300, 3.060)$	B	0.000	0.000
	C	0.300	2611.800
	D	0.360	4867.200
$s_7 = (3.200, 3.005, 3.060)$	B	0.200	520.000
	C	0.005	43.530
	D	0.260	3515.200
$s_8 = (3.200, 3.140, 3.060)$	B	0.200	520.000
	C	0.140	1218.840
	D	0.260	3515.200
$s_9 = (3.200, 3.300, 3.060)$	B	0.200	520.000
	C	0.300	2611.800
	D	0.360	4867.200

related delays.

Moreover, to ensure cooperation among the partners, the profit allocation based on the Shapley value must satisfy the individual rationality condition, meaning that each participant receives at least their standalone payoff. The presented allocation scheme guarantees this condition, thereby ensuring all partners' willingness to cooperate under the selected strategy.

The matrices of zero-sum games used to determine the value of the coalitions are shown in Fig. 6. Let us examine one of these matrices. Subfigure (a) shows the matrix for the coalition that includes work package B. Regardless of the strategy played by {C, D}, it is better for B to choose the strategy with a completion time of 3.2 because it costs less. However, considering that each cost for B related to a strategy in this zero-sum game is equivalent to the profit for the competing player, i.e., {C, D}, the strategy (3.005, 3.060) provides the highest profit for the competing players in any case, and therefore is their dominant strategy.

Consequently, the strategy in row 3 and column 1 is the best responsive strategy in the game, resulting in the value of $V_{\{B\}}$ = -19784.270. A similar evaluation could be conducted to determine the value of other coalitions, as highlighted in Fig. 6.

Considering the coalition values in Fig. 6 and applying the Shapley value, the final assigned costs for the work packages are as $\phi = (\phi_B, \phi_C, \phi_D) = (18686.700, 9877.070, 12090.200)$. Comparing these allocated costs under the partnership strategy (ϕ_B, ϕ_C, ϕ_D) with the actual costs, it is evident that the costs allocated to work packages B and C have decreased, while those for work package D have increased. Consequently, under this participation scheme, the firm responsible for work package D must pay $2176.100 out of $9658.000 and $1028.730 out of $ 4877.000 toward the investment costs for quality improvement in work packages B and C, respectively, to make participation in the JV project more favorable and effective. In fact, $2176.100 and $1028.730 represent side payments from the firm responsible for D to those responsible for B and C, which should be incorporated as new terms into the JV project partners' collaborative contract.

3.5. A sensitivity analysis

Up to this point, it has been demonstrated that the proposed collaborative framework and its selected strategies can lead to a reduction in overall project costs. Such a strategy functions similarly to risk management approaches, as it seeks to mitigate potential adverse effects caused by initial measurement inaccuracies by improving data

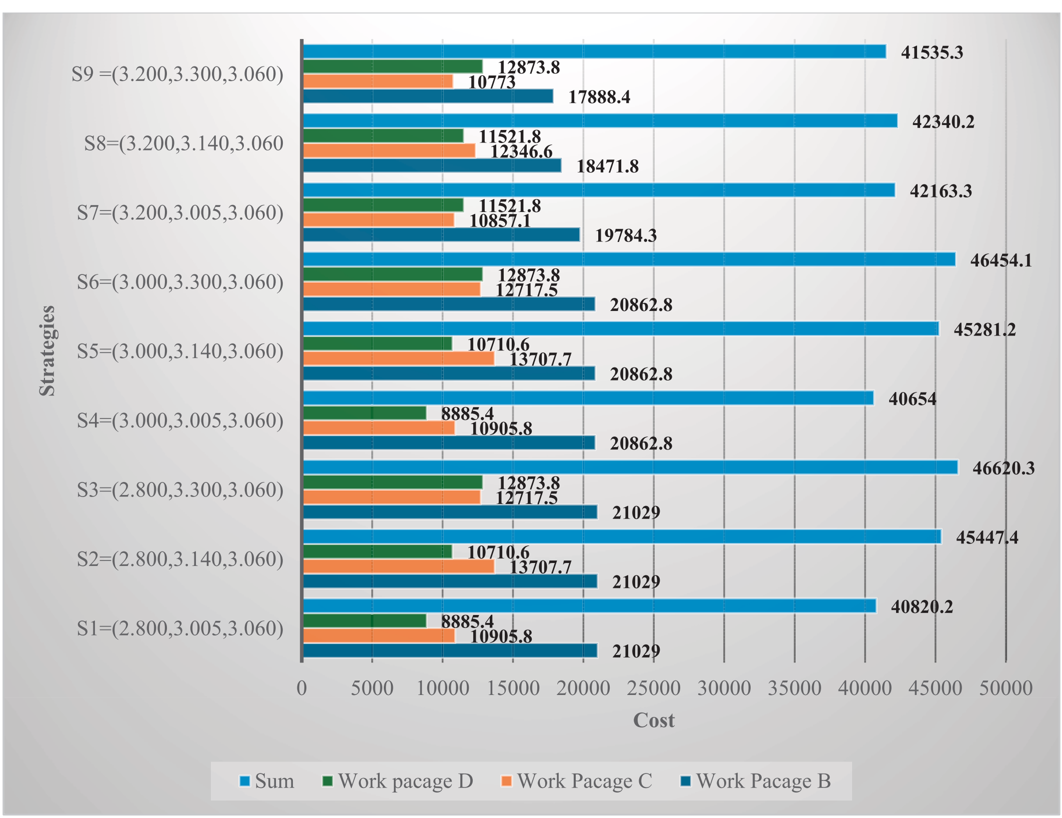

Fig. 5. The afforded costs of the work packages in the strategies.

a) $V_{\{B\}}$ = -19784.270

{C; D} / {B}	(3.005; 3.060)	(3.140;3.060)	(3.300; 3.060)
2.800	21029.000	21029.000	21029.000
3.000	20862.800	20862.800	20862.800
3.200	19784.270	18471.780	17888.440

b) $V_{\{C\}}$ = -10905.750

{B; D} / {C}	(2.800; 3.060)	(3.000;3.060)	(3.200; 3.060)
3.005	10905.750	10905.750	10857.144
3.140	13707.706	13707.706	12346.600
3.300	12717.470	12717.470	10773.030

c) $V_{\{D\}}$ = -12873.84

{B; C} / {D}	(2.800; 3.005)	(2.800;3.140)	(2.800;3.300)	(3.000; 3.005)	(3.000;3.140)	(3.000;3.300)	(3.200; 3.005)	(3.200;3.140)	(3.200;3.300)
3.06	8885.444	10710.644	12873.844	8885.444	10710.644	12873.844	11521.844	11521.844	12873.844

d) $V_{\{C, D\}}$ = -22378.990

{B} / {C; D}	2.800	3.000	3.200
(3.005;3.060)	19791.190	19791.190	22378.990
(3.140;3.060)	24418.350	24418.350	23868.440
(3.300;3.060)	25591.310	25591.310	23646.870

e) $V_{\{B, D\}}$ = -31119.170

{C} / {B; D}	3.005	3.140	3.300
(2.800; 3.060)	29914.440	31739.640	33902.840
(3.000;3.060)	29748.240	31573.440	33736.640
(3.200; 3.060)	31306.110	29993.620	30762.280

f) $V_{\{B, C\}}$ = -28661.470

{D} / {B, C}	3.060
(2.800; 3.005)	31934.750
(2.800;3.140)	34736.710
(2.800;3.300)	33746.470
(3.000; 3.005)	31768.550
(3.000;3.140)	34570.510
(3.000;3.300)	33580.270
(3.200; 3.005)	30641.410
(3.200;3.140)	30818.380
(3.200;3.300)	28661.470

Fig. 6. The equivalent zero-sum games matrix to determine the value of the work packages coalition.

estimation methods and developing mitigation solutions in advance. In this context, certain parameters influence the effectiveness of the collaborative strategy, reveal the model's behavioral dynamics, and provide managers with valuable insights into the strategic nature of collaboration. These effects can be further examined through sensitivity analysis.

In the sensitivity analysis, the costs associated with partners' resource idleness and the investment coefficient for quality improvement are evaluated. During each sensitivity test, all other parameters are kept constant, while the selected parameter is multiplied by a scaling factor that represents the percentage of change applied to it. In Figs. 7 and 8, the effects of changes on α and $unuc_i$ have been shown, respectively.

As shown in Fig. 7, changes in the investment coefficient have no impact on the costs of the non-cooperative strategy, since quality investments are not considered in that case. In contrast, increasing this coefficient has a progressively greater effect on reducing the costs of the cooperative strategy. This occurs because, on one hand, it lowers investment costs, and on the other hand, it accelerates the improvement of quality.

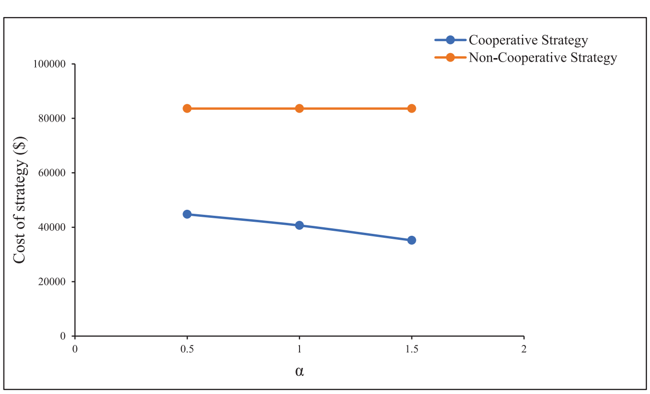

Fig. 7. Impact of changes in the investment coefficient α.

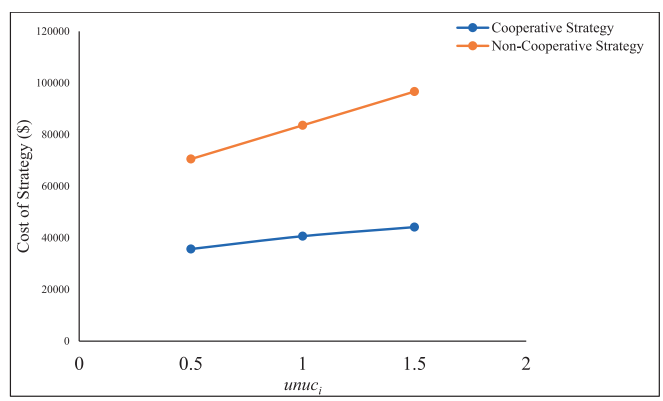

Fig. 8. Impact of changes in the idleness cost of the work package.

However, an increase in the idleness cost of resources raises the costs of both the cooperative and non-cooperative strategies, since this cost is unavoidable in both cases. At the same time, the effectiveness of the proposed cooperative strategy improves with higher idleness costs. This result aligns with expectations, as the delay-penalty allocation mechanism assigns all such costs to the responsible partners, while the main motivation for participating in quality investment was to reduce resource idleness costs.

3.6. A local search on the partnership strategy

The studied problem was complex, involving multiple dimensions that necessitated several distinct analysis models. Ultimately, we integrated the results to comprehensively evaluate the partnership strategy.

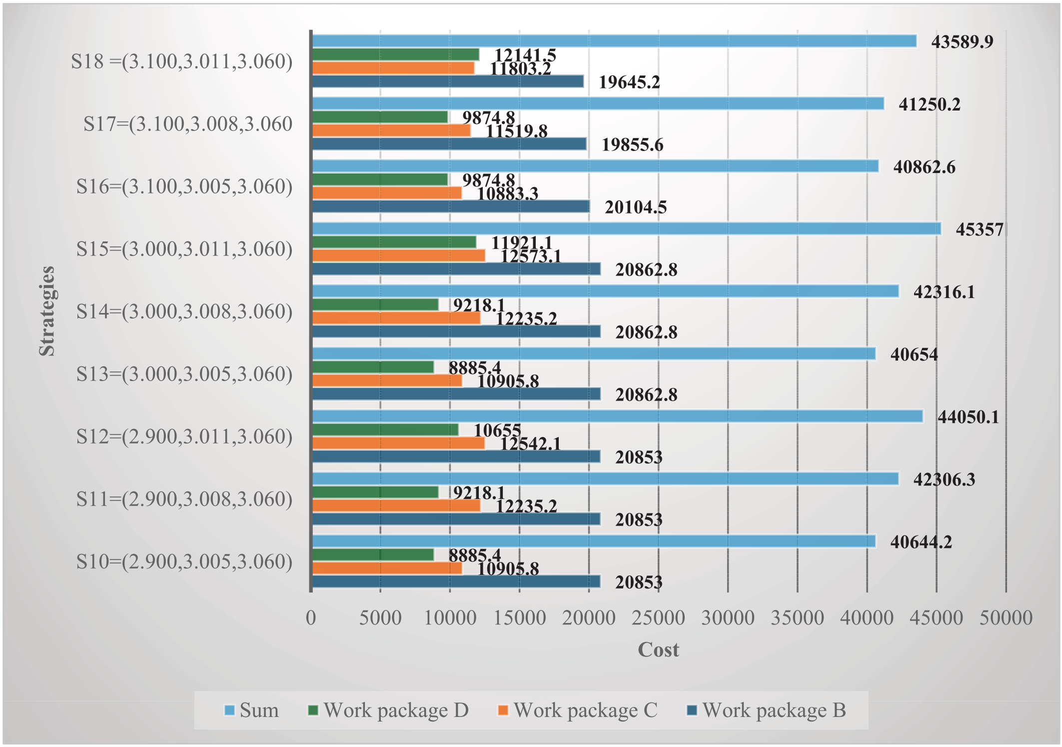

Fig. 9. The afforded costs of the work packages in the new strategies.

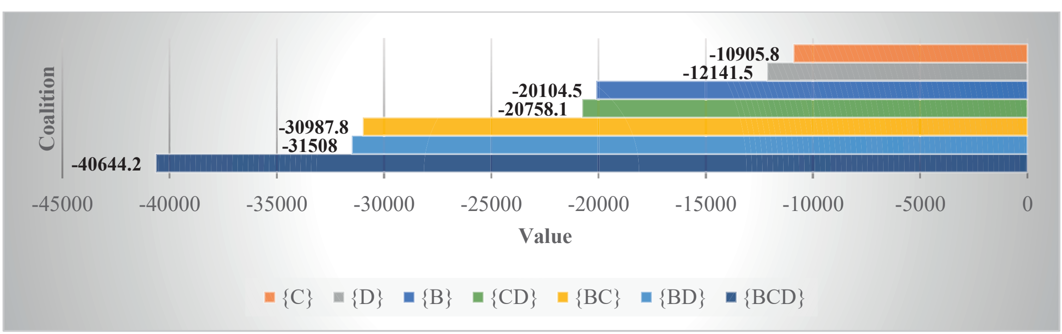

Fig. 10. The values of the coalitions concerning the new strategies.

Our evaluation framework diverged from conventional approaches, which often involve selecting tested strategies from discrete scenarios. However, the strategy identified in the previous section can be further refined to enhance the decision model's performance. This entails extending the timeframe for executing work packages to align more closely with the previous best strategy and developing new strategies. Once these new strategies are formulated, the outlined steps can be applied to identify the most effective one. This approach is akin to local search heuristics commonly found in optimization methods and contributes to solution improvement through iterations. Figs. 9 and 10 present the costs of new strategies and the coalition values of work packages concerning the new strategies.

The local search procedure employed here builds upon the best strategy identified in the previous stage, specifically strategy s_4 . For each work package whose completion time can be adjusted, two new candidate times are generated. These are chosen as intermediate values between the work package's completion time in s_4 and the adjacent times observed in other strategies. For instance, work package B has a completion time of 3 in s_4 , with the closest lower and higher times in other strategies being 2.800 and 3.200, respectively. Thus, 2.900 and 3.100 are considered as new candidate times. For work package C where the completion time in s_4 corresponds to $T_4^{\min}$, the interval between this minimum and the next higher time is divided into two parts, and the resulting intermediate values are used as new candidate times in the local search process (i.e., 3.008 and 3.011). This procedure can be iteratively applied to newly selected strategies until a predefined stopping criterion is met. However, in this study, the aim is to illustrate the application of local search to refine a solution—not to provide a full detailed description of such a method and since the improvement observed in the best new strategy in Fig. 9 (s_{10}) is less than 0.003%, further iterations are unlikely to produce any significant enhancement.

In Fig. 9, the new strategy $s_{10} = (2.900, 3.005, 3.060)$ has a lower cost than s_4 indicating an improvement of the solution after applying the local search. Moreover, using the Shapley value stipulates that $\phi = (\phi_B, \phi_C, \phi_D) = (19905.000, 9930.650, 10808.600)$ meaning lateral transfers of \$948.000 and \$975.150 from D to B and C, respectively.

Notably, based on computational experiments, each of the proposed game-theoretic and optimal control models can be solved in less than a few seconds. When the problem is properly structured, meaning that the project paths are identified, the completion times of work packages and other relevant data are accurately estimated, the payoff matrices of the zero-sum games are constructed, and the corresponding linear models are solved the solution time becomes practically negligible. The main effort is associated with structuring the problem correctly and preparing accurate and consistent data rather than with computation itself.

It should also be emphasized that in this study, each work package corresponds to a major project phase undertaken by one of the partners. Even in large-scale projects, the number of such strategic phases is usually limited. Although each work package can be further decomposed into many operational activities leading to a large number of nodes in the detailed project network, the computational burden at the strategic level of work packages remains insignificant.

5. Managerial insights

The primary managerial insight emphasizes the critical role of quality and its influence on cost and time. If project managers do not prioritize the quality of deliverables and fail to take preventive measures before project implementation, the negative impacts of quality defects can result in irreversible damage. The proposed models serve as valuable decision-support tools to evaluate and control quality in projects, offering effective strategies to enhance project performance.

The research results show that collaborative investment in the quality of project work packages leads to better performance in joint venture projects compared to independent investments by partners. This underscores the need for partners, who are legally independent according to the contract, to consider each other's quality issues and cooperate to improve them due to the project's network relations. When project managers grasp the significance of collaborative investment, they are likely to support and enhance the quality of their partners' work. Institutionalizing this approach can not only leverage the benefits of collaborative investment within strategic alliances but also motivate partners to form such alliances by enhancing each other's quality.

The proposed modeling approach enables managers to evaluate and select quality improvement programs that enhance operational performance. Each potential program consists of specific operational actions that directly contribute to improving efficiency and reducing completion time. For instance, the quality improvement program selected in Section 4.2 for work package D, as identified by the model, includes proper adjustment of electric arcs, regulation of electrode movement, correction of current amperage, effective cleaning of the welding area, selection of appropriate connection types, and optimization of weld dimensions to comply with the intended geometry. Implementing such program-specific actions allows project managers and engineers to achieve measurable improvements in both quality and time performance.

One of the intriguing topics explored was the allocation of delay costs to partners in a project, particularly in joint ventures. This issue often leads to disputes in many projects, prompting researchers to develop mechanisms to prevent conflicts. For this purpose, we utilized the approach from (Estévez-Fernández, 2012), a widely recognized tool for efficiently resolving project issues. Without such a mechanism, accurately modelling the role of quality in project delay costs is challenging, even with simplified assumptions for optimizing partner behavior. Despite the complexity of this model, both conceptually and practically, it highlighted the importance of not overlooking the cost of project delays as a key consequence of quality defects when developing risk reduction strategies. Allocating delay penalties, investment strategies, and idleness costs offers project managers a valuable tool for managing conflicts effectively and fairly, which is crucial for the success of strategic alliances.

Considering that knowledge sharing is a primary goal of forming joint ventures from a knowledge-based perspective, the current study reinforces this view. Partners are encouraged to assist each other in enhancing quality-related knowledge, thereby benefiting a strategy aimed at improving gains for all partners, rather than just a select few (Steensma & Lyles, 2000). Moreover, the proposed strategy is vital for fostering trust and joint success in business. As noted by (Kogut, 1991), such joint experiences can act as real options, potentially leading to future technological and market advancements if successful. Additionally, (Liu et al., 2024) highlights trust, commitment, and fairness as key factors in developing firms' social networks. Finally, the more precise and efficient the evaluation model for decision-making, the clearer the sense of justice in these matters becomes. In the studied problem, it was found that developing more precise strategies through local search could reduce both the project's overall costs and the costs incurred by participating firms in quality improvement programs for other partners. Without quality defects, these additional costs would not be necessary.

In line with current managerial trends and challenges, the proposed framework can also contribute to the ongoing transition toward digitalization, sustainability, and resilience in project management practices. Contemporary joint ventures and large-scale infrastructure projects are increasingly adopting data-driven and digitally integrated management systems to enhance transparency, performance monitoring, and collaborative decision-making (Marques & Ferreira, 2020; Hosseini et al., 2022). The presented hybrid approach, by combining optimal control and game-theoretical mechanisms, aligns well with these trends, providing managers with a structured tool to plan and evaluate quality investments under uncertainty. This not only contributes to the optimization of cost–time–quality trade-offs but also supports the development of transparent and fair partnerships that can adapt to evolving economic and technological conditions.

From a broader managerial perspective, the results emphasize that quality improvement should be regarded not merely as a technical activity but as a strategic managerial choice that affects long-term collaboration, learning, and competitiveness. The proposed cooperative mechanism demonstrates how equitable cost allocation—achieved through tools such as the Shapley value—can strengthen trust and participation among partners (Tadelis, 2019; Müller et al., 2023). This perspective is particularly relevant in today's environment, where global supply chains and international joint ventures face heightened pressures related to cost escalation, technological change, and sustainability expectations. Therefore, integrating the insights and mechanisms of this framework into practical management processes can guide project leaders and policymakers in achieving more sustainable, balanced, and mutually beneficial collaborations.

6. Discussion

In this paper, we introduced the concept of joint investment to enhance the quality of work packages in joint venture (JV) projects. While quality issues from one partner may not always affect others' performance, the interconnected nature of work packages often means they can impact each other. We examined the costs resulting from resource non-utilization due to delays caused by quality defects and proposed a collaborative investment in quality improvement programs to mitigate these effects. Alternatively, firms might negotiate to assign the costs of resource idleness due to other partners' quality shortcomings, thereby addressing network dependencies without requiring joint investment. However, this approach is uncommon and may not be advisable, as it can hinder long-term partner relationships and synergy and profitability goals often sought in alliances. Imposing such costs could deter partners from forming agreements. That said, transferring costs between partners may be appropriate if a partner fails to meet commitments due to reasons such as bankruptcy or an unwillingness to continue the project. Intentional negligence can be avoided by carefully selecting partners using criteria from existing literature.

The study by (Momeni, Yaghoubi, & Aliha, 2019) highlighted the effectiveness of quality improvement programs by analyzing alpha, demonstrating that programs with a larger alpha achieve higher quality levels in less time. However, since time, cost, and quality are interrelated and crucial goals for project managers, evaluating these programs solely based on the time for quality improvement is insufficient. An integrated approach, such as the framework proposed in this research, is necessary for a comprehensive evaluation. Although the study did not directly address this issue, incorporating scenarios for different quality improvement programs into the research model could effectively address this important aspect.

A key point regarding the game-theoretic models in this paper is the application of the Shapley value to distribute the gains from cooperation among JV partners. Alternative solution concepts include the *core* and the *nucleolus*, each with distinct properties suitable for strategic alliances like joint ventures. The core's most important property is "stability": no partner has an incentive to leave the coalition for greater profit elsewhere. Formally, if $\vec{u_i}$ is the allocated payoff to partner i in a feasible solution vector $\vec{u}$, S denoted a possible coalition, and $v(S)$ its value, then for $\vec{u}$ to be a core solution, the relation $\forall_{S\subset A}: \sum_{i\in S}\vec{u}_i \geqslant v(S)$ must hold (Ferguson, 2020). However, some coalitional games may have no core solution or multiple ones, requiring further selection criteria.

In contrast, the Shapley value is always feasible and unique, and embodies fairness by allocating payoffs in proportion to each partner's marginal contribution. Its drawback is that it does not necessarily belong to the core and thus may not guarantee stability. Fortunately, in the case study presented here, the Shapley value is also a core solution. This can be verified using the selected payoff vector $\vec{u} = (18686.700, 9877.070, 12090.200)$ and checking the core condition against all coalition values in Fig. 5. For instance, for coalition {B, C}, $(-18686.700) + (-9877.070) =$ -28563.770 $<$ -28661.470, which satisfies the inequality $\forall_{S\subset A}: \sum_{i\in S}\vec{u}_i \geqslant v(S)$, confirms stability.

Another alternative, the nucleolus, always exists and minimizes partners' incentives to deviate according to a specific criterion (the lexicographic minimization of excess), though it does not eliminate them entirely and typically involves a higher computational cost. In our case study, the Shapley value is not only unique and computationally straightforward but also resides within the core, guaranteeing coalitional stability. While the nucleolus would also lie within the core and share this stability property, the Shapley value provides a fair and directly applicable solution for this specific problem. Its successful application in other project allocation problems further supports its suitability for JV contexts (Yan and Hsueh, 2011; San Cristóbal, 2012; Zarei et al., 2018; Asghari et al., 2022).

The proposed research framework is best suited to a large-scale project with multiple work packages. Doing so, independent partners form a non-integrated joint venture. In these non-integrated joint venture alliances, each partner maintains operational independence, and work packages are technical so that quality variations can spread, delay, and incur idleness costs. Given the limited investment levels in joint venture alliances, this approach not only leverages the benefits of collaborative investment but also motivates partners to form such alliances by enhancing each other's quality. The primary context of the study is construction and infrastructure projects. However, the model can be applied to other industries, such as energy, research and development collaborations, or complex supply chains, where quality-time relationships and delay-cost interrelationships are present.

Nonetheless, the main contributions of this paper lie in structuring a project problem with complex network relations and proposing a clear, fair allocation method. This opens the field for future research to explore other desirable solution concepts under different settings.

7. Conclusion

This paper investigated the issue of quality defects in joint venture projects where partners are contractually independent. The study introduced investment in quality improvement of work packages as a strategy to mitigate these defects' adverse effects, particularly relevant when partners have differing quality standards due to being from different countries. It was explained that, based on prerequisite relationships in a project, quality defects affecting the timing of a work package also influence the timing and costs of other packages. This includes resource idleness and overall project delay. By investing in the quality of work packages and involving other partners, project losses can be reduced. To encourage this strategy and ensure its implementation, it is crucial to examine the role of work packages in costs and benefits thoroughly. Three models are proposed for this analysis:

- A modified optimal control model from (Momeni, Yaghoubi, & Aliha, 2019) to determine optimal investment paths for improving quality levels of work packages.
- A modified cost-sharing model from (Estévez-Fernández, 2012) to assign delay penalties to firms responsible for delayed work packages.
- A model to calculate the non-utilization costs of resources incurred by partners due to waiting for prerequisite work packages.

These models allowed us to estimate the value of potential coalitions formed by the partners. Using these coalition values as inputs, a cooperative game theory approach based on the Shapley value was applied to allocate the costs of the proposed strategy to each partner. This ensures the implementation of the most effective investment strategy for improving the quality of work packages, minimising project costs. Additionally, implementing side payments from benefiting partners to those experiencing losses ensures that all partners gain more from the strategy compared to a non-integrated approach. The values of side payments between partners were determined by comparing the allocated costs of the selected strategy and the actual costs of partners, and then justifying the collaborative contract terms such that by sharing investment costs of the partners, the actual costs after adding or reducing the side payment values will be equal to the allocated cost of the strategy. Also, by conducting a local search on the chosen strategy, we identified an improved approach and demonstrated that increased cost reduction aligns with achieving fairness and utility goals in the joint venture project.

Finally, the sensitivity analysis confirmed that the effectiveness of the proposed cooperative strategy is particularly influenced by the quality-conversion coefficient and the idleness cost of resources. Higher values of these parameters further enhanced the cost advantage of the cooperative approach over the non-cooperative one, highlighting the practical importance of quality investments in large-scale joint projects.

The current research has several limitations that could be explored in future studies:

- This paper did not consider the concept of learning over time, which can lead to quality improvement. Future research could develop a dynamic quality investment model incorporating learning effects.
- Quality defects were only examined in the production of deliverables. Future research could evaluate other sources of quality defects, such as weaknesses in procurement, communication, conflict resolution, and funding.
- The development of alternative bargaining models that factor in the competitive advantages of partners is suggested for future studies. This is particularly relevant for projects involving foreign firms that might not agree with the mechanism proposed in this paper.
- The proposed framework can be specifically adapted to address the unique challenges of *green building* and *sustainable construction* joint ventures. Future research could extend the model by integrating environmental and social parameters into the quality-cost function. For instance, the "quality" metric could be expanded to encompass *sustainability performance indicators* (e.g., energy efficiency, carbon footprint, or circular material use), with investments targeting both technical quality and green certification.
- The cooperative game model could be enhanced to allocate not only financial costs and delays but also *shared environmental benefits* (such as carbon credits) or *social value creation* among partners. This would enable the evaluation of incentive mechanisms that align economic

objectives with sustainability targets, providing a holistic decision-support tool for managers of modern, eco-conscious JV projects.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Grammarly for English language editing. After using Grammarly, the author's reviewed, edited and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Mojtaba Arab Momeni: Writing – original draft, Data collection, Formal analysis, Methodology, Validation, Conceptualization. **Amirhossein Mostofi:** Writing – original draft, Validation, Methodology, Formal analysis, Conceptualization. **Vipul Jain:** Writing – review & editing, Validation, Supervision, Project administration, Methodology.

Declaration of competing interest

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

Appendix 1:. List of Symbols and notations used in the paper

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Indexes and sets	Description
T	Index of continues time
I	Index of work packages
G	Index of coalitions
G	Set of all coalitions
ε	Set of work packages completed earlier than schedule
N	Set of players in the cost-sharing mechanism
N_P	Set of work packages in path P
P_P^i	Set of work packages in path P that should be executed before work package i
X_i	Set of possible execution times of work package i
S	Index for strategies in the n-player cooperative game
S	Set of possible strategies for the players in the n-player cooperative game

Parameters	Description
TC, TC_i	Standard completion time of a single work package (when there are no quality defects), Standard completion time of a work package i
c, c_i	Reworking cost per unit of time of a single work package, Reworking cost per unit of time of work package i
$\delta^{\max}$,$\delta_i^{\max}$	Maximum possible investment rate in the quality of a single work package, Maximum possible investment rate in the quality of work package i
Dr	Discount rate
α,α_i	Quality-conversion coefficient (representing the effectiveness of investment) of a single work package, Quality-conversion coefficient of work package i
R	Vector of actual durations of work packages, where r_i denotes the actual duration of work package i
P	Vector containing the scheduled durations of work packages, where p_i denotes the scheduled duration of work package i
$d_i(r)$	Delay of work package i for a given r
$D_P(r)$	Completion time of path P in the project given the actual duration vector r
$D(p)$	Completion time of path P in the project given the scheduled duration vector p
$e_i(r)$	Earliness of work package i for a given r
Q	Demand vector in the cost-sharing mechanism, where q_i indicates the demand of player i
R	Delay penalty function of the project
$unuc_i$	Idleness cost of work package i per unit of time
T_{ij}	j'th duration considered for work package i
A	Zero-sum matrix to determine the final value of work packages coalitions

Variables	Description
$\lambda(t)$,$\lambda_i(t)$	Quality level of a single work package, Quality level of a work package i.
T	Completion time of a work package
$T_i^{\min}$	Minimum possible time to complete work package i.
$T_i^{\max}$	Maximum possible time to complete work package i.
$\delta(t)$,$\delta_i(t)$	Investment rate of a single work package in quality at time t, Investment rate of work package i in quality at time t.
$\tau(t)$,$\tau_i(t)$	State variable of a work package (providing the relationship between standard and completion time of single work package), State variable of work package i
y^s	Vector of costs assigned to players in the cost-sharing mechanism, where y_i^s is the cost assigned to player i
$c_g(r)$	Cost assigned to coalition g based on the delay penalty assignment model for a given r
$v_g(r)$	Value of coalition g based on the delay penalty assignment model for a given r
V_g	Overall value of coalition g of work packages
$\phi_i(r)$	Shapely value for work package i based on the delay penalty assignment model for a given r
$nut_i(r)$	Idleness time of work package i for a given r
$nuc_i(r)$	Non-utilization cost of work package i for a given r
$u_i(s)$	Payoff of player i for strategy s
$U_g(s)$	Payoff of coalition g for strategy s

Data availability

Data will be made available on request.

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