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Quantitative Holistic Assessment of Implementing Collaborative Planning Practices

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Abstract: Practices of collaborative planning—as related to novel project delivery methods, information technologies, lean construction, and supply chain practices—can impact the cost and schedule performance of projects in the architectural, engineering, and construction (AEC) industry. However, there is a lack of research providing a quantitative holistic assessment of implementing collaborative planning practices. This paper fills this knowledge gap. Using an interdependent multistep research methodology, the authors (1) analyzed a holistic literature-based list of collaborative planning risks using 46 responses from industry expert surveys; (2) calculated the criticality of these risks and compared the obtained results using Spearman rank correlation; (3) statistically analyzed the impact of these risks—based on a project-based survey that collected data from 65 different projects—using distribution fitting analysis and weighted average calculations; (4) developed a framework for predicting the cost and schedule performance impacts in relation to utilizing collaborative planning in the AEC industry; and (5) mathematically verified the research steps using an extreme condition test and sensitivity analysis, and practically validated the research output utilizing a case study example and the insights of 25 industry experts. Within the context of collaborative planning, this paper highlighted and discussed the top six risks that affect cost and schedule project performance: resistance to change, no early involvement of key project participants, lack of construction coordination, late and ineffective communication, lack of leadership, and absence of flexibility and coordination of design. Ultimately, this study provides a necessary and highly customizable metric for industry practitioners to manage their collaborative planning practices efficiently and improve their project performance. **DOI: 10.1061/(ASCE)ME.1943-5479.0001032.**

Introduction

Projects in the architectural, engineering, and construction (AEC) industry are well-known to be prone to numerous risks and uncertainties which considerably influence the project performance with regard to cost and schedule overruns (Vaagen et al. 2017). That is ascribed mainly to the unique traits that define projects in the AEC industry, such as complexity, project size, fragmentation, heterogeneity, and variation of trades' performance (Ratajczak et al. 2018). Moreover, the coronavirus pandemic (COVID-19) is recognized to have significant impacts on projects in the AEC industry, in both the short and the long term (Assaad and El-adaway 2021). Furthermore, numerous conflicts, claims, and disputes occur in AEC projects, and this triggers considerable cost and schedule overruns (Elsayegh et al. 2020). Therefore, it is not strange or surprising that large projects in the AEC industry were reported to have 80% cost overruns and 20% schedule overruns (Agarwal et al. 2016). KPMG International organized a survey to study project performance in construction and concluded that only 31% projects were completed within 10% of the planned budget and only 25% of projects were finished within 10% of the planned schedule (KPMG 2015). Furthermore, it is estimated that only about 2.5% of construction firms fulfill 100% of their projects effectively (Assaad et al. 2020).

Companies in the AEC industry started embracing collaborative planning practices to address the aforementioned challenges because of the foreseeable positive effects of such practices on project performance (Liu et al. 2013). Collaborative planning is founded on the principles of novel project delivery methods, new collaborative information technologies, lean construction, and effective supply chain practices (Elsayegh and El-adaway 2021b). Despite the favorable prospects of collaborative planning, many firms opt to implement traditional management processes because they lack knowledge of and experience with collaborative planning (Adegbembo et al. 2016). Additionally, collaborative planning is not prioritized compared with the project engineering aspects, but the impacts of collaborative planning risks on project performance usually outweigh the risks associated with engineering and technical aspects (Valentin et al. 2018; Alarcón et al. 2011). However, along with its well-known negative impacts, COVID-19 has had positive impacts on the AEC industry by working as a catalyst to encourage firms to adopt collaborative planning to overcome the new challenges of social distancing and remote working environment (Assaad and El-adaway 2021).

There is an increasing trend in research studies to investigate collaborative planning in the AEC industry. Collaboration has been linked closely with lean construction principles such as pull planning and the Last Planner System (LPS) (Zhang et al. 2018; Sacks et al. 2010). Collaborative planning also is causing a paradigm shift in the AEC industry by using novel information technologies such as building information modeling (BIM), digital twins, and mobile applications (Lai et al. 2019; Park et al. 2017; Zhang et al. 2017).

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For example, a four-dimensional model has been presented to enable real-time collaborative planning among a group of planners from multiple disciplines (Zhou et al. 2012). Moreover, collaborative planning relies on innovative project delivery methods and relational contracting such as integrated project delivery (IPD) and partnering (Deep et al. 2019; Hall et al. 2018; Ibrahim et al. 2018). For example, the concepts of novel project delivery approaches—such as lean project delivery, relational contracts, alliancing, and partnering—have been studied through extensive literature review, and a tool was presented to improve the relationships between project stakeholders (Palacios et al. 2014). Furthermore, collaborative planning contributed to increased reliability and improved project performance in various case studies (Abdirad and Dossick 2019; Koseoglu et al. 2018; Ghosh et al. 2017; AlSehaimi et al. 2014).

Prior research efforts have studied and highlighted specific risks, associated with different facets of collaborative planning, that impact the project performance. The lack of a collaborative team environment, which hinders exchanges of information and experience among project parties, has significant adverse effects on project performance in terms of cost, schedule, productivity, and quality (Carpenter and Bausman 2016). Moreover, resistance to change has been mentioned in various studies as a major risk that impedes the application of collaborative planning in AEC projects (Hastie et al. 2017; Enegbuma et al. 2014; Kokkonen and Vaagaasar 2018; AlSehaimi et al. 2014; Faris et al. 2019). Without early and continuous involvement of key stakeholders from project inception stages, collaboration cannot be achieved in AEC projects (Abdirad and Dossick 2019; Barutha 2018). Furthermore, lack of construction coordination also has been considered to obstruct collaborative work in AEC projects and substantially impact the project performance (Zhang et al. 2017; Koseoglu et al. 2018; AlSehaimi et al. 2014). Such risks are numerous, and the need to study and evaluate them properly has been highlighted in many previous studies (Siraj and Fayek 2019; Tereso et al. 2018; Gangolells et al. 2013). Practitioners are urged to identify and address risks at the outset of their projects to facilitate proactive measures and thus yield better project performance (Choudhry et al. 2014). In addition, existing prediction models that are focused on BIM, lean construction, and relational contracting generally were constrained from achieving their full potential by data availability and several other reasons (Elsayegh and El-adaway 2021b). Previous research studies and models that predict project performance were limited to a specific area of construction management. Moreover, a holistic planning viewpoint is limited in the AEC industry, in contrast to other industries (Svalestuen et al. 2018). Several researchers indicated the necessity of a holistic predictive framework or model that incorporates all collaborative planning risk factors in the AEC industry (Oraee et al. 2019; Ibrahim et al. 2018; Liu et al. 2017; Faehnle and Tyrväinen 2013; Meng et al. 2011).

Therefore, there is a dire need for a prediction model of project performance, particularly from a collaborative planning perspective (Elsayegh and El-adaway 2021b). This research fills this knowledge gap by providing a quantitative holistic assessment of implementing collaborative planning practices.

Literature Review

Collaborative Planning in AEC Industry

Projects in the AEC industry have become more complex with further use of specialty subcontractors, leading to increased needs of information flow and project organization (Tallgren 2018). Although the construction sector in the US is a main contributor to the country's total gross output, with an estimated value of $1,895 billion in 2021, many projects in the AEC industry still are experiencing significant cost and schedule overruns (US Bureau of Economic Analysis 2021; Barbosa et al. 2017). Therefore, increased focus from the project control team is guided toward managing the project cost and schedule overruns (Assaad et al. 2020). Adequate scope definition and implementing efficient cooperation, collaboration, and communication techniques in AEC projects are considered to be the solution to the aforementioned issues (Faris et al. 2019). For example, one of the earliest frameworks developed for measuring the level of project scope definition in the planning phase was the project definition rating index (PDRI) (Elzomor et al. 2018). After its success, and to address the specific needs of different project sectors, customized versions of this framework were developed for industrial, building, and infrastructure project sectors (CII 1995, 1999, 2010). Because collaboration and communication are invaluable social actions in AEC projects, it is essential to provide a well-defined framework to facilitate these behaviors in the early project phases (Tallgren 2018; Sackey et al. 2015).

Collaborative planning in the AEC industry is defined as "a process that requires the involvement and integration of different stakeholders on construction projects to provide more reliable project planning and scheduling, promote a sense of involvement and ownership, and lead to enhanced project performance" (Elsayegh and El-adaway 2021b). A comprehensive list of factors was identified based on an extensive literature review of collaborative planning over a period of 30 years (1990–2019). Through a social network analysis approach, Elsayegh and El-adaway (2021b) identified the gaps in the literature, highlighted the understudied factors, and provided recommendations for future research on the topic of collaborative planning. A key finding was the need for a holistic prediction model that includes all factors associated with collaborative planning in the AEC industry. The collaborative planning index (CPI), an objective rating system, was developed to measure the effectiveness of collaborative planning using analytical hierarchy process (AHP) (Elsayegh and El-adaway 2021a). Elsayegh and El-adaway (2021a) classified the 50 identified collaborative planning factors into 6 categories as follows: behaviors (7 factors), communication (8 factors), team (9 factors), management (14 factors), technology (5 factors), and contractual aspects (7 factors). The scale of the CPI comprises 7 levels, and it measures the studied project CPI in contrast to an industry average that is based on the obtained survey results.

On a more specific level of the collaborative planning process, which is the scheduling aspect, a study by the Construction Industry Institute (CII) highlighted the drivers of and obstacles to collaborative scheduling, and presented a scoring system to gauge the maturity of the process (CII 2021). Collaborative scheduling was defined in this context as "a comprehensive process that aligns and engages stakeholders throughout the life cycle of the project in order to coordinate activities and resources on a project and achieve its goal" (CII 2021). CII (2021) also presented strategies to apply such practices in projects in the AEC industry. Shayboun and Schenström (2018) attempted to predict the project performance (i.e., cost, schedule, and satisfaction) with respect to project attributes and organization and outside factors in the Swedish construction industry. Based on a survey conducted in 2014, their findings highlighted that the human factors, such as collaboration, client interaction, and performance and engagement of architect are the most relevant factors to provide a reliable performance prediction model.

Existing Performance Prediction Models

There are two main approaches in the reviewed literature to mitigate the cost and schedule overruns in the AEC industry: (1) early identification of risks and predicting the project performance, and (2) presenting practitioners with recommendations to efficiently implement collaborative planning.

Safapour and Kermanshachi (2019) presented early indicators of rework that pose major risks to the project schedule, and highlighted that handling these risks will result in enhancing the project performance. To eliminate discrepancies among indicators of cost and schedule overruns, Habibi et al. (2018) presented a list of primary performance indicators that impact different stages of construction projects. Moreover, a comprehensive list of risks associated with modular construction was studied and used in the development of a prediction model for the project cost performance (Abdul Nabi and El-adaway 2021). Based on a case study approach, indicators of project delay were identified, and tools were developed to alleviate schedule delays caused by starting projects prematurely (Griego 2016).

Various prediction models investigated various aspects of the construction management process in the AEC industry and their impacts on project performance, such as modular construction, out-of-sequence work, unconventional stakeholder involvement, implementing different management approaches, and utilizing various project delivery methods (Abdul Nabi and El-adaway 2021; Ibrahim et al. 2020; El Asmar and Assainar 2017; Silva and Harper 2018; Francom et al. 2016a; Lipke et al. 2009; Attalla et al. 2003; Ling et al. 2004, 2008). For example, the project cost at completion was predicted by incorporating 16 risks within an earned value management approach (Babar et al. 2017). A framework was introduced for forecasting project cost using a probabilistic method employing Bayesian inference and the Bayesian model average method (Kim and Reinschmidt 2011). Multivariate linear regression models were presented to predict the performance of design–bid–build (DBB) and design–build (DB) projects using data collected from 87 projects (Ling et al. 2004). A Markov chain simulation focused on predicting the final cost of construction projects (Du et al. 2016). Moreover, a comparative analysis was conducted, using data from 211 projects, to analyze the project cost and schedule performance of three major delivery methods [i.e., DBB, DB, and construction manager at risk (CMR)] (Franz et al. 2020). The performance of public transportation projects was predicted, in terms of cost and schedule, based on team integration practices (Silva and Harper 2018). Silva and Harper obtained and analyzed data from 62 projects that used different delivery methods (i.e., DBB, DB, and public–private partnership).

Previous research studies predicted the project performance with respect to certain risk factors based on project data. The number of projects utilized in each study varied based on the scope of the study (Elsayegh and El-adaway 2021b). The availability of data was proven to be easier for studies that investigated broad issues such as project delivery methods (Franz et al. 2020; Silva and Harper 2018; Babar et al. 2017; Du et al. 2016; Kim and Reinschmidt 2011; Ling et al. 2004); the number of projects used ranged from 52 to 211. However, as the scope of study became more specific and focused, the relevant project data were rather limited. Ibrahim et al. (2020) studied the impact of out-of-sequence work on project performance using data collected from 42 projects. The impact of utilizing alternate project delivery methods such as job order contracting was studied using the project performance using data from 25 projects (Francom et al. 2016a). Using data collected from 30 projects, the impact of unconventional stakeholder involvement was investigated in terms of the performance of AEC projects (El Asmar and Assainar 2017). Linear regression models were constructed to predict the performance of projects using different management methods embraced by foreign companies in China, featuring 33 case studies (Ling et al. 2008). The outcomes of AEC projects were forecasted using 12 case studies using statistical methods concerned with earned schedule performance and earned value management (Lipke et al. 2009). Therefore, using the data collected from 65 projects in the present research is considered to be reasonable and adequate compared with previous published studies.

The majority of the reviewed literature was dedicated to one facet of project performance (i.e., cost or schedule). This study analyzed a comprehensive list of collaborative planning risks and developed prediction models for the project cost and schedule performance.

Research Methodology

Triggered by the hypothesis that efficient implementation of collaborative planning practices in AEC projects should result in cost and schedule savings, an interdependent multistep research methodology was followed in this study (Fig. 1). Each step is detailed further in this section.

Collaborative Planning Risks

A comprehensive set of 50 factors that affect construction collaborative planning was adopted from Elsayegh and El-adaway (2021b). For the present study, the phrasing of the factors was adjusted to assess their impacts on the project performance from a risk

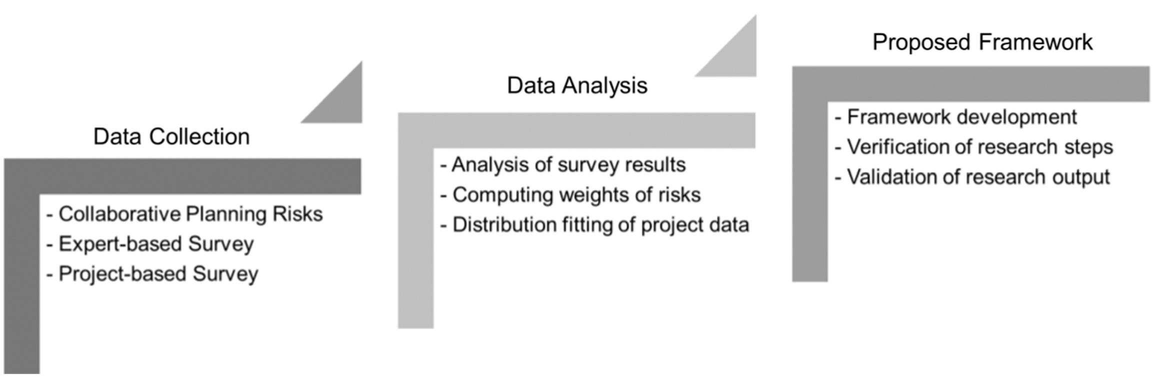

Fig. 1. Research methodology.

viewpoint. For example, the factor Pull planning effectiveness was changed to Absence of pull planning, and the factor Leadership was changed to Lack of leadership. More details about the factors, including their definitions and how they were collected and validated, were presented by Elsayegh and El-adaway (2021b). Elsayegh and El-adaway (2021a) developed a CPI benchmark that discusses a general theme of the collaborative planning research. However, the CPI did not encompass the prediction of the cost and schedule impacts associated with the collaborative planning risks, and thus does not contribute to this paper.

Expert-Based Survey Development

An expert-based survey was developed to study the impact of the aforementioned risks on project performance. The objective of this survey was to rank the importance of the identified risks to serve as a first step toward interpreting their impacts on the project performance. Respondents were asked to evaluate the likelihood, cost, and schedule impact of each of the 50 identified risks based on a standard 5-point Likert scale (Table 1).

Such a 5-point Likert scale was provided in the International Project Risk Assessment Implementation Resource (IR181-2) established by the CII [IR181-2 (IPRA 2013)], and has been used in various research efforts (Eissa et al. 2021; Ibrahim et al. 2021; Assaad et al. 2020; Abotaleb et al. 2019; Liu et al. 2017). For example, this scale was used to develop a scoring system for out-of-sequence construction based on 88 risks (Abotaleb et al. 2020). Using this scale minimizes subjectivity because it matches objective and standard scaling techniques adopted by industry practitioners. This minimizes biases of survey respondents regarding the probability of having various scale interpretations.

Qualtrics was used for the survey distribution because it enables collecting responses online. The survey collected information about the survey respondents such as position, category of the respondent's company, and years of experience. The purposive sampling method was used in this study to control the quality of the collected survey data (Owusu and Chan 2019; Leung et al. 2017). The survey population was acquired from the Associated General Contractors (AGC) directory, which also was used in prior studies (e.g., Tymvios et al. 2012). This directory fit the objective of this research because it encompasses a variety of project stakeholders who are diverse in terms of type, size of company, and locations within the US. The survey population was selected carefully according to specific criteria (Cooper and Schindler 2006): (1) maintaining contacts that can contribute to collaborative planning (e.g., general contractors, consultants, subcontractors, and suppliers), (2) selecting representatives who had thorough experience and knowledge in the construction collaborative planning process, and (3) examining the profile of each representative's firm to choose firms that embrace collaborative planning methods such as DB and IPD. In this study, consultants represented all categories of consultants in the AEC industry, such as engineers, architects, and so forth. Moreover, the survey population was checked to ensure that it encompassed various firms from different project sectors, projects sizes, and types of services offered so as to collect more-representative and reliable responses of the AEC industry. The developed survey was sent to 312 representatives who met the criteria.

Analysis of Risk Criticality

The expert-based survey responses were classified based on respondent category and then evaluated according to the risk criticality, in terms of cost and schedule. Risk criticality is identified as the estimated value of risk probability multiplied by impact (Valentin et al. 2018). Because both the probability and the impact of the risks are based on a 5-point Likert scale, the criticality in this analysis ranged from 1 to 25. For each risk, the mean criticality was computed along with the standard deviation (STD) and rank (i.e., from 1 to 50) (Abotaleb et al. 2019).

Testing the Validity of Survey Results

Sufficiency of the response rate was checked using statistical verification to determine the minimum acceptable number of responses. The authors used Eq. (1) (Cochran 1977), which has been utilized in various survey-based studies (e.g., Assaad et al. 2020; Kamali and Hewage 2017; Pereira et al. 2018)

$$n = \frac{(t^2)(s^2)}{(e^2)} \tag{1}$$

where n = number of obtained responses; $t = Z$-statistic of selected significant value α; s = variance deviation estimate for the scale utilized, i.e., computed by dividing the scale range by the number of standard deviations for approximately all possible range values; and e = number of scale points (i.e., 5) times the acceptable margin of error (i.e., 0.05) (Assaad et al. 2020). This test has been utilized in many prior studies with a significance level of 95%, which corresponds to value of $\alpha = 0.05$ (Kamali and Hewage 2017; Pereira et al. 2018; Assaad et al. 2020).

The survey responses were classified into three main categories: general contractors and construction managers (GCs/CMs), upstream (i.e., consultants, engineers, and architects), and downstream (i.e., suppliers and subcontractors) (Davis 2008). Spearman rank correlation was used to test the validity of the obtained survey responses in this research by computing its corresponding coefficient (r_s), as performed in prior research work (Chan et al. 2010; Park 2009). The Spearman rank correlation is a nonparametric assessment of the direction and correlation in risk ranking between two respondent parties according to an ordinal scale (Yap et al. 2020). The correlation coefficient ranges from −1 to 1, where −1 signifies the highest level of disagreement, and 1 signifies the highest level of agreement (Bagaya and Song 2016). If r_s is significant at $p = 0.05$ (i.e., the most commonly used p-value), it is assumed that there is no substantial disparity between the two ranking groups (Chan et al. 2010). The coefficient was calculated using

Table 1. Likelihood, cost, and schedule impact assessment scale

Scale	Likelihood	Cost and schedule impact
1	Less than 10% probability (rare possibility)	Less than 5% increase (routine procedures can handle the results)
2	10%–35% probability (not likely in most cases)	5%–10% increase (could threaten a portion of the work)
3	35%–65% probability (possible in most cases)	10%–20% increase (include significant adjustment to the project goal)
4	65%–90% probability (high probability in most cases)	20%–50% increase (considerable threat to the project objectives)
5	More than 90% probability (near certain to occur)	More than 50% increase (serious obstacle to the project objectives)

Source: Data from IPRA (2013).

$$r_s = 1 - \frac{6\sum d^2}{N(N^2-1)} \quad (2)$$

where d = difference in risk ranking between two categories; and N = number of responses. The survey results provide a clear view of how various project stakeholders observed the cost and schedule impacts of the identified risks.

Calculation of Weights of Risks

Similar to previous relevant studies that used a 5-point Likert scale, the weights of the risks were computed using a weighted average method based on their corresponding criticality (Eissa et al. 2021; Ibrahim et al. 2021; Assaad et al. 2020; Castillo et al. 2018). For example, the weighted average method was used to calculate weights for 25 risks to forecast the performance of AEC projects (Assaad et al. 2020) and to calculate the weights for 228 factors to measure the construction readiness of projects (Ibrahim et al. 2021). Because project characteristics in the AEC industry differ from one project sector to another, the weights also were computed based on the different project sectors in which the survey respondents worked. Therefore, the relative weight for each risk was computed using

$$W_i = \frac{C_i}{\sum_{i=1}^{i=50} C_i} \quad (3)$$

where W_i = weight for risk i; and C_i = mean criticality for risk i.

Project-Based Survey Development

Project data were collected to study the project cost and schedule performance in relation to the application of collaborative planning. A project-based survey was developed and distributed to industry practitioners in 10 construction companies. The project selection criteria stipulated the ability to capture cost and schedule performance in relation to the existing project risks associated with collaborative planning. Multiple responses were obtained from all companies documenting some of their projects and the associated collaborative planning practices implemented. Partial or incomplete responses were excluded, and only complete responses were considered for further analysis in this study. The survey included a set of structured questions concerning the project cost and schedule performance in relation to the existing collaborative planning risks. The survey incorporated multiple sections, including general project information (project sector, delivery method, contract type, and so forth), project performance (i.e., cost and schedule), and collaborative planning metrics.

Due to the diversity of the collected project data, a two-tailed t-test was performed between each two sets of data from different project sectors, delivery methods, and contract types. By assuming unequal variance and taking into account that the sample sizes were not equal, the Welch–Satterthwaite equation was utilized by applying the corrected t-test and comparing the two sample means (Liu et al. 2018). To conduct the t-test for different delivery methods, the project data first were classified into two main groups of delivery methods: separate contracts for engineer and contractor [i.e., DBB and construction management at risk (CMAR)], and collaborative contracts [i.e., DB, engineer–procure–construct (EPC), and IPD) (Francom et al. 2016b). The null hypothesis in this test was that the means of the project data for different project sectors, delivery methods, or contract types were the same. The test assumes that the two studied data sets have unequal variances, and a p-value of 0.05 was considered as the significance level for this test. If the p-value is less than 0.05, then the null hypothesis can be rejected, and it can be concluded that there is evidence of a statistically significant difference between the means of different project sectors, delivery methods, or contract types. In contrast, if the p-value is more than 0.05, the null hypothesis cannot be rejected, and it can be concluded that there is no evidence of a statistically significant difference between the means of different project sectors, delivery methods, or contract types. Details of the collected data are provided in the section "Results, Analysis, and Discussion."

Distribution Fitting

For enhanced data handling, the collected project data were all presented in terms of percentage of the project total cost and schedule, reflecting either savings or growth. XLSTAT version 2020.1 software was used to assess multiple distributions that fit the data using the Kolmogorov–Smirnov goodness-of-fit test and to summarize these distributions and their associated p-values. Distribution fitting was used to map the identified risks to the project performance of projects in the AEC industry (Assaad et al. 2020). The goodness-of-fit test has two hypotheses.

H_0: The sample follows a specified distribution; and

H_a: The sample does not follow a specified distribution.

A p-value of 0.05 was used as the significance level for the goodness-of-fit test (Neve et al. 2020; Assaad et al. 2020). If the calculated p-value is less than 0.05, the null hypothesis H_0 can be rejected. On the other hand, if the computed p-value is greater than 0.05, the null hypothesis cannot be rejected, and it can be concluded that the distribution is a good fit for the data.

Model candidates were highlighted and the best model was identified by evaluating and comparing the model candidates using various model evaluation metrics [i.e., log-likelihood, Akaike Information Criteria (AIC) (Akaike 1998), and Bayesian information criteria (BIC) (Schwarz 1978)]. The best model should have the lowest AIC and BIC, and the highest log-likelihood values (Calahorra-Jimenez et al. 2021). For a reliable prediction of the project performance, truncation was applied to the best model to guarantee that the developed model had proper boundary conditions to match the range of the obtained data (Assaad et al. 2020). Thus, the parameters of the fitted distribution were estimated with a 95% confidence interval, meaning that these parameters were computed with 95% certainty.

Performance Prediction Framework Development

Data Normalization

Because the risk criticality ranged from 1 to 25, data normalization was conducted to convert risk scores to a scale of [0,1] using the min-max normalization technique which is appropriate for variables with known bounds (i.e., minimum and maximum) and it also maintains the original variable distribution (Assaad et al. 2020; He et al. 2010). The normalized risk criticality was calculated using

$$Cn_i = \frac{C_i - C_{\min}}{C_{\max} - C_{\min}} \quad (4)$$

where Cn_i = normalized criticality for risk i; C_i = criticality of risk i based on survey results; $C_{\min}$ = minimum value of C_i; and $C_{\max}$ = maximum value of C_i.

Project Performance Prediction

Fig. 2 illustrates the logic of the proposed performance prediction framework. The weighted risk criticality (WRC) is calculated first by the summation of the normalized risk criticality multiplied by its associated weight from the survey results [Eq. (5)] (Ibrahim et al. 2021). This produced a decimal value with a range from 0 to 1. That enabled the use of the obtained WRC as an input in the inverse

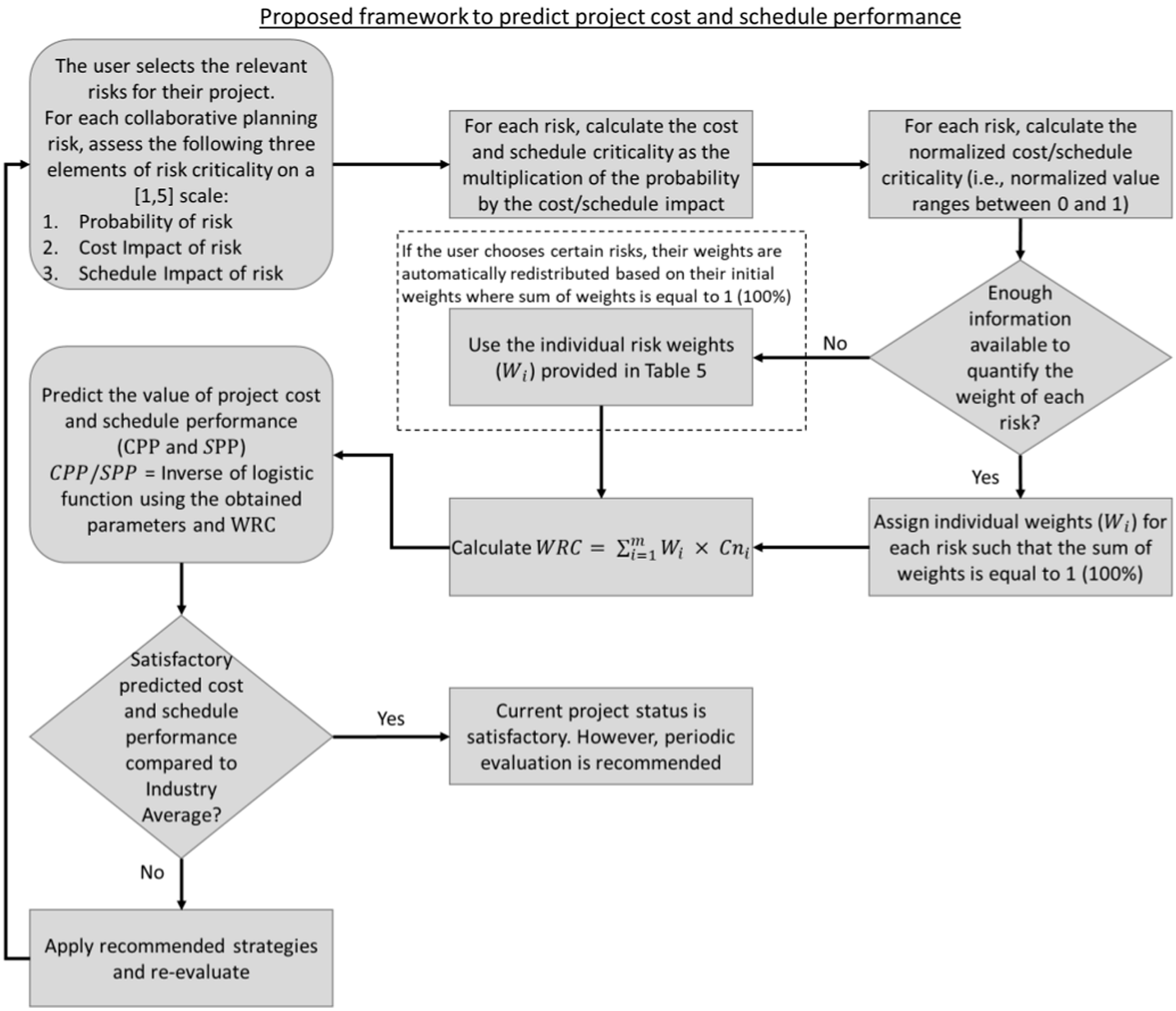

Fig. 2. Logic of the performance prediction framework.

function of the fitted distribution (i.e., logistic) [Eq. (6)] to obtain the cost performance prediction (CPP) and schedule performance prediction (SPP) as a percentage of the project budget and duration, respectively

$$\mathrm{WRC} = \sum_{i=1}^{m} W_i \times Cn_i \tag{5}$$

where W_i = weight of risk i; Cn_i = normalized criticality of risk i; and m = number of selected risks

$$F^{-1}(\mathrm{WRC}) = \mu + \beta \ln\left(\frac{\mathrm{WRC}}{1 - \mathrm{WRC}}\right) \tag{6}$$

where μ and β = parameters of fitted distribution.

The criticality assesses the risks present in the specific project under consideration (i.e., to differentiate high-risk factors and low-risk factors), whereas the weights determine which risks should take priority over others based on the industry's overall pattern. The proposed framework was developed using Visual Basic for Applications (VBA version 16.0) and macros in Excel. The user provides their inputs with respect to the existing risks in the studied project to compute the project's CPP and SPP and compare them with the industry average. The industry average is calculated using the same selected risks, but the input values for the cost and schedule impacts are replaced with the survey averages. Moreover, the framework highlights the five top risks in terms of cost and schedule criticality for the project.

Verification and Validation

The research steps were verified mathematically using the extreme condition test and sensitivity analysis, because it is important for any developed model to ensure that it mimics the real system (Assaad et al. 2020; Zhuang 2014). In the extreme condition test, the developed model is expected to have a realistic behavior regardless of the extreme inputs provided. Moreover, the cost and schedule overruns are expected to increase when the criticalities of risks increase, and vice versa (Assaad et al. 2020). Sensitivity analysis was conducted on the developed models by assuming that all risks

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had the same criticality value in every iteration. The cost and schedule criticality started with a value of 1, and the corresponding prediction values were computed. The criticality then was increased in increments of 1 until it reached the maximum value, 25, and the corresponding prediction values were computed.

The research validation consisted of two main steps. First, a case study example was presented by investigating the impacts of collaborative planning risks on the cost and schedule performance of an actual project. The case study was a large-scale infrastructure project (more than $100 million) using the EPC delivery method in Colorado. The project team utilized the developed framework and then shared the obtained results and their feedback on its benefits and applicability. Second, the research output further was validated practically by 25 subject matter experts who critically reviewed the proposed framework, its usability, and the user experience. The responding experts were affiliated with companies that are experienced in DB and IPD projects and have an average yearly income of $2.45 billion, an average of 1,300 employees, and an average of 70.4 years of construction experience. Details of the experts are provided in the section "Results, Analysis, and Discussion."

Results, Analysis, and Discussion

Expert-Based Survey

A total of 46 complete survey responses were collected, and all partial responses were removed before proceeding with the analysis. The sufficiency of response rate test was determined using Eq. (1) with a significance level of 95%, and the associated t value was 1.96. Because a 5-point Likert scale was used, the associated s value was 5/6 (Randiwela and Wijayaratne 2017; Fellows and Liu 2015). Moreover, using a 5% margin of error, which is used commonly (Kamali and Hewage 2017; Pereira et al. 2018), and a 5-point Likert scale, the e value was (5×0.05). Therefore, the value of n was computed to be 43, as follows:

$$n = \frac{(1.96^2)\left(\frac{5^2}{6}\right)}{(5 \times 0.05)^2} = 42.68 \approx 43$$

Therefore, the 46 obtained responses were deemed to be sufficient from a statistical viewpoint (i.e., $46 > 43$). Furthermore, empirical verification is provided to support the sample-size sufficiency. The obtained number of survey responses is analogous to relevant research work with a national focus, e.g., 30, 36, 39, and 63 in Akroush and El-adaway (2017), O'Connor and Woo (2017), Gurmu and Aibinu (2018), and Assaad et al. (2020), respectively. The 46 responses corresponded to a response rate of 14.74%. Compared with prior relevant studies, 14.74% was deemed to be an adequate response rate, because it exceeded 10% of the targeted population (Akroush and El-adaway 2017; Cole 2008). This response rate was deemed to be in line with that of previous studies in different construction management areas, e.g., 10.5% in Akroush and El-adaway (2017), 8.75% in Hanna et al. (2016); 8% in Al Qady and Kandil (2013), 12% in Jin and Zhang (2011), 13.02% in Yuan et al. (2009), and 8% and 9% in Salman et al. (2007). Thus, confidence is conveyed in the quality of the obtained responses in this research. Table 2 presents the descriptive statistics of the survey respondents.

The percentage of each of the three respondent categories with respect to total survey respondents was consistent with the percentage of these categories present in the total population. The survey respondents collectively had 1,252 years of construction experience, with an average of 27.22 years. Furthermore, 80.43% of the respondents had more than 10 years of construction experience, and 67.39% of the respondents possessed more than 20 years of experience, indicating vital contributions to the research outcomes. Regarding the collaborative planning aspect, the respondents collectively had 630 years of experience with an average of 13.70 years, and 54.35% of the respondents had over 10 years of collaborative planning experience. Additionally, over 70% of the respondents were top management executives in their organizations. Top management executives in construction firms usually have invaluable experience in construction-related processes, especially project management, before being promoted to such positions. These figures, coupled with the range of years of experience, indicate that the majority of the respondents were skilled practitioners in the AEC industry. The aforementioned attributes of the responses imply that they offer useful data with a dependable depiction of the AEC industry in the US.

Table 2. Descriptive statistics of survey respondents

Information	Type	Count
Role and position	CEO/president	12
	Vice president/department manager	22
	Project manager	5
	Engineer/consultant	7
Size of firm (employees)	25–50	9
	51–200	12
	201–500	7
	501–1,000	4
	1,001–5,000	8
	>5,000	6
Construction experience (years)	<5	3
	5–10	6
	10–20	6
	>20	31
Collaborative planning experience (years)	<5	11
	5–10	10
	10–20	14
	>20	11
Type of organization	Upstream	10
	General contractor	20
	Downstream	16
Industry sector[a]	Commercial	25
	Industrial	23
	Infrastructure	30
	Building	21

[a]Firms can work in multiple industry sectors.

Analysis of Risks

The identified risks were analyzed in this study according to their criticality in terms of cost and schedule. For each risk, the mean, standard deviation, and rank of the criticality for each respondent category were calculated for the cost and schedule impacts (Tables 3 and 4, respectively).

From a cost impact perspective, resistance to change (R1) was considered to be the most critical risk by the GCs/CMs and downstream stakeholders, and in terms of the total number of survey respondents. When an organization faces a change in the way they do business, there is no doubt that it will be faced with resistance from the people involved in the organization, which significantly will impact the project performance (Lines et al. 2015; Erdogan et al. 2008). In contrast, inappropriateness of project delivery

Table 3. Cost criticality results based on different survey respondent categories

Category	Upstream			GCs/CMs			Downstream			Total respondents		
Risk	Mean	Standard deviation	Rank	Mean	Standard deviation	Rank	Mean	Standard deviation	Rank	Mean	Standard deviation	Rank
R1	10.7	4.27	17	15	5.21	1	11.63	6.70	1	12.30	5.81	1
R11	11.7	4.79	8	14.75	6.62	2	10.31	5.77	5	12.06	6.19	2
R28	11.8	4.24	5	14.15	4.61	3	10.75	7.43	3	11.84	5.78	3
R8	11.9	6.98	4	12.65	6.55	5	11.50	6.81	2	11.28	6.60	4
R5	11.7	5.64	6	12	4.78	7	9.13	6.79	12	10.38	5.76	5
R25	11.4	4.06	11	11.25	6.31	10	10.44	7.20	4	10.33	6.13	6
R47	10.4	5.52	22	11.4	6.27	9	10.00	6.58	6	9.96	6.13	7
R2	9.5	4.33	30	12.05	6.19	6	8.44	4.80	18	9.89	5.51	8
R6	9.6	4.33	29	13.3	6.89	4	7.69	6.26	27	9.79	6.58	9
R10	11.7	4.40	7	10.85	5.73	12	9.19	7.45	10	9.72	6.10	10
R50	11.7	4.40	10	10.85	5.73	13	9.19	7.45	11	9.72	6.10	11
R36	10.8	5.09	15	10.35	3.94	19	8.38	5.14	19	9.56	4.65	12
R33	11.1	6.06	12	11.8	5.33	8	7.88	6.25	23	9.52	5.97	13
R32	10.4	5.30	21	11.15	4.40	11	7.75	4.89	25	9.40	4.92	14
R12	9.4	3.98	33	10.2	5.00	23	9.00	5.59	13	9.20	4.94	15
R14	8.5	4.53	44	10.4	5.46	17	9.44	6.28	8	9.18	5.51	16
R48	11.7	6.58	9	9.85	5.52	25	8.56	5.40	16	9.17	5.71	17
R46	10.2	5.03	24	10.35	5.57	20	8.56	5.77	15	9.14	5.47	18
R21	9.9	5.84	27	10.2	5.43	22	8.50	5.57	17	9.12	5.50	19
R38	8.9	4.20	40	9.65	4.42	28	9.38	6.47	9	8.84	5.08	20
R26	10.9	4.86	13	10.35	4.55	18	7.06	5.56	35	8.84	5.16	21
R29	10.2	5.25	23	9.35	4.38	30	8.38	5.73	20	8.73	5.00	22
R3	10.8	5.35	14	10.75	5.20	15	6.69	5.49	38	8.73	5.57	23
R44	13.7	5.14	1	8.8	5.09	35	7.25	5.66	32	8.66	5.73	24
R45	12.1	6.38	2	7.9	4.05	38	9.75	7.43	7	8.60	6.01	25
R18	10.5	5.58	19	9.7	5.02	27	7.81	5.81	24	8.56	5.41	26
R19	8.1	4.01	47	10.35	5.41	21	8.63	8.00	14	8.46	6.16	27
R13	8.5	3.92	43	10.8	4.84	14	6.94	5.70	36	8.45	5.18	28
R20	9.9	6.64	26	9.85	4.61	26	7.56	5.78	29	8.42	5.50	29
R39	10.8	6.78	16	8.85	5.11	34	8.13	5.10	22	8.29	5.47	30
R7	10.4	5.32	20	9.4	4.30	29	7.44	5.07	31	8.28	4.84	31
R34	9.8	6.48	28	10.55	6.00	16	6.25	5.21	43	8.16	6.05	32
R16	9.4	4.12	34	10.15	5.63	24	6.50	5.67	40	7.94	5.50	33
R30	10.7	3.95	18	9	5.07	33	6.50	4.98	41	7.92	4.98	34
R22	9.3	6.13	36	9.35	5.77	31	7.63	6.05	28	7.86	5.87	35
R49	10	4.83	25	7.75	4.38	41	8.31	6.19	21	7.82	5.13	36
R40	12	6.80	3	7	4.38	45	7.56	5.35	30	7.81	5.56	37
R37	7.9	5.86	48	9.15	4.25	32	7.75	5.16	26	7.80	4.88	38
R35	9.3	4.35	37	8	3.67	37	7.13	4.38	34	7.74	4.06	39
R4	9.2	4.39	38	7.9	3.24	39	6.88	4.08	37	7.53	3.82	40
R24	8.7	5.42	42	8.65	4.98	36	6.38	3.83	42	7.43	4.74	41
R41	9.2	4.21	39	7.8	4.12	40	6.63	3.40	39	7.38	3.94	42
R31	9.5	2.72	32	7.6	4.06	42	5.88	3.22	46	7.15	3.70	43
R42	8.8	6.03	41	7.1	4.36	44	7.25	4.49	33	6.86	4.75	44
R43	8.4	5.76	46	7.45	4.24	43	6.06	4.51	44	6.64	4.67	45
R23	9.5	4.70	31	5.55	3.90	47	5.44	3.69	47	5.92	4.26	46
R9	9.3	6.25	35	5.4	4.27	48	6.00	3.81	45	5.91	4.77	47
R27	8.5	4.14	45	6	4.63	46	5.06	4.15	48	5.46	4.46	48
R15	6.3	5.48	49	4.55	4.78	50	4.69	3.09	49	4.35	4.40	49
R17	6	4.50	50	5.15	4.75	49	4.19	3.31	50	4.26	4.21	50

method (R44) was ranked first by the upstream stakeholders, showing its criticality from their perspective in terms of the project cost performance. This risk is evident when conventional project delivery methods are chosen because such delivery methods still encounter inefficiencies in communication and poor project performance caused by adversarial relationships (Abdirad and Dossick 2019).

Four of the top five risks were common between GCs/CMs and downstream stakeholders. For the upstream stakeholders, the top five risks were inappropriateness of project delivery method (R44), project fragmentation and subcontracting (R45), absence/poor use of nD modeling (e.g., BIM) (R40), late and ineffective communication (R8), and lack of construction coordination (R28). For the GCs/CMs, the top five risks were resistance to change (R1); no early involvement of key project participants (R11); lack of construction coordination (R28), lack of trust, confidence, and respect (R6); and late and ineffective communication (R8).

From the downstream stakeholders' perspective, the top five risks were resistance to change (R1), late and ineffective communication (R8), lack of construction coordination (R28), absence of flexibility and coordination of design (R25), and no early involvement of key project participants (R11). The close agreement between GCs/CMs and downstream stakeholders on ranking the

Table 4. Schedule criticality results based on different survey respondent categories

Category	Upstream			GCs/CMs			Downstream			Total respondents		
Risk	Mean	Standard deviation	Rank	Mean	Standard deviation	Rank	Mean	Standard deviation	Rank	Mean	Standard deviation	Rank
R11	12.00	4.90	6	15.05	6.50	1	10.50	5.77	3	12.35	6.17	1
R1	11.30	4.37	15	14.15	5.13	2	11.38	6.44	2	12.06	5.54	2
R8	12.20	6.76	4	13.00	6.73	5	11.75	6.01	1	11.71	6.37	3
R28	11.60	4.86	13	14.00	4.80	3	10.25	7.33	5	11.57	5.93	4
R25	11.80	4.71	10	11.25	6.31	12	10.50	7.34	4	10.40	6.28	5
R5	12.00	5.37	5	11.75	4.72	9	8.81	5.59	14	10.38	5.27	6
R2	11.00	5.37	19	12.45	6.11	7	8.44	4.69	17	10.34	5.66	7
R33	11.90	5.47	7	12.50	5.61	6	8.44	6.28	16	10.17	6.00	8
R14	9.00	4.57	40	11.30	5.62	11	10.00	5.79	6	9.99	5.43	9
R6	10.20	4.42	28	13.15	6.88	4	7.75	6.20	26	9.92	6.52	10
R47	10.00	2.75	30	11.30	6.17	10	9.69	6.95	7	9.90	5.85	11
R10	11.80	4.05	9	10.35	5.95	18	9.69	7.56	8	9.78	6.16	12
R50	11.80	4.05	11	10.35	5.95	19	9.69	7.56	9	9.78	6.16	13
R36	10.10	5.90	29	10.40	3.80	17	7.94	4.73	24	9.38	4.67	14
R3	11.40	6.75	14	12.00	5.76	8	6.63	5.38	39	9.35	6.25	15
R48	12.70	6.65	2	9.65	4.86	28	8.38	5.33	19	9.30	5.56	16
R12	9.70	4.30	34	10.10	5.23	25	9.00	5.24	12	9.26	4.96	17
R38	8.80	4.34	43	10.60	5.26	16	9.38	6.04	11	9.21	5.31	18
R21	9.80	5.03	32	10.30	5.41	21	8.56	5.57	15	9.18	5.33	19
R26	11.70	5.96	12	10.70	4.88	15	7.19	5.64	34	9.08	5.60	20
R32	10.60	6.48	24	10.30	5.36	20	7.38	5.14	31	8.79	5.61	21
R18	10.80	5.57	22	9.70	5.02	27	7.94	6.10	25	8.68	5.52	22
R46	9.90	5.84	31	10.10	6.12	24	8.06	6.14	22	8.60	6.01	23
R37	7.40	5.10	48	10.90	4.63	14	8.06	5.31	21	8.58	5.11	24
R13	8.70	5.77	45	10.95	4.83	13	7.13	6.08	36	8.57	5.64	25
R45	12.60	5.78	3	7.45	3.73	43	9.63	7.52	10	8.54	5.95	26
R19	8.10	4.82	46	10.25	5.38	22	8.88	8.30	13	8.52	6.37	27
R44	13.20	4.69	1	8.25	4.42	37	7.19	5.60	35	8.47	5.33	28
R20	10.30	6.90	26	9.80	4.91	26	7.44	5.89	30	8.42	5.72	29
R29	8.80	3.43	42	9.30	4.11	32	7.56	4.73	29	8.40	4.19	30
R39	11.20	6.61	16	9.10	5.22	33	7.63	4.76	28	8.35	5.44	31
R7	10.80	5.73	21	9.55	4.33	29	7.25	5.07	32	8.34	5.00	32
R42	9.50	5.64	39	8.85	5.20	34	8.00	4.91	23	8.18	5.12	33
R16	10.90	5.43	20	10.15	6.06	23	6.63	5.68	40	8.17	5.96	34
R49	11.20	5.37	17	7.70	3.89	42	8.31	6.20	20	8.16	5.19	35
R40	11.90	6.40	8	7.15	4.56	45	8.44	5.68	18	8.14	5.58	36
R34	9.60	6.08	37	9.45	5.81	30	7.25	5.36	33	8.10	5.69	37
R22	9.60	5.42	36	9.30	5.48	31	7.63	6.05	27	7.98	5.61	38
R30	11.10	4.28	18	8.80	4.67	35	6.63	5.20	41	7.92	4.97	39
R35	9.70	4.60	35	8.05	3.44	38	7.13	4.38	37	7.80	4.07	40
R4	9.70	4.24	33	7.90	3.11	39	6.94	4.60	38	7.64	3.97	41
R41	10.40	5.46	25	7.85	3.99	40	6.63	3.40	42	7.62	4.30	42
R31	10.30	4.00	27	7.75	4.05	41	6.13	3.22	45	7.38	4.00	43
R24	8.80	4.47	41	8.30	4.84	36	6.25	3.87	43	7.32	4.48	44
R43	8.10	5.63	47	7.45	4.24	44	6.19	4.42	44	6.64	4.58	45
R9	8.70	4.99	44	6.05	4.83	46	5.56	3.44	46	6.10	4.50	46
R23	9.50	4.70	38	5.75	4.13	48	5.31	3.70	47	5.92	4.35	47
R27	10.60	6.55	23	5.90	4.20	47	4.88	3.88	48	5.72	5.09	48
R15	6.80	6.91	49	4.40	4.68	50	4.69	3.09	49	4.35	4.79	49
R17	5.90	3.73	50	5.15	4.75	49	3.88	3.03	50	4.22	4.00	50

top five risks suggests that they experience the same challenges, especially because they are the stakeholders who participate the most in the construction process.

No early involvement of key project participants (R11) was the most significant risk from a schedule impact perspective. This risk hinders collaboration in design and construction plan development, leading to cost overruns and risks in project delivery (Hastie et al. 2017). There were four common risks in the list of top five risks identified by GCs/CMs, downstream stakeholders, and all survey respondents. For the GCs/CMs, the top five risks were no early involvement of key project participants (R11); resistance to change (R1); lack of construction coordination (R28); lack of trust, confidence, and respect (R6); and late and ineffective communication (R8). For the downstream stakeholders, the top five risks were late and ineffective communication (R8), resistance to change (R1), no early involvement of key project participants (R11), absence of flexibility and coordination of design (R25), and lack of construction coordination (28).

From the perspective of the upstream stakeholders, the most critical risks were inappropriateness of project delivery method (R44), poor/restrictive policies and contractual obligations (R48), project fragmentation and subcontracting (R45), late and ineffective

Table 5. Results of Spearman rank correlation

Ranking assessment	Cost		Schedule	
	r_s	Significance	r_s	Significance
Upstream versus GCs/CMs	0.456	Correlated samples ($p = 0.001$)	0.327	Correlated samples ($p = 0.020$)
Upstream versus downstream	0.522	Correlated samples ($p = 0.000$)	0.44	Correlated samples ($p = 0.001$)
GCs/CMs versus downstream	0.692	Correlated samples ($p = 0.000$)	0.679	Correlated samples ($p = 0.000$)

communication (R8), and lack of leadership (R5). The results imply that upstream stakeholders are more concerned with the contractual aspect of the risks for the project schedule performance than with the actual collaboration practices, which were highlighted by the GCs/CMs and downstream stakeholders.

The top six critical risks that were identified, in terms of both cost and schedule criticality, were no early involvement of key project participants (R11), resistance to change (R1), late and ineffective communication (R8), lack of construction coordination (28), absence of flexibility and coordination of design (R25), and lack of leadership (R5) (Tables 3 and 4). All survey respondents agreed that the collaborative planning risks with the least impact on the project performance are culture differences (R17), multicultural team members and language barrier (R15), and inapplicability of colocation/centralized working place (R27).

Evaluation of Agreement among Respondents

Table 5 presents the ranking agreement of the risks between different categories of respondents based on Spearman rank correlation coefficients. All computed p-values were less than 0.05, which demonstrates the correlation significance of the samples. Moreover, all coefficients had positive values which means that the association of the ranking of each two respondent categories was directly proportional. Nonetheless, the strength of agreement differed according to the coefficient value. The GCs/CMs versus downstream ranking had the highest values, 0.692 and 0.679 for the cost and schedule impacts, respectively. This implies their strong agreement and risk ranking correlation. The upstream versus downstream ranking had a value of 0.522 and 0.44 for the cost and schedule impacts, respectively, implying a moderate agreement on ranking the studied risks.

The upstream versus GCs/CMs ranking obtained the lowest values, 0.456 and 0.327 for the cost and schedule impacts, respectively. This still indicates a moderate correlation between respondents of the two categories.

Weights of Risks

Based on the survey responses, the calculated weights of the risks are presented in Table 6. These weights are to be used in the forthcoming proposed framework to serve as basis for predicting the cost and schedule performance of projects in the AEC industry.

The framework user can change these weights if there is existing information and expertise to assess quantitively each risk and its associated contribution to the cost and schedule performance of the studied project. The sum of the new weights should equal 1. Furthermore, Table 7 demonstrates the calculated weights per project sector to serve as a reference for the user regarding how each project sector views different collaborative planning risks.

Table 6. Weights of collaborative planning risks as identified by survey respondents

Risk	Average of responses			Criticality		Weights	
	Likelihood	Cost impact	Schedule impact	Cost	Schedule	Cost	Schedule
R1	3.674	3.348	3.283	12.300	12.060	0.029	0.028
R2	2.935	3.370	3.522	9.889	10.336	0.023	0.024
R3	2.848	3.065	3.283	8.729	9.348	0.020	0.022
R4	2.565	2.935	2.978	7.528	7.640	0.018	0.018
R5	2.826	3.674	3.674	10.383	10.383	0.024	0.024
R6	2.870	3.413	3.457	9.794	9.919	0.023	0.023
R7	2.761	3.000	3.022	8.283	8.343	0.019	0.019
R8	3.304	3.413	3.543	11.278	11.709	0.026	0.027
R9	2.174	2.717	2.804	5.907	6.096	0.014	0.014
R10	3.000	3.239	3.261	9.717	9.783	0.023	0.023
R11	3.283	3.674	3.761	12.060	12.345	0.028	0.029
R12	3.022	3.043	3.065	9.197	9.262	0.022	0.021
R13	2.717	3.109	3.152	8.448	8.566	0.020	0.020
R14	2.891	3.174	3.457	9.177	9.994	0.022	0.023
R15	2.000	2.174	2.174	4.348	4.348	0.010	0.010
R16	2.609	3.043	3.130	7.940	8.166	0.019	0.019
R17	2.000	2.130	2.109	4.261	4.217	0.010	0.010
R18	2.609	3.283	3.326	8.563	8.677	0.020	0.020
R19	2.739	3.087	3.109	8.456	8.515	0.020	0.020
R20	2.848	2.957	2.957	8.420	8.420	0.020	0.019
R21	2.761	3.304	3.326	9.123	9.183	0.021	0.021
R22	2.761	2.848	2.891	7.862	7.983	0.018	0.018
R23	2.543	2.326	2.326	5.916	5.916	0.014	0.014
R24	2.630	2.826	2.783	7.434	7.319	0.017	0.017
R25	3.065	3.370	3.391	10.328	10.395	0.024	0.024
R26	2.804	3.152	3.239	8.840	9.084	0.021	0.021

Table 6. (*Continued.*)

Risk	Average of responses			Criticality		Weights	
	Likelihood	Cost impact	Schedule impact	Cost	Schedule	Cost	Schedule
R27	2.370	2.304	2.413	5.460	5.718	0.013	0.013
R28	3.130	3.783	3.696	11.841	11.569	0.028	0.027
R29	3.043	2.870	2.761	8.733	8.403	0.020	0.019
R30	2.783	2.848	2.848	7.924	7.924	0.019	0.018
R31	2.739	2.609	2.696	7.146	7.384	0.017	0.017
R32	2.826	3.326	3.109	9.400	8.785	0.022	0.020
R33	2.978	3.196	3.413	9.517	10.165	0.022	0.023
R34	2.761	2.957	2.935	8.163	8.103	0.019	0.019
R35	2.804	2.761	2.783	7.742	7.803	0.018	0.018
R36	2.783	3.435	3.370	9.558	9.376	0.022	0.022
R37	2.761	2.826	3.109	7.802	8.583	0.018	0.020
R38	2.804	3.152	3.283	8.840	9.206	0.021	0.021
R39	2.783	2.978	3.000	8.287	8.348	0.019	0.019
R40	2.565	3.043	3.174	7.807	8.142	0.018	0.019
R41	2.804	2.630	2.717	7.377	7.621	0.017	0.018
R42	2.630	2.609	3.109	6.862	8.177	0.016	0.019
R43	2.609	2.543	2.543	6.635	6.635	0.016	0.015
R44	2.804	3.087	3.022	8.657	8.474	0.020	0.020
R45	2.804	3.065	3.043	8.596	8.535	0.020	0.020
R46	2.804	3.261	3.065	9.145	8.596	0.021	0.020
R47	2.957	3.370	3.348	9.962	9.898	0.023	0.023
R48	2.870	3.196	3.239	9.170	9.295	0.022	0.021
R49	2.587	3.022	3.152	7.817	8.155	0.018	0.019
R50	3.000	3.239	3.261	9.717	9.783	0.023	0.023
Total				426.339	432.682	1.000	1.000

Table 7. Weights of collaborative planning risks based on different project sectors

Project sector	Building and commercial		Industrial		Infrastructure		Total	
Risk	Cost	Schedule	Cost	Schedule	Cost	Schedule	Cost	Schedule
R1	0.029	0.028	0.027	0.027	0.029	0.028	0.029	0.028
R2	0.024	0.025	0.024	0.023	0.022	0.022	0.023	0.024
R3	0.021	0.022	0.019	0.021	0.020	0.021	0.020	0.022
R4	0.018	0.018	0.016	0.016	0.018	0.017	0.018	0.018
R5	0.026	0.026	0.022	0.022	0.022	0.022	0.024	0.024
R6	0.024	0.024	0.023	0.022	0.021	0.021	0.023	0.023
R7	0.018	0.019	0.018	0.018	0.022	0.021	0.019	0.019
R8	0.027	0.027	0.027	0.028	0.026	0.027	0.026	0.027
R9	0.013	0.014	0.010	0.010	0.016	0.016	0.014	0.014
R10	0.021	0.020	0.026	0.028	0.024	0.025	0.023	0.023
R11	0.028	0.028	0.029	0.028	0.029	0.029	0.028	0.029
R12	0.022	0.021	0.020	0.023	0.021	0.021	0.022	0.021
R13	0.018	0.018	0.027	0.024	0.020	0.021	0.020	0.020
R14	0.020	0.022	0.026	0.028	0.022	0.024	0.022	0.023
R15	0.009	0.009	0.009	0.009	0.012	0.012	0.010	0.010
R16	0.019	0.019	0.021	0.022	0.017	0.017	0.019	0.019
R17	0.009	0.009	0.012	0.012	0.011	0.010	0.010	0.010
R18	0.019	0.019	0.018	0.018	0.023	0.022	0.020	0.020
R19	0.019	0.020	0.023	0.022	0.019	0.019	0.020	0.020
R20	0.019	0.018	0.020	0.021	0.021	0.021	0.020	0.019
R21	0.021	0.021	0.022	0.024	0.022	0.021	0.021	0.021
R22	0.018	0.018	0.019	0.018	0.019	0.019	0.018	0.018
R23	0.013	0.013	0.015	0.015	0.014	0.014	0.014	0.014
R24	0.017	0.017	0.018	0.017	0.017	0.016	0.017	0.017
R25	0.024	0.024	0.025	0.024	0.024	0.023	0.024	0.024
R26	0.021	0.021	0.017	0.017	0.022	0.022	0.021	0.021
R27	0.013	0.014	0.014	0.013	0.012	0.012	0.013	0.013
R28	0.030	0.029	0.023	0.021	0.026	0.026	0.028	0.027
R29	0.022	0.021	0.018	0.017	0.019	0.018	0.020	0.019
R30	0.018	0.018	0.021	0.021	0.019	0.018	0.019	0.018
R31	0.017	0.018	0.018	0.018	0.015	0.015	0.017	0.017
R32	0.023	0.021	0.019	0.017	0.022	0.020	0.022	0.020
R33	0.022	0.023	0.018	0.023	0.025	0.025	0.022	0.023

Table 7. (*Continued*.)

Project sector	Building and commercial		Industrial		Infrastructure		Total	
Risk	Cost	Schedule	Cost	Schedule	Cost	Schedule	Cost	Schedule
R34	0.020	0.018	0.018	0.021	0.018	0.018	0.019	0.019
R35	0.018	0.018	0.017	0.018	0.019	0.018	0.018	0.018
R36	0.023	0.022	0.022	0.021	0.022	0.022	0.022	0.022
R37	0.018	0.019	0.023	0.024	0.018	0.020	0.018	0.020
R38	0.021	0.021	0.026	0.026	0.019	0.021	0.021	0.021
R39	0.019	0.020	0.018	0.016	0.020	0.020	0.019	0.019
R40	0.021	0.020	0.016	0.019	0.016	0.016	0.018	0.019
R41	0.017	0.018	0.019	0.019	0.017	0.017	0.017	0.018
R42	0.016	0.019	0.018	0.020	0.016	0.018	0.016	0.019
R43	0.014	0.014	0.012	0.013	0.019	0.019	0.016	0.015
R44	0.023	0.021	0.017	0.017	0.018	0.018	0.020	0.020
R45	0.021	0.021	0.020	0.017	0.019	0.019	0.020	0.020
R46	0.023	0.022	0.020	0.015	0.020	0.019	0.021	0.020
R47	0.023	0.023	0.027	0.024	0.022	0.022	0.023	0.023
R48	0.022	0.022	0.018	0.018	0.023	0.022	0.022	0.021
R49	0.018	0.019	0.017	0.018	0.019	0.019	0.018	0.019
R50	0.021	0.020	0.026	0.028	0.024	0.025	0.023	0.023
Total	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Discussing Top Collaborative Planning Risks

Tables 3 and 4 rank the top collaborative planning risk from a cost and schedule perspective, and the aforementioned steps provided further confidence in the reliability of these results. This section discusses these top risks in more details.

Resistance to change (R1) means that when an organization faces a change in the way they do business, there is no doubt that it will be faced with resistance from the people involved in the organization, and that requires proper management (Erdogan et al. 2008). Resistance to change often is cited as a critical risk that significantly impacts project performance, and it is among the psychological and systematic barriers that affect collaborative planning, knowledge integration among project stakeholders, and successful implementation of new systems (Hastie et al. 2017; Lines et al. 2015; Enegbuma et al. 2014). That justifies the results of this research, in which R1 was ranked first among the risks for cost performance and second for schedule performance. To overcome resistance to change, there should be incremental implementation of such change, the importance of this change should be provided, feedback should be collected from affected stakeholders to increase their confidence in it, and the desired outcome upon such change should be highlighted (Faris et al. 2019; Kokkonen and Vaagaasar 2018; AlSehaimi et al. 2014).

Early involvement of key project participants (R11) describes the stage in which key project stakeholders are actively engaged in the project, particularly in the project development and design phases (Elsayegh and El-adaway 2021b). Early and continuous involvement from project inception stages is considered to be a major characteristic of true collaborative projects in the AEC industry, and has been listed as one of the principles of collaboration and integration for IPD projects (Abdirad and Dossick 2019; Barutha 2018). The absence of a contractor's early involvement makes it challenging to establish project team integration and essential team culture (Suprapto et al. 2015). That supports the findings of this study, in which R11 was ranked second for cost performance and first for schedule performance. Choosing early contractor involvement as the project delivery approach is an effective relationship-based approach to reducing the uncertainty in projects, thus improving project performance (Song et al. 2009).

Construction coordination (R28) describes the work sequencing between various trades and parties, and represents the daily construction coordination to guarantee work continuity and quick problem solving (Elsayegh and El-adaway 2021b). The construction coordination process demands close follow-up with the project participants and quick problem solving (Koseoglu et al. 2018). That matches with the results of this study, in which R28 was ranked third for cost performance and fourth for schedule performance. Construction coordination is facilitated with lean construction using the LPS technique to guarantee successful project implementation and delivery (AlSehaimi et al. 2014). Moreover, BIM adoption has been identified as one of the tools for construction coordination that will facilitate collaborative work mode in AEC projects (Zhang et al. 2017).

Late and ineffective communication (R8) can be the result of a lack of team collaboration in the AEC industry (Oraee et al. 2019). Interaction in the construction environment involves different groups of people working together for short periods then parting ways to perform other projects, which makes communication a difficult task (Dainty 2007). Moreover, the overuse of conventional communication techniques such as paper-based communication and formal client approval procedures can cause considerable delays in decision-making, can lead to major rework, and can affect the performance of AEC projects (Kamalirad et al. 2017; AlSehaimi et al. 2014). That justifies the results of this study, in which R8 was ranked fourth for cost performance and third for schedule performance. Communication and information exchange can be enhanced with a shared IT-based database (Eriksson et al. 2009).

Lack of leadership (R5) is a major obstacle for implementing innovation and collaboration in the AEC industry (Leoto and Lizarralde 2019). Leadership is believed to influence the performance of AEC projects with respect to time, cost, and quality (Larsson et al. 2015). Contractor leadership is considered to be the most crucial success factor in the incorporation of lean construction (Orr 2005). That matches with the study results, because R5 was ranked fifth for cost performance and sixth for schedule performance. Good leadership is the main facilitator when a change is introduced in AEC projects to support collaboration because it can cause the required change in attitude and behavior of the project

Table 8. Summary of collected project data

Characteristic	Type	Count
Project sector	Building and commercial	41
	Industrial	16
	Infrastructure	8
Delivery method	Design bid build	3
	Design build	14
	Integrated project delivery	26
	Construction management at risk	10
	Engineering, procurement, and construction	12
Contract type	Lump sum	22
	Guaranteed maximum price	43

team (Zimina et al. 2012). Moreover, the usefulness of having a good leader on a project is demonstrated through firm belief and confidence in their mission, resulting in all project parties following by example. To obtain the required outcome of leadership in collaborative AEC projects, leadership should be assigned to the most competent person on the project team (Abdirad and Dossick 2019).

Flexibility and coordination of design (R25) refers to coordinating all activities, processes, and teams involved in the design phase to produce a suitable and consistent design (Elsayegh and El-adaway 2021b). Flexibility and coordination of design on a construction project is highly dependent on the project delivery method used (Zhang et al. 2017). However, proper flexibility and coordination of design in megaprojects can be very challenging, because any design adjustment in one subproject could cause a snowball effect on adjacent subprojects (El-Sabek and McCabe 2018). That supports the results of this study, in which R25 was ranked sixth for cost performance and fifth for schedule performance. To address this risk, most current commercial BIM platforms aim at achieving better collaboration in terms of design coordination, review, and issue management (Lai et al. 2019).

Project-Based Survey

Table 8 presents the characteristics of the collected data from 65 projects.

Because the collected project data incorporated multiple project sectors, delivery methods, and contract types, two-tailed t-tests were performed between each two sets of these distinctive characteristics, assuming unequal variances (Table 9). All p-values were more than 0.05, resulting in failure to reject the null hypothesis. Therefore, it can be concluded that there is no evidence of statistically significant differences between the means of different project sectors, delivery methods, or contract types. This finding provides confidence in the proposed cost and schedule prediction models.

Table 9. Two-tailed t-test results based on data from different project sectors, delivery methods, and contract types

Comparison	Variance	Hypothesized mean difference	Degrees of freedom	t statistic	$P(T \leq t)$ two-tailed
Project sector					
Cost data					
Building and commercial versus industrial					
Building and commercial	82.177	0	14	−2.030	0.062
Industrial	51.571	—	—	—	—
Building and commercial versus infrastructure					
Building and commercial	82.177	0	8	−1.912	0.092
Infrastructure	16.607	—	—	—	—
Industrial versus infrastructure					
Industrial	51.571	0	10	0.347	0.736
Infrastructure	16.607	—	—	—	—
Schedule data					
Building and commercial versus industrial					
Building and commercial	72.077	0	17	−0.881	0.391
Industrial	54.857	—	—	—	—
Building and commercial versus infrastructure					
Building and commercial	72.077	0	15	−0.619	0.545
Infrastructure	6.962	—	—	—	—
Industrial versus infrastructure					
Industrial	54.857	0	10	0.488	0.636
Infrastructure	6.962	—	—	—	—
Delivery method					
Cost data					
Separate contract (DBB, CMAR)	3.846	0	38	1.424	0.163
Collaborative contract (DB, EPC, IPD)	83.259	—	—	—	—
Schedule data					
Separate contract (DBB, CMAR)	4.300	0	23	−0.699	0.491
Collaborative contract (DB, EPC, IPD)	69.438	—	—	—	—
Contract type					
Cost data					
GMP	82.962	0	27	−1.957	0.061
Lump sum	38.770	—	—	—	—
Schedule data					
GMP	37.012	0	17	0.628	0.539
Lum p sum	81.273	—	—	—	—

Note: GMP = guaranteed maximum price.

Table 10. Summary of proposed distributions to fit cost and schedule data

	p-value	
Distribution	Cost	Schedule
Beta	0.236	0.086
Gumbel	<0.0001	<0.0001
Logistic	0.402	0.309
Normal	0.075	0.230
Normal (standard)	<0.0001	<0.0001
Student	<0.0001	0.049

Table 11. Evaluation metrics for logistic and normal fitted distributions

Data	Distribution	Log-likelihood	AIC	BIC
Cost	Logistic	−138.5287	281.0574	284.4351
	Normal	−141.1725	286.3449	289.7227
Schedule	Logistic	−84.90511	173.8102	176.248
	Normal	−85.03812	174.0762	176.514

Table 12. Estimated parameters of logistic distribution for cost and schedule data

Distribution	Parameter	Value	Standard error
Cost	μ	−4.523	0.634
	s	4.167	0.448
Schedule	μ	−0.538	1.398
	s	4.036	0.681

Distribution Fitting of Collected Project Data

Collaborative planning data were collected from 65 projects; 40 projects examined the project cost performance, and 25 projects examined the schedule performance. Table 10 presents the goodness-of-fit test results for the tested distributions.

The model candidates were logistic, normal, and beta distributions, because their corresponding p-values were more than 0.05. Because a beta distribution can plot values only from 0 to 1, it was not considered further in the analysis because the obtained data had negative values, such as for cost and schedule savings. Therefore, the logistic and normal distributions were investigated using the log-likelihood, AIC, and BIC model evaluation metrics (Table 11).

The logistic distribution was considered to be the best fit for the cost and schedule data because it had lower AIC and BIC values and higher log-likelihood values. Table 12 presents the obtained logistic distribution parameters for the cost and schedule data.

Fig. 3 illustrates the associated histograms and cumulative histograms of this distribution. Truncation was conducted on the fitted distribution to ensure that the distribution range properly reflected the obtained data. The fitted logistic distribution provides a range of values for the project cost and schedule performance that can be used for the proposed framework with respect to the identified collaborative planning risks. The main research hypothesis was confirmed with the collected project data: by applying collaborative planning in projects in the AEC industry, the realized benefits can be represented quantitatively in terms of cost and schedule savings in the project budget and duration, respectively.

Performance Prediction Framework

By combining the obtained risk weights and the logistic models, the proposed framework provides a reliable prediction of the project cost and schedule performance. The following subsections present the details of the verification and validation process of this research.

Verification of Proposed Framework

The developed cost and schedule models were verified mathematically using the extreme condition test and sensitivity analysis (Zhuang 2014). For the extreme condition test, because the cost and schedule criticalities ranged from 1 to 25, the extreme conditions were set at 1 and 25, respectively. Because the value of the cost and schedule criticality was 1 for all risks, the corresponding WRC for the cost and schedule impacts was 0. Therefore, the cost and schedule prediction values were −34 and −20, respectively. These values represent the minimum possible values for this variable based on the fitted distributions and collected project data. Similarly, because the value of the cost and schedule criticality was 25 for all risks, the corresponding WRC for the cost and schedule impacts was 1. Therefore, the cost and schedule prediction values were 10 and 12.66, respectively, which also represent the maximum possible values based on the collected project data. It is concluded that the prediction values, as a result of the extreme condition test, match the extreme values of the inputs.

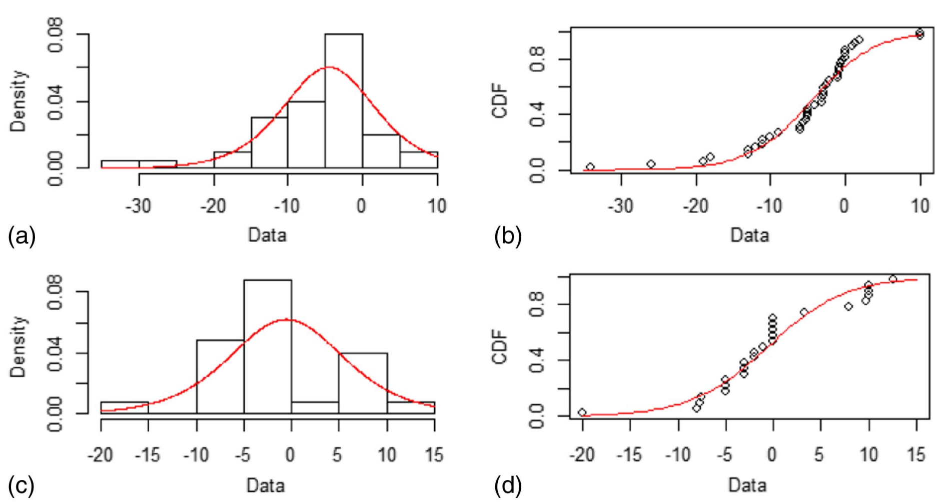
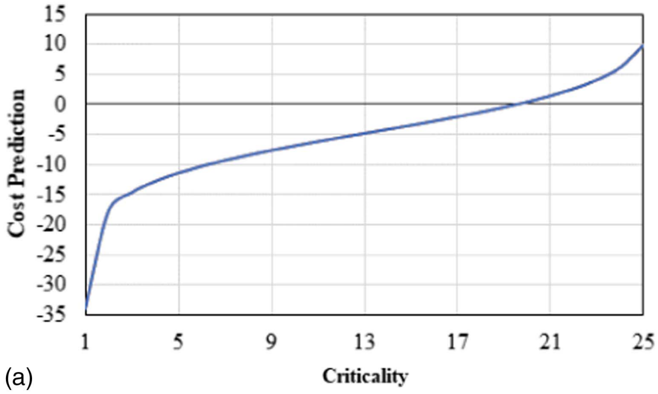
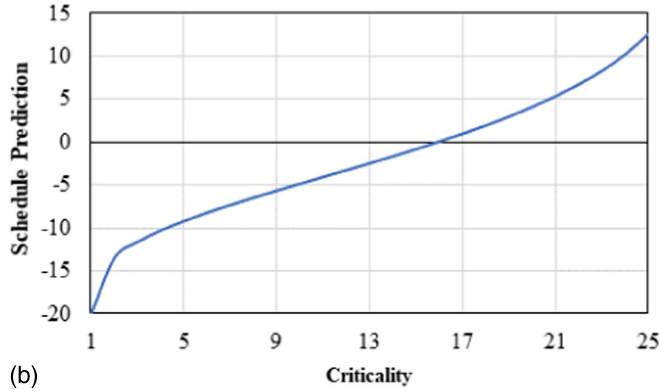


Fig. 3. Logistic distribution: (a) histogram of cost data; (b) cumulative histogram of cost data; (c) histogram of schedule data; and (d) cumulative histogram of schedule data.



(a)



(b)

Fig. 4. Sensitivity analysis: (a) cost performance prediction; and (b) schedule performance prediction.

Sensitivity analysis also was conducted on both the cost and schedule performance prediction models by assuming that all risks had the same criticality value in every iteration. The cost and schedule criticality started with a value of 1 and the corresponding prediction values were computed. The criticality was increased in increments of 1 until it reached the maximum value, 25, and the corresponding prediction values were computed (Fig. 4). The results of the extreme value test and sensitivity analysis indicated that the developed models were consistent and working as intended to predict the project cost and schedule performance. Therefore, the proposed framework is deemed to be valuable in forecasting the project cost and schedule performance with respect to the identified risks.

Validation of Proposed Framework

The validation process of this research included two steps. Firstly, a case study example is presented. Based on the user inputs of the likelihood and cost and schedule impacts of the case study risks, the cost and schedule criticality of these risks were computed (Table 13), and summarized results were produced by the proposed framework (Fig. 5).

For this case study, the framework provided a cost performance prediction of 13.52% savings in the project budget, compared with the industry average of 13.26% savings in the project budget. Similarly, the framework provided a schedule performance prediction of 10.82% savings in the project duration, compared with the industry average of 10.59% savings in the project duration. For the

Table 13. Criticality and weights of case study risks

	Cost			Schedule		
Risks	User	Industry average	Weights used	User	Industry average	Weights used
R1	3.00	3.38	0.028	3.00	3.30	0.027
R2	3.00	3.46	0.023	3.00	3.54	0.024
R3	3.00	3.00	0.019	3.00	3.30	0.021
R4	7.00	5.90	0.017	7.00	6.00	0.018
R5	3.50	3.73	0.024	3.50	3.70	0.024
R6	3.00	3.59	0.024	3.00	3.62	0.024
R7	3.50	3.05	0.019	3.50	3.08	0.019
R8	6.00	7.02	0.027	6.00	7.18	0.028
R9	2.00	2.78	0.014	2.00	2.86	0.014
R10	3.50	3.32	0.023	3.50	3.27	0.022
R11	3.50	3.68	0.027	3.50	3.73	0.027
R12	3.00	3.11	0.022	3.00	3.14	0.022
R13	2.50	3.19	0.020	2.50	3.27	0.020
R14	3.50	3.30	0.022	3.50	3.57	0.023
R15	2.00	2.22	0.010	2.00	2.22	0.010
R16	3.00	3.24	0.020	3.00	3.27	0.020
R17	2.50	2.24	0.011	2.50	2.19	0.010
R18	5.00	6.70	0.020	5.00	6.82	0.020
R19	3.00	3.11	0.020	3.00	3.14	0.020
R20	2.50	2.97	0.019	2.50	3.00	0.019
R21	3.50	3.41	0.021	3.50	3.41	0.021
R22	3.00	2.97	0.019	3.00	2.97	0.019
R23	3.50	2.35	0.013	3.50	2.35	0.013
R24	3.00	2.97	0.018	3.00	2.89	0.017
R25	5.00	7.08	0.024	5.00	7.08	0.024
R26	2.50	3.24	0.021	2.50	3.32	0.021
R27	6.00	6.90	0.012	6.00	7.14	0.013
R28	3.50	3.89	0.028	3.50	3.76	0.027
R29	2.00	2.78	0.019	2.00	2.65	0.018

Table 13. (*Continued.*)

Risks	Cost			Schedule		
	User	Industry average	Weights used	User	Industry average	Weights used
R30	3.00	2.86	0.018	3.00	2.86	0.018
R31	2.00	2.62	0.016	2.00	2.68	0.017
R32	3.50	3.38	0.022	3.50	3.14	0.020
R33	3.50	3.27	0.023	3.50	3.51	0.024
R34	3.00	3.03	0.020	3.00	3.03	0.020
R35	9.00	8.43	0.018	9.00	8.43	0.017
R36	3.50	3.54	0.022	3.50	3.41	0.021
R37	2.50	2.92	0.019	2.50	3.22	0.020
R38	3.00	3.27	0.021	3.00	3.35	0.021
R39	4.00	3.08	0.019	4.00	3.11	0.019
R40	3.50	3.11	0.017	3.50	3.22	0.018
R41	3.50	2.62	0.017	3.50	2.70	0.017
R42	3.00	2.68	0.016	3.00	3.24	0.019
R43	3.50	2.51	0.015	3.50	2.51	0.014
R44	4.00	3.19	0.020	4.00	3.08	0.019
R45	4.00	3.16	0.020	4.00	3.05	0.019
R46	7.00	6.76	0.022	7.00	6.22	0.020
R47	3.00	3.51	0.024	3.00	3.43	0.024
R48	2.50	3.32	0.022	2.50	3.30	0.022
R49	3.00	3.11	0.019	3.00	3.22	0.019
R50	3.00	3.32	0.023	3.00	3.27	0.022
Savings (%)						
User	13.52	—	—	10.82	—	—
Industry average	13.26	—	—	10.59	—	—

studied project, based on the user inputs, the top five risks were highlighted in terms of cost and schedule criticality. The project team mentioned that the results of the prediction framework were realistic compared with the actual project performance. Moreover, the top five critical risks highlighted by the framework were considered to be some of the key issues that the project was experiencing. The following sample comments were obtained from the case study team:

- "Overall, I think this tool would be good to issues throughout various points of the project. It would help identify any trends, or current issues and resolve them quickly."
- "With the weight adjustments, I think the tool would produce the correct results. Collaborative Planning has more to do with the individuals on the team than the outside factors such as technology and contractual items. Without the right team the other factors don't matter."

The top five critical risks highlighted after using the framework vary from project to project. Therefore, the user is expected in all cases to address these risks promptly to enhance the performance of their project. Moreover, the framework has multiple features, and the user can view detailed results of the risks, tailored recommended strategies based on the risks selected, save their results to view them later, or clear all inputs and start again.

For the second validation step, the study results were validated practically using the input of 25 subject matter experts. Table 14 presents information about the experts who validated the proposed framework.

All experts highlighted the applicability and benefits in evaluating and predicting the project cost and schedule as result of collaborative planning, and they provided some constructive remarks. For example, it was mentioned that multiple team members should provide their input to this framework, and there is a need to aggregate their individual results in a way that maintains the confidentiality of who provided which input. A random number generator for saving the individual results was considered to be the most viable solution in that case. Consequently, the revised framework incorporates an additional feature to aggregate such results into one consolidated output to enable team discussion of the existing risks after accounting for the inputs of each team member.

Thus, in case the project team cannot provide their inputs collaboratively, the added feature can load saved results of multiple users for the same project and provide aggregated results based on the overall inputs. This feature also provides the number of users who provided their input and divides this by the total number of possible project users to present an overall team response rate, which provides confidence in the aggregated results.

Because all comments and feedback obtained on the framework already have been addressed and the subject matter experts have indicated their satisfaction, and bearing in mind the aforementioned results of the mathematical verification step, it can be concluded that the proposed framework is effective and efficient in attaining its goal and objectives.

Contributions of Proposed Framework

Theoretical Additions

Based on the collective input of expert and project data, this research successfully (1) evaluated the criticality of a holistic list of collaborative planning risks and calculated the weight of each risk, (2) statistically analyzed the impact of these risks using distribution fitting analysis as well as weighted average calculations, (3) highlighted the top collaborative planning risks that impact cost and schedule performance of AEC projects, and (4) developed a comprehensive framework that measures the project cost and schedule performance as result of collaborative planning.

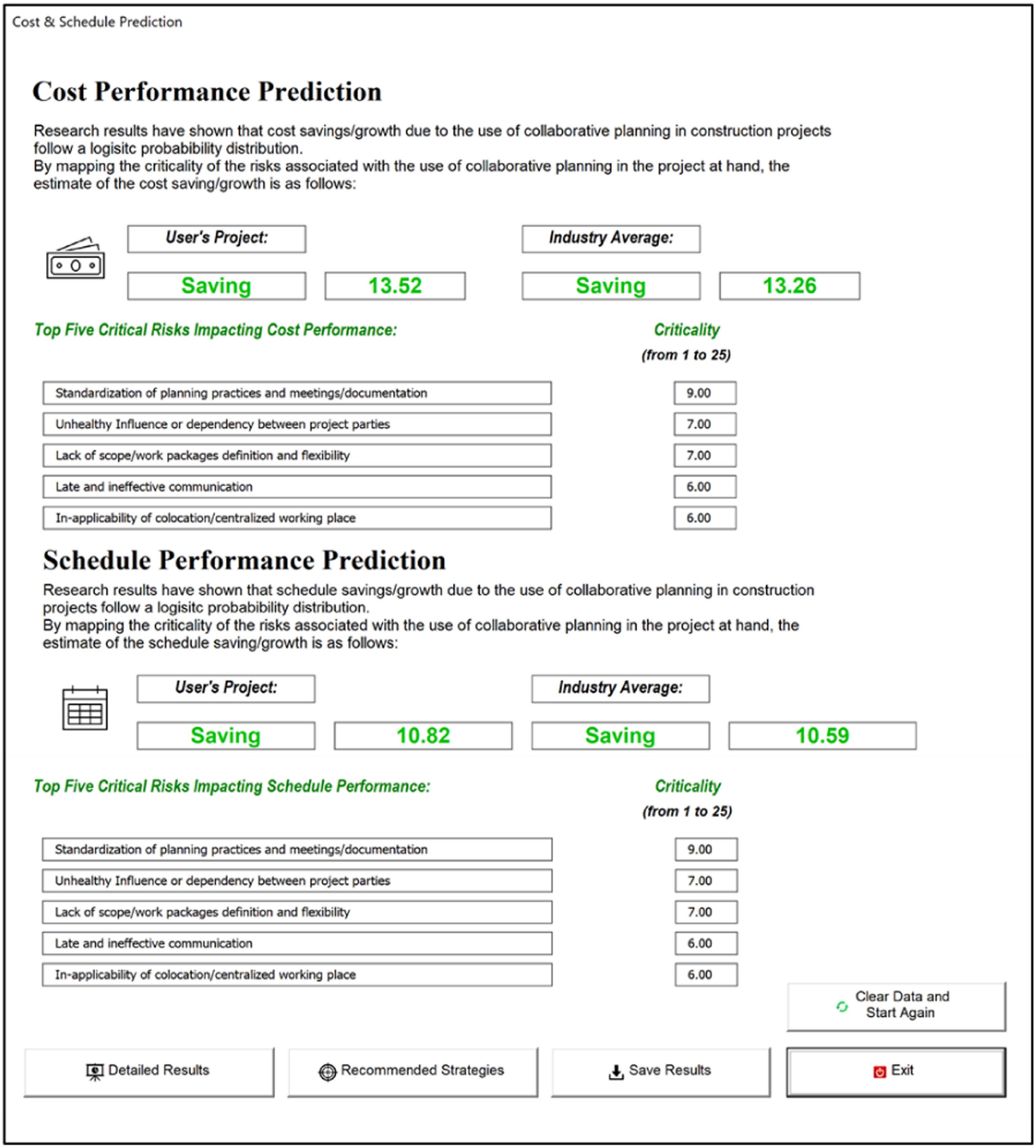


Fig. 5. Snapshot of the case study results for the performance prediction framework.

Practical Additions

For collaborative planning practices, the proposed framework is capable of pointing out aspects that requires immediate attention in AEC projects, and providing tailored recommended strategies to enhance the project performance.

Using the proposed framework in the beginning of an AEC project should yield the greatest benefits in detecting and addressing the critical project risks. Thus, users are advised to utilize the proposed framework in the initial project phase to realize its full potential and enable taking proactive measures against critical risks in their projects. The proposed framework has the capability to demonstrate the individual risk and overall performance of the studied project in contrast with an industry average performance. The top five critical risks are highlighted for the user, and the

Table 14. Information summary of subject matter experts

Characteristic	Category	Count
Role and position	Top management executive	10
	Project manager/engineer	15
Construction experience (years)	<10	4
	10–20	6
	>20	15
Industry sector[a]	Commercial	4
	Industrial	5
	Infrastructure	3
	Residential	5

[a]Firms can work in multiple industry sectors.

framework proposes tailored recommended strategies for the studied project. The user is advised to apply the recommended strategies and revisit the framework to measure the progress with respect to such risks. Moreover, the user should revisit the framework when there are new project risks, or when the criticality of risks varies with the project development. The user is provided with a detailed report of the results based on their inputs. Therefore, the proposed framework shows how effective collaborative planning practices are being implemented in terms of predicting the corresponding project cost and schedule savings. Moreover, a tailored user experience allows the selection of the relevant project risks, and the weights are reallocated automatically by the proposed framework, which ensures that the new weights sum to 1.

The proposed framework highlights the critical risks and proposes tailored strategies to address and manage these risks. For example, if the lack of lean construction adoption and awareness risk (R29) is evident in the studied project and there is a cost or schedule growth estimate, the framework provides necessary action items during project execution to address this risk directly, as in the following examples:

- The project team should check and validate the effectiveness of the scheduling tool used and how frequent the schedule is updated. The project team should use, when appropriate, innovative, and effective tools on the project such as the Last Planner System (LPS).
- The project team should adopt and apply lean construction to promote waste reduction and increase the efficiency of project implementation.

After employing these proposed recommendations, the user should revisit the framework to evaluate the progress that occurred regarding the existing risks.

Limitations and Future Work

The study focused is mainly on the building and commercial project sector, which represents the majority of the collected data. Future work should collect more project data representing each project sector to facilitate developing customized versions of the proposed framework to address the specific needs of each project sector. Additionally, the process of collecting project data yielded a limited number of relevant projects, which is analogous to prior research work with a similar focus. Therefore, more project data should be collected and used as further validation of the results of this research. Researchers are also recommended to perform modeling using system dynamics of the obtained project data, which will enable retrospective and prospective quantitative assessment of numerous collaborative planning parameters and the corresponding project performance (Abotaleb and El-adaway 2018).

Conclusion

Despite the promising prospects of implementing collaborative planning in projects in the AEC industry, practitioners still are facing significant risks that impact the performance of their projects as related to collaborative planning. This paper filled this knowledge gap.

The research findings present the different perceptions of project stakeholders of the risks associated with collaborative planning risks in terms of their criticality to project cost and schedule performance. The top six risks, that impact the cost and schedule performance, are resistance to change, no early involvement of key project participants, lack of construction coordination, late and ineffective communication, lack of leadership, and absence of flexibility and coordination of design. This study extensively discussed these top risks to better understand and proactively manage such risks in AEC projects. Moreover, Spearman rank correlation analysis was conducted on the obtained responses based on the three respondent categories, and it was concluded that there was a reasonable level of consensus on the rankings of the risks in terms of their cost and schedule criticalities. These risks were analyzed statistically using distribution fitting analysis and weighted average calculations. Furthermore, the results showed that there is no statistically significant difference in cost and schedule performance based on project sector, delivery method, and contract type. The research steps were verified mathematically using the extreme condition test and sensitivity analysis, and the results of both tests concluded that the developed models are consistent and work as intended to predict the project cost and schedule performance. Moreover, the research output was validated practically with a case study example and using the insights of 25 industry experts who were associated with notable AEC stakeholders. The case study was a large infrastructure project in the US. The project team utilized the proposed framework, and then shared the obtained results and their feedback. The project team considered the framework results to be realistic compared with issues that the case study project was experiencing in terms of collaborative planning risks.

This research offers a unique holistic framework for industry practitioners that enables prediction of the project cost and schedule performance based on the existing collaborative planning risks in their respective projects and compares that with the industry average performance. This research makes substantial theoretical contributions by highlighting and discussing the critical risks that affect construction collaborative planning and proposing a framework that evaluates and predicts project cost and schedule performance in the AEC industry. This research has practical implications for industry practitioners; it provides a tailored decision-making experience that allows selection of relevant project risks, highlights the top risks in their respective projects that require immediate attention, and provides tailored recommended strategies to enhance the collaborative planning practices.

The research outcomes are considered to be distinctive in linking the collaborative planning risks with the project cost and schedule performance. Ultimately, the established framework offers a vital instrument for projects in the AEC industry to improve project performance.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

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