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A Decision-Support Tool for Risk and Complexity Assessment and Visualization in Construction Projects

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ABSTRACT

Risk assessment in projects requires the integration of various information on project characteristics as well as external and internal sources of uncertainty and is based on assumptions about future and project vulnerability. Complexity is a major source of uncertainty that decreases the predictability of project outputs. In this research, the aim was to develop a decision-support tool that can estimate the level of risk and required contingency in a project by assessment of complexity factors as well as contextual information such as contract conditions and mitigation strategies. A process model and a tool were developed using the data of 11 mega construction projects. The tool was tested on a real project, and promising results were obtained about its usability. The tool has the potential to support decision-making during bidding in construction projects with its visualization and prediction features. On the other hand, as a limited number of cases and experts were involved in this study, findings on its performance cannot be generalized. The identified complexity and risk factors, proposed process model, and visual representations may help the development of similar decision-support tools according to different company needs.

Keywords: Project management, Risk, Complexity, Contingency, Visualization

1. Introduction

Uncertainty, as an inherent characteristic of projects, shall be assessed and managed to ensure project success. From the project management perspective, risk is an uncertain event or condition that may affect the project objectives (PMI, 2021). Internal uncertainties such as vagueness of project conditions and external uncertainties due to unstable social and economic conditions constitute major sources of risk in projects. Project risk management is concerned with the identification of uncertainties, assessment of their possible impacts on the project, and developing strategies to reduce/eliminate risks and maximize opportunities. For this purpose, risk models are developed to simulate the behavior of projects under different scenarios, and mitigation strategies are formulated considering the outputs of a risk model. Risk modeling requires the integration of information on several project characteristics as well as external factors where the complexity of the project may create uncertainty about its behavior. There are several sources of complexity that may have varying impacts on the project performance

(Kermanshachi et al., 2020). Thus, complexity assessment appears to be an indispensable part of risk management.

There are different opinions in the project management literature regarding the relationship between concepts such as uncertainty, risk, and complexity (Dao et al., 2017; Padalkar & Gopinath, 2016). According to Vidal and Marle (2008), complexity makes it difficult to perceive, predict and control the behavior of the project even with sufficient information. Dao et al. (2016) assert that project complexity is related to known factors requiring special effort to keep project risks under control. Qazi et al. (2016) also associate complexity with known attributes of the project that may lead to risks. For example, although the number of stakeholders involved in a project is known at the commencement stage, the complexity of their interactions can affect the project objectives and thus create uncertainty. Uncertainty is recognized as a consequence of project complexity based on the argument that complexity may result in a more unpredictable/uncertain project system (Floricel et al., 2016; Vidal & Marle, 2008). Contrary to this view, some researchers consider uncertainty a driver of project complexity since it may lead to dynamic interactions that increase the overall complexity level in the project system (Dunović et al., 2014; Geraldi et al., 2011). Regardless of the perspective adopted, it is evident that complexity has direct or indirect effects on risks and should be considered during risk modeling and management. There is a need for new approaches that can integrate complexity factors into the risk management process (Erol et al., 2020; Kardes et al., 2013; Thomé et al., 2016).

Taroun (2014) proposes that obtaining a realistic project risk level requires an effective mechanism and simple analytical tools. From this point of view, this paper aims to develop a process model and a tool that can be used to assess risks in a project considering project complexity. Risk and complexity assessment is necessary to give decisions regarding the project, such as selection of methods/technologies, scheduling, cost estimation, formulation of proactive risk mitigation strategies, and determination of contingency. In this paper, the focus is on the estimation of contingency in construction projects considering both project complexity and risks at the bidding stage, as will be discussed in the forthcoming sections.

2. State of the art

Risk management is a structured and iterative process of risk identification, qualitative and quantitative assessment (analysis), response generation, and monitoring. The risk management process starts at the initial stages of a project, such as feasibility and/or bid preparation, continues throughout the project realization, and is a part of the post-project evaluation to enable learning from actual risks. In project-based industries, better project management that also includes successful risk management processes is conceptualized as a driver of project success and lower risk (Sanchez et al., 2020). In the construction industry, instruments for project risk management have been proposed to better respond to risks and opportunities at different stages of the project's life-cycle (Arena et al., 2013). Construction companies carry out risk assessment at the bidding stage to determine an appropriate contingency and a bid mark-up. The primary purpose of contingency is to allocate a reserve to offset the risk of spending beyond the estimated project cost (Ford, 2002). Determination of an appropriate contingency is a critical success factor for construction companies because if the contingency is set too high to stay on the safe side, winning the tender will be less likely. On the other hand, setting a low contingency may cause financial problems for the contractor if risks occur (Farooq et al., 2018). Therefore, using a decision support tool for risk assessment may enable project management companies to prepare more competitive bids (Alquier & Tignol, 2007), and there are various methods proposed in the literature for this purpose.

Risk assessment is a knowledge-intensive process (Dikmen et al., 2008; Xing et al., 2019). When probabilistic data exists, Monte Carlo simulation is widely used to estimate contingency (Cooper and Chapman 1987; Barraza and Bueno 2007; Panthi et al., 2009). The logic behind this method is to allocate project contingency by simulating the overall impact of risks with probability distributions assigned to each risk-prone variable in the project. Gu et al. (2011) proposed the hierarchy probability cost analysis model and utilized Monte Carlo simulation for managing contingency according to the work breakdown structures of EPC projects. Computer-based simulations, in general, can be used to estimate the cost of the projects through historical data (Chou et al., 2009). Other data-driven methods such as correlation and regression analysis can also be used for this purpose (Sonmez et al., 2007). In addition to these probabilistic and statistical approaches, fuzzy sets that convert the linguistic variables into mathematical measures have also been utilized for risk-price estimation (Salah & Moselhi, 2016). In particular, fuzzy expert systems have been developed to support decision-making under uncertainty and/or vagueness. For instance, Idrus et al. (2011) proposed a risk analysis model that incorporates the experience and judgment of contractors through a fuzzy methodology. Moreover, fuzzy logic can be integrated into the knowledge-based expert systems to assess cost overrun risks, which enhances the prediction of accurate contingency amounts for contractors in the planning stage (Islam et al., 2019). Since risk management itself involves perspectives of multiple decision-makers and multiple aspects from different levels, risk assessment can also be approached as multi-criteria decision-making (MDCM) problem (Ebrahimnejad et al., 2010; Wang et al., 2022). For instance, Erol et al. (2022) developed a risk assessment model using Analytic Network Process (ANP) to investigate the interactions between risk-related concepts in mega construction projects.

As a computer-based contingency estimation method, Jung et al. (2016) proposed a tool based on analysis of the contract change status and project cost overrun risks, thus can be used to estimate cost contingency. Similarly, Chou (2009) developed a web-based case-based reasoning system for early cost budgeting using available information from previous projects. Moreover, there are several commercially available risk analysis software (Leopoulos et al., 2007) as well as tools developed by researchers in the project management domain (Cañizares et al., 2022; Han et al., 2008; Okudan et al., 2021; Yildiz et al., 2014) for contingency estimation. However, none of these directly evaluates the complexity-induced risks during the project contingency calculation.

Although various quantitative methods and tools have been proposed in the literature, the utilization level of analytical methods such as Monte Carlo Simulation is rather low in the construction industry (Senesi et al., 2015). Construction companies usually assess the level of risk in a project using risk matrices and use their subjective judgments while deciding on contingency. It is a common practice in the construction industry that experts assess risks by assigning Probability (P) and Impact (I) values and calculating PxI to identify the overall risk rating of the project. PxI values of risks are usually assigned using predetermined likelihood and impact scales to reflect the subjective judgments of risk experts. When visualized in risk matrices, these risk scores are used to make sense of the level of risk in a project, and the overall risk level is referenced for the estimation of project contingency. Although extensively used in practice, this traditional qualitative method fails to take into account the interrelations between risk factors clearly, and assumptions behind ratings about mitigation strategies, contract conditions, risk allocation, etc., are not revealed (Qazi and Dikmen, 2021). Furthermore, subjective probabilities based on expert judgment demonstrate a “degree of belief” about an uncertain issue based on personal experience and values (Aven, 2016). These judgments are conditional on a specific background knowledge, which covers data, information, and justified beliefs often formulated as assumptions. If subjective probabilities are used to express uncertainties, the information behind the probabilities should be clearly reflected so that the risk assessment results can be interpreted correctly. Taroun (2014) argues that traditional risk assessment methods based on probability and impact ratings cannot reflect the true nature of risk, especially under high complexity and alternative methods are necessary to assess complexity-induced risks. Better ways to quantify and visualize risk ratings as well as analytical models to link risk ratings with performance measures, such as contingency, are needed.

There is a need to fill the research gap by developing a practical tool that estimates project contingency considering complexity-induced risks as well as background knowledge and visualizes risk-related information, which constitutes the major aim of this study.

3. Research scope and objectives

The aim of this research is to develop a tool that can estimate cost contingency by assessment of risks considering complexity factors in a construction project. For this purpose, subjective ratings assigned by experts are utilized to estimate risk and contingency, and contextual information on risk-complexity relationships, assumptions, and contract conditions are visualized so that a decision-maker can make sense of the alternative scenarios and their impacts. The importance of the formalization of information with visual representations during risk identification and assessment has been proposed by various researchers (Eppler and Aeschimann, 2009; Kamsu-Foguem and Tiako, 2017). Thus, this study envisions not to limit the risk assessment to PxI values but to integrate with complexity-related information and expected contingency values by means of visualization.

The tool is expected to support the decision-making process of users by:

i. Communication of risk and complexity information: Visualization of relations between complexity and risk factors as well as background information behind subjective ratings.

ii. Prediction of cost contingency: Assessment of complexity-induced risks and estimation of cost contingency.

For this purpose, first, a process model was developed, and then a tool was designed to improve the risk-informed decision-making process during bidding. The developed tool is expected to be used during risk identification workshops to integrate all risk and complexity-related information considered during brainstorming sessions to better estimate cost contingency.

4. Research design and methodology

This study pursued four stages to develop a tool that quantifies cost contingency by assessing complexity and risk. The first stage followed a mixed-method research approach through semi-structured interviews with 18 senior-level project managers to understand the risk-complexity relationship. The second stage covered the development of a risk-complexity assessment process model through the analysis of interview transcripts. The third stage operationalized the proposed risk-complexity assessment process through the development of a Project Risk and Complexity Visualization Tool (PRICOVIS), and the final stage tested and verified the tool through real cases (see Fig. 1).

Fig. 1: Research steps

A brief explanation of each step is depicted as follows:

i. First, an exploratory analysis was performed through interviews with 18 project managers working on 11 different projects (Erol et al., 2020). In order to determine the projects suitable for this research, public documents, press releases, company reports, and internet sources were investigated. As a result of this process, 50 candidate megaprojects that have been carried out by Turkish contractors in the last 20 years were listed. Then, 32 companies engaged in these projects were contacted by e-mail. In the end, eight companies involved in 11 mega construction projects participated in the study, resulting in an acceptable sampling rate. The research data were collected from the senior managers of these projects. Interviews, which spread over nine months, were composed of two major sections where both open-ended (semi-structured) and close-ended (survey) questions were asked. A substantial amount of interview-related data was acquired at this stage to explore the complexity-risk relationship. A range of projects with different characteristics and types were targeted to satisfy data diversity. Project types include transport infrastructure, pipeline, power plant, hospital, and airport. Six projects were undertaken by joint ventures or consortiums, while the remaining projects did not have any partnership. Three of them were public-private partnership (PPP) projects, and other projects had a variety of delivery systems and payment methods. At the time of the interviews, most of the projects had been completed recently, whereas three projects were in progress with a completion rate of more than 50%. Except for two international power plant projects constructed in Bahrain and Iraq, all projects were located in different regions of Turkey. The minimum and maximum size of the case projects were 0.3 billion USD and 7.5 billion USD, respectively. The audio-recorded interviews lasted between one and four hours. A mixed-method research approach was used to acquire both qualitative (interview transcriptions to explain the conceptual relationship of risk and complexity) and quantitative (numerical survey results to quantify the relationship) data. During the semi-structured interviews, the participants were required to evaluate eight categories of risk factors (e.g., financial risks, contractual risks) and seventeen complexity factors (e.g., cultural diversity, size of the project) and their impact on the overall project complexity for their projects. Quantitative data analysis led to the calculation of the magnitude of complexity factors and their contribution to the unpredictability of risk factors. More information about this step can be found in Erol et al. (2020). As a result, it was found that risks can be assessed by evaluating complexity, and identification of assumptions as well as management strategies constitute key components of the risk assessment process. Moreover, utilizing a grounded theory approach, open-ended questions about complexities and risk events experienced in projects were asked to the experts, and interview transcriptions were analyzed using QSR NVivo to understand the emergence of project complexity and risk. More information about the findings of qualitative data analysis can be found in Bilgin (2021).

ii. As the second step, a process model was developed using the identified complexity-risk relationship to reflect how complexity and risks shall be assessed and managed in practice. Integrated Risk Assessment Process (IRAP) uncovers the core components that should be taken into account during qualitative risk assessment and considers the dynamic interaction between risk and complexity. For more detailed information about IRAP, interested readers may consult Erol (2020); Erol et al. (2020, 2022).

iii. PRICOVIS was developed using the risk and complexity factors as well as relations identified with qualitative data analysis and operationalizing the proposed complexity-risk assessment process determined at the second step of the research. Horlick-Jones and Rosenhead (2002) pointed out the importance of understanding organizational risk management and capturing the real-world character of risk with ethnographic studies. In this study, based on experiences gained from previous projects via interviews, (i) a rule-based expert system to quantify the complexity-risk relationship was developed via expert panels, (ii) the cost contingency prediction method was enabled, and (iii) requirements of the tool were identified. The data of 11 projects served to determine the complexity and risk factors to be included in the tool and the rules explaining their relationships. Eliciting knowledge from the instances in the interviews is a useful method for rule-based expert systems design (Moody et al., 1996). For example, Lamersdorf et al. (2012) and Xie et al. (2022) utilized interview data to develop rule-based models in the area of project risk management. In this research, a similar inductive approach was used to define rules for estimation of risk, and expert panels were conducted to verify the rules. The tool was designed to reflect the project-based nature of the construction industry and provide a platform to take into account complexity, assumptions, and related background information (such as contract conditions) to assess risks and estimate cost contingency. PRICOVIS was developed as a standalone application for the assessment of complexity-induced risks and related contingencies. In order to protect company-private data, the platform is used through a web browser on the client-side, where no data is stored on a server. While all the specifications and deliverables were set initially, frequent meetings and testing were performed to adhere to a transparent development process and provide room for improvements through short iterations.

iv. Finally, the testing and verification of the tool were performed using two methods. First, the data of 11 projects were used to verify that the rule-based expert system produces reliable results. Then, a case study application was designed to acquire insights from experts on the performance of the tool. The usability of the tool was tested with the participation of project management experts in an actual case project. Five experts and the research team held a meeting to test the tool and record the experts' comments and evaluations (Likert-scale evaluation). Tool's usability was tested, positive and negative aspects were determined, and the necessary revisions were made accordingly. While the first step verifies that the tool provides a structured process to uncover the risk-complexity situation in construction projects, the case study reflects how the risk-complexity assessment tool relates to the current risk management process in practice.

5. Research findings

5.1. About the relationship between complexity and risk

Data collected from 11 projects in the first stage of the research served to reveal the relationship between complexity and risk as well as to shed light on the nature of this relationship. According to the empirical findings, a high level of complexity makes it more difficult to predict the impact of risks. For instance, the unpredictability of the external risk factors, such as political, economic, and financial, were more closely associated with high environmental complexity. The qualitative analysis of the interview transcripts, on the other hand, further confirmed that complexity affects the emergence of risk events. The findings also revealed the roles of implemented strategies, project characteristics, and experience on the emergence of complexity-induced risk events.

5.2. Integrated Risk Assessment Process (IRAP)

Based on the findings of the first stage, an integrated approach, IRAP, was proposed to account for the links between complexity, uncertainty, management strategies, and risk concepts during the risk assessment. The first step of IRAP is the identification of the potential risk sources in the project. Besides the uncertainty, it incorporates complexity into the risk assessment process. At the beginning of the project, complexity factors, such as size, originality of design, and environmental constraints, can be identified by analyzing the known attributes of the project. Similarly, based on their knowledge and experience, project management teams can determine the uncertainty-related factors that may affect the project. The next step is formulating management strategies for the identified risk sources to reduce their negative impact on the project. However, as these strategies may trigger the emergence of new risks, IRAP includes an iterative process between the first two steps. This process results in a network that links risks to their sources and planned strategies. The last step of IRAP is analyzing the network to prioritize the risk sources, update the existing strategies, and develop high-level action plans, such as allocating a contingency reserve, to manage the overall impact of risks on the project. As the precautions taken as a consequence of the last step may introduce new risk sources into the project, previous steps are repeated through a feedback loop before finalizing the risk assessment. Furthermore, due to the dynamic nature of construction projects, IRAP should be repeated periodically to update the risk plan.

IRAP constitutes the theoretical base of the risk assessment process utilized during tool development. Accordingly, users are expected to initially assess the level of various complexity factors as sources of risk in the project. The strategies and other critical information about each factor shall be recorded as assumptions during the assessment process. Based on the magnitude of risks and project contingency calculated by the tool, complexity factors and related assumptions are allowed to be updated with an iterative process. Thus, the cyclic relationship between complexity and risk is also taken into account. The details of the tool are discussed in the next section.

5.3. PRICOVIS (Project Risk and Complexity Visualization Tool)

PRICOVIS is a web-based expert system that has been created to improve current risk management practices by enabling risk assessment based on project complexity factors, visualizing assumptions and background information, and finally producing a risk and complexity map that can be used by decision-makers while formulating strategies. It can be retrieved from the web **(note: the address is withheld due to the double anonymized review process)** and is free to use for the purposes of education and research.

PRICOVIS operationalizes the relationship between complexity and risk factors and enables the assessment of cost impacts and related contingencies based on the gathered knowledge through interviews and expert panels. First, qualitative data analysis using QSR NVivo was carried out with a total of 113320 words from the transcripts of the interviews. The analysis revealed contextual information related to complexity and risk concepts and their relationship. To elicit domain expertise and induce into a structured representation, expert knowledge elicitation sessions were performed with three experts. Experts involved in these sessions were experienced construction professionals (each having at least 20 years of experience in the construction industry and expertise in mega construction projects) who did not participate in the previous interviews on risk and complexity. The expert panels were moderated by the first author of this paper. During the panels, all complexity constructs were reinterpreted so that the hierarchy and relationship between the complexity factors could be represented and a rule-based system could be generated. The initial session led to the simplification of complexity constructs and the identification of categories of complexity factors, risk factors, and key influencing factors (e.g., experience) that affect the magnitude and manageability of risks. Complexity factors were grouped into six categories, as shown in Table 1. Six groups of risk factors were identified as scope and design risks, construction/technical risks, country risks, managerial risks, stakeholder/client risks, and contractual risks. The influencing factors were identified as project size and duration, and experience, including experience in similar projects, experience with country, and experience with stakeholders.

Table 1: Complexity factors in PRICOVIS

In the second session of expert knowledge elicitation sessions, lessons learned from the projects were expressed in terms of a set of variables to develop structure from instances, following an inductive approach. The identified variables include complexity factors (C_i), risk factors (R_i), experience (E_i), and exceptional size and duration of the project (S). The experience of project participants regarding the complexity and risk of projects were induced as simple rules. Table 2 shows an instance of rule development related to the financial risk, reflecting the relationship between complexity constructs. The rationality and relevancy of the rules were assessed and verified during the session.

Table 2: Rule Example

In the final session, the impact of presence/absence and level of complexity and influential factors on risks were assessed so that the patterns of judgments could be represented as an algorithm. Initially, three levels (low, medium, high) and equal weights were assumed for all influencing factors. Testing extreme scenarios and revisiting the expertise captured from the interviews, the levels and weights of the factors were reiterated until the experts were satisfied with the identified relationships. Finally, a rule-based system was developed in the form of clear IF (condition) THEN (action) rules using the following constructs with the given values:

- Complexity factors: (C_i) = C_1, C_2,…C_{33}, where C_i can take on three values (Yes = 1, Partial = 0.5, No = 0)
- Risk factors: (R_i) = R_1, R_2,…R_6, where R_i has five levels (very low, low, moderate, high, very high)
- Experience: (E) = E_1, E_2, E_3, where E_i can take on three values (Yes = 1, Partial = 0.5, No = 0)
- Exceptional size and duration of the project: (S), where S_i can take on two values (Yes = 1, No = 0)

A set of 26 rules was built in the form of single statements or multiple statements joined by "AND" or "OR" conditions. While some rule actions depend on values of single complexity factors, some rules take into account the weights of multiple complexity factors. For instance, the financial risk related rule presented in Table 2 was extended into the following actionable ruleset:

IF {C_{25}, OR C_{26}. OR C_{27} is yes, THEN R_5 is High,

{otherwise R_5 = Average (C_{25}, C_{26}, C_{27}), where {If $R_5 \leq 0.5$ Then R_5 is Low, Else R_5 is Moderate}}}

IF E_3 is no, THEN R_{5+}

IF E_3 is yes, THEN R_{5-}

IF S is yes, THEN R_{5+}

The rules were tested on 11 projects one by one, and consistent results were detected, matching with the risk ratings assigned by experts. Albeit acquiring acceptable results, it is acknowledged that the complexity-risk relationship might be different in other contexts (e.g., projects, companies, countries). Since the rules cannot be generalized for all projects, the tool was designed in a flexible way so that companies can update them according to their specific conditions or using their own project data. Hence, the logical process and rulesets were designed as simple statements so that they could be altered or expanded in the tool.

The process diagram of PRICOVIS is given in Fig. 2. As it can be seen from Fig. 2, first, the tool prompts the users to enter project-related information. Then, 33 complexity factors are presented to the users (See Table 1). Users assess the complexity factors using a 1-3 Likert scale. The tool uses this information along with the experience of the company and project size and duration to infer the risk ratings based on the rule-based expert system.

Fig. 2: Process diagram

Estimated risks are visualized as a bar chart. Then, cost impacts of risks are estimated by the decision-maker, and cost contingency is calculated by the tool based on these cost values. As the cost impact of project risks depends on factors such as assumptions on controllability and contract conditions, users are asked to specify the background information while assigning a cost to risk factors. After the project contingency is displayed, the user can consider changing the complexity levels by changing the assumptions and monitoring the results of these changes on cost contingency. After these iterations are over, the final step is a visual map showing all inputs and outputs of the assessment process. The following section demonstrates the utilization of PRICOVIS in an actual construction project.

6. Demonstrative case study

6.1. Information about the case study

PRICOVIS was used for risk assessment of a mega wastewater treatment project carried out in Turkey. The tool was used by the project team to assess complexities, estimate complexity-induced risks, predict project contingency, and develop risk management strategies. The project is one of the largest industrial wastewater treatment plants in the region constructed by the joint venture of two experienced construction companies. Some of the complexities in the project are originated from dependence on specific materials and equipment, strategic importance for the country that creates additional pressure for early completion, and expected revisions by the owner. Moreover, the contract had some vague conditions related to risk allocation between the parties on project revisions and progress payments.

The application was carried out with the involvement of five experts and four researchers from the research team. In the following section, details of the case study, outputs of the test application, and reviews of the experts will be explained.

6.2. Case project application

Five experts and the research team tested the usability of the tool and how it can be incorporated into current risk management procedures in a real construction project. Starting with the first screen, the participants shared project information and their technical reviews, such as the understandability of the tool's interface and the clarity of the questions.

Firstly, the experts evaluated the complexity levels of the project in six parts. While answering the questions, participants evaluated the complexities and stated their assumptions and background information that supports their assessments. The scope/design-related factors of the application can be seen in Fig. 3 as an example.

Fig. 3: Scope/design complexity inputs of the case project

The complexity-induced risks were calculated and presented to experts in the form of a bar chart, as seen in Fig. 4. The risks estimated by the tool were found appropriate by the experts, verifying the risk assessment methodology of the tool.

Fig. 4: Risk ratings in the case project

Lastly, the project contingency value was calculated by the estimated risk levels and the cost impacts entered by the users. Participants stated that the determined project contingency value is close to the actual/expected value. Also, at this stage, users reviewed their predictions and observed the effects of potential changes on contingency. Fig. 5 shows the final map.

Fig. 5: Risk-complexity map

The experts evaluated the overall performance of the tool on the Likert scale by considering criteria such as functionality, visuality, and level of integration to decision making. According to Table 3, the user satisfaction regarding all criteria was between 3 and 5 out of 5. In general, experts stated that PRICOVIS was practical and user-friendly, and its output was reliable and realistic. The visual map was informative for the team to better investigate complexities, risks, assumptions, contract conditions, and costs during the bidding stage of projects. It was recommended that PRICOVIS could be used as a tool during project risk assessment to visualize information about risks, encourage brainstorming among project participants, and conduct "what if" analysis for developing strategies to minimize risks.

Table 3: User evaluations in 5-point Likert-scale

7. Conclusions

Research findings demonstrate the relations between complexity, risk, and contextual factors such as strategies and contract conditions that affect contingency. Based on the findings from 11 projects, a process model to explain the risk and complexity assessment process was developed, and a tool, PRICOVIS, that integrates all related information and predicts cost contingency was built. PRICOVIS was tested by users, and its performance was verified in terms of its functionality, visuality, and level of integration to decision making. The study has several contributions to practice. The tool can be used in risk workshops during the bidding phase of construction projects and is expected to improve the quality of decisions by enhancing communication between decision-makers with the visualization of risk-related information. Users can create alternative scenarios and monitor the impact of assumptions, strategies, and complexity sources on the level of risk and amount of cost contingency. Confidence of decision-makers on estimated contingency is expected to increase due to a better understanding of risk context with visual representations and consideration of alternative scenarios.

It is believed that this study makes a contribution to the body of knowledge on project management by proposing a new process model that can be used to assess complexity-induced risks and estimate cost contingency. It also has contributions to the body of knowledge on the utilization of Information and Communication Technology (ICT) in the construction industry. PRICOVIS can be used as a tool to support risk-based decision-making in construction companies. Risk and complexity factors and visual representations identified in this research can be utilized to develop similar assessment models and visualization tools. Although the model is developed for cost contingency, it can be easily updated for other purposes such as delay estimation. However, it has to be noted that both the model and the tool have been developed based on data from a limited number of projects and the experience of a limited number of experts. The rules mainly reflect the lessons learned from 11 mega infrastructure projects during semi-structured interviews and knowledge elicitation sessions conducted with three experts; thus, they may not be applicable for all contexts. For this reason, the tool was developed as a flexible system where users can input their own rule-based algorithms. The usability of the tool was tested in a different project and proved to have a satisfactory level of performance. Although the tool's algorithm was developed based on a limited number of case projects and identified relationships between the variables cannot be generalized, it is believed that research findings may have practical contributions as they demonstrate how complexity and risk data can be integrated and visualized to support decision-making. The performance of PRICOVIS can be tested in the long run by comparing predicted values with actual values of several projects and getting the opinion of a higher number of experts to identify its strengths and weaknesses.

CRediT authorship contribution statement

Irem Dikmen: Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Software, Supervision, Validation, Writing - Original Draft, Writing - Review & Editing. **Guzide Atasoy:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Software, Validation, Writing - Original Draft. **Huseyin Erol:** Conceptualization, Formal analysis, Methodology, Software, Validation, Writing - Original Draft. **Hazal Deniz Kaya:** Formal analysis, Software, Validation, Writing - Original Draft. **M. Talat Birgonul:** Funding acquisition, Project administration, Supervision.

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.

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References

Alquier, A. M. B., & Tignol, M. H. L. (2007). Risk management in small- and medium-sized enterprises. *Production Planning & Control*, *17*(3), 273–282. https://doi.org/10.1080/09537280500285334

Arena, M., Azzone, G., Cagno, E., Ferretti, G., Prunotto, E., Silvestri, A., & Trucco, P. (2013). Integrated Risk Management through dynamic capabilities within project-based organizations: The Company Dynamic Response Map. *Risk Management*, *15*(1), 50–77. https://doi.org/10.1057/rm.2012.12

Aven, T. (2016). Risk assessment and risk management: Review of recent advances on their foundation. *European Journal of Operational Research*, *253*(1), 1–13. https://doi.org/10.1016/J.EJOR.2015.12.023

Barraza, G. A., & Bueno, R. A. (2007). Cost Contingency Management. J*ournal of Management in Engineering 23*(July), 140–146. https://doi.org/10.1061/(ASCE)0742-597X(2007)23:3(140)

Bilgin, G. (2021). An Exploratory Study on Complexity in Mega Construction Projects. [Master's thesis, Middle East Technical University]

Cañizares, P. C., Estévez-Martín, S., & Núñez, M. (2022). SINPA: SupportINg the automation of construction PlAnning. *Expert Systems with Applications*, *190*, 116149. https://doi.org/10.1016/J.ESWA.2021.116149

Chou, J. S. (2009). Web-based CBR system applied to early cost budgeting for pavement maintenance project. *Expert Systems with Applications*, *36*(2 PART 2), 2947–2960. https://doi.org/10.1016/J.ESWA.2008.01.025

Chou, J. S., Yang, I. T., & Chong, W. K. (2009). Probabilistic simulation for developing likelihood distribution of engineering project cost. *Automation in Construction*, *18*(5), 570–577. https://doi.org/10.1016/j.autcon.2008.12.001

Cooper, D., & Chapman, C. (1987). Risk Analysis for Large Systems. Wiley.

Dao, B., Kermanshachi, S., Shane, J., Anderson, S., & Hare, E. (2016). Identifying and Measuring Project Complexity. *Procedia Engineering*, *145*, 476–482. https://doi.org/10.1016/j.proeng.2016.04.024

Dao, B., Kermanshachi, S., Shane, J., Anderson, S., & Hare, E. (2017). Exploring and Assessing Project Complexity. *Journal of Construction Engineering and Management*, *143*(5), 04016126. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001275

Dikmen, I., Birgonul, M.T., Anac, C., Tah, J. H. M., & Aouad, G. (2008). Learning from risks: A tool for post-project risk assessment. *Automation in Construction*, *18*(1), 42–50. https://doi.org/10.1016/j.autcon.2008.04.008

Dunović, I. B., Radujković, M., & Škreb, K. A. (2014). Towards a New Model of Complexity – The Case of Large Infrastructure Projects. *Procedia - Social and Behavioral Sciences*, *119*, 730–738. https://doi.org/10.1016/J.SBSPRO.2014.03.082

Ebrahimnejad, S., Mousavi, S. M., & Seyrafianpour, H. (2010). Risk identification and assessment for build–operate–transfer projects: A fuzzy multi attribute decision making model. *Expert Systems with Applications*, *37*(1), 575–586. https://doi.org/10.1016/J.ESWA.2009.05.037

Eppler, M. J., & Aeschimann, M. (2009). A systematic framework for risk visualization in risk management and communication. *Risk Management*, *11*(2), 67–89. https://doi.org/10.1057/RM.2009.4

Erol, H. (2020). Incorporating Complexity into Risk Management: An Integrated Risk Assessment Process for Mega Construction Projects. [Doctoral dissertation, Middle East Technical University]

Erol, H., Dikmen, I., Atasoy, G., & Birgonul, M. T. (2020). Exploring the Relationship between Complexity and Risk in Megaconstruction Projects. *Journal of Construction Engineering and Management*, *146*(12), 04020138. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001946

Erol, H., Dikmen, I., Atasoy, G., & Birgonul, M. T. (2022). An analytic network process model for risk quantification of mega construction projects. *Expert Systems with Applications*, *191*, 116215. https://doi.org/10.1016/J.ESWA.2021.116215

Farooq, M. U., Thaheem, M. J., & Arshad, H. (2018). Improving the risk quantification under behavioural tendencies: A tale of construction projects. *International Journal of Project Management*, *36*(3), 414–428. https://doi.org/10.1016/J.IJPROMAN.2017.12.004

Floricel, S., Michela, J. L., & Piperca, S. (2016). Complexity, uncertainty-reduction strategies, and project performance. *International Journal of Project Management*, *34*(7), 1360–1383. https://doi.org/10.1016/J.IJPROMAN.2015.11.007

Ford, D. N. (2002). Achieving Multiple Project Objectives through Contingency Management. *Journal of Construction Engineering and Management*, *128*(1), 30–39. https://doi.org/10.1061/(ASCE)0733-9364(2002)128:1(30)

Geraldi, J., Maylor, H., & Williams, T. (2011). Now, let's make it really complex (complicated): A systematic review of the complexities of projects. *International Journal of Operations and Production Management*, *31*(9), 966–990. https://doi.org/10.1108/01443571111165848

Gu, X., Geng, Z., Xu, W., & Zhu, Q. (2011). Hierarchy probability cost analysis model incorporate MAIMS principle for EPC project cost estimation. *Expert Systems with Applications*, *38*(7), 8087–8098. https://doi.org/10.1016/J.ESWA.2010.12.150

Han, S. H., Kim, D. Y., Kim, H., & Jang, W. S. (2008). A web-based integrated system for international project risk management. *Automation in Construction*, *17*(3), 342–356. https://doi.org/10.1016/J.AUTCON.2007.05.012

Horlick-Jones, T., & Rosenhead, J. (2002). Investigating Risk, Organisations and Decision Support through Action Research. *Risk Management*, *4*(4), 45–63. https://doi.org/10.1057/PALGRAVE.RM.8240132

Idrus, A., Fadhil Nuruddin, M., & Rohman, M. A. (2011). Development of project cost contingency estimation model using risk analysis and fuzzy expert system. *Expert Systems with Applications*, *38*(3), 1501–1508. https://doi.org/10.1016/j.eswa.2010.07.061

Islam, M. S., Nepal, M. P., Skitmore, M., & Kabir, G. (2019). A knowledge-based expert system to assess power plant project cost overrun risks. *Expert Systems with Applications*, *136*, 12–32. https://doi.org/10.1016/J.ESWA.2019.06.030

Jung, J. H., Kim, D. Y., & Lee, H. K. (2016). The computer-based contingency estimation through analysis cost overrun risk of public construction project. *KSCE Journal of Civil Engineering*, *20*(4), 1119–1130. https://doi.org/10.1007/s12205-015-0184-8

Kamsu-Foguem, B., & Tiako, P. (2017). Risk information formalization with graphs. *Computers in Industry*, 85, 58–69. https://doi.org/10.1016/j.compind.2016.12.004

Kardes, I., Ozturk, A., Cavusgil, S. T., & Cavusgil, E. (2013). Managing global megaprojects: Complexity and risk management. *International Business Review*, *22*(6), 905–917. https://doi.org/10.1016/J.IBUSREV.2013.01.003

Kermanshachi, S., Rouhanizadeh, B., & Dao, B. (2020). Application of Delphi Method in Identifying, Ranking, and Weighting Project Complexity Indicators for Construction Projects. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *12*(1), 04519033. https://doi.org/10.1061/(ASCE)LA.1943-4170.0000338

Lamersdorf, A., Münch, J., del Viso Torre, A. F.-, Sánchez, C. R., Heinz, M., & Rombach, D. (2012). A rule-based model for customized risk identification and evaluation of task assignment alternatives in distributed software development projects. *Journal of Software: Evolution and*

Process, *24*(6), 661–675. https://doi.org/10.1002/smr.576

Leopoulos, V. N., Kirytopoulos, K. A., & Malandrakis, C. (2007). Risk management for SMEs: Tools to use and how. *Production Planning & Control*, *17*(3), 322–332. https://doi.org/10.1080/09537280500285136

Moody, J., Will, R. P., & Blanton, J. E. (1996). Enhancing knowledge elicitation using the cognitive interview. *Expert Systems with Applications*, *10*(1), 127–133. https://doi.org/10.1016/0957-4174(95)00039-9

Okudan, O., Budayan, C., & Dikmen, I. (2021). A knowledge-based risk management tool for construction projects using case-based reasoning. *Expert Systems with Applications*, *173*, 114776. https://doi.org/10.1016/J.ESWA.2021.114776

Padalkar, M., & Gopinath, S. (2016). Are complexity and uncertainty distinct concepts in project management? A taxonomical examination from literature. *International Journal of Project Management*, *34*(4), 688–700. https://doi.org/10.1016/J.IJPROMAN.2016.02.009

Panthi, K., Ahmed, S. M., & Ogunlana, S. O. (2009). Contingency estimation for construction projects through risk analysis. *International Journal of Construction Education and Research*, *5*(2), 79–94. https://doi.org/10.1080/15578770902952181

PMI (Project Management Institute) (2021) *The Standard for Project Management and A Guide to the Project Management Body of Knowledge: (PMBOK® Guide).* 7th ed. Newtown Square, PA: Project Management Institute.

Qazi, A., & Dikmen, I. (2021). From risk matrices to risk networks in construction projects. *IEEE Transactions on Engineering Management*, *68*(5), 1449–1460. https://doi.org/10.1109/TEM.2019.2907787

Qazi, A., Quigley, J., Dickson, A., & Kirytopoulos, K. (2016). Project Complexity and Risk Management (ProCRiM): Towards modelling project complexity driven risk paths in construction projects. *International Journal of Project Management*, *34*(7), 1183–1198. https://doi.org/10.1016/j.ijproman.2016.05.008

Salah, A., & Moselhi, O. (2016). Risk identification and assessment for engineering procurement construction management projects using fuzzy set theory. *Canadian Journal of Civil Engineering*, *43*(5), 429–442. https://doi.org/10.1139/cjce-2015-0154

Sanchez, F., Bonjour, E., Micaelli, J. P., & Monticolo, D. (2020) An Approach Based on Bayesian Network for Improving Project Management Maturity: An Application to Reduce Cost Overrun Risks in Engineering Projects. *Computers in Industry*, *119*, 103227. https://doi.org/10.1016/j.compind.2020.103227

Senesi, C., Javernick-Will, A., & Molenaar, K. R. (2015). Benefits and Barriers to Applying Probabilistic Risk Analysis on Engineering and Construction Projects. *Engineering Management Journal*, *27*(2), 49–57. https://doi.org/10.1080/10429247.2015.1035965

Sonmez, R., Ergin, A., & Birgonul, M. T. (2007). Quantitative Methodology for Determination of Cost. *Journal of Management in Engineering*, *23*(January), 35–39. https://doi.org/10.1061/(ASCE)0742-597X(2007)23:1(35)

Taroun, A. (2014). Towards a better modelling and assessment of construction risk: Insights from a literature review. *International Journal of Project Management*, *32*(1), 101–115. https://doi.org/10.1016/J.IJPROMAN.2013.03.004

Thomé, A. M. T., Scavarda, L. F., Scavarda, A., & Thomé, F. E. S. de S. (2016). Similarities and contrasts of complexity, uncertainty, risks, and resilience in supply chains and temporary multi-organization projects. *International Journal of Project Management*, *34*(7), 1328–1346. https://doi.org/10.1016/J.IJPROMAN.2015.10.012

Vidal, L. A., & Marle, F. (2008). Understanding project complexity: Implications on project management. *Kybernetes*, *37*(8), 1094–1110. https://doi.org/10.1108/03684920810884928

Wang, Z. C., Ran, Y., Chen, Y., Yang, X., & Zhang, G. (2022). Group risk assessment in failure mode and effects analysis using a hybrid probabilistic hesitant fuzzy linguistic MCDM method. *Expert Systems with Applications*, *188*, 116013. https://doi.org/10.1016/J.ESWA.2021.116013

Xie, H., Hong, Y., & Brilakis, I. (2022). Analysis of User Needs in Time-Related Risk Management for Holistic Project Understanding. *Journal of Construction Engineering and Management*, *148*(4), 05022002. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002241

Xing, X., Zhong, B., Luo, H., Li, H., & Wu, H. (2019). Ontology for safety risk identification in metro construction. *Computers in Industry*, *109*, 14–30. https://doi.org/10.1016/j.compind.2019.04.001

Yildiz, A. E., Dikmen, I., Birgonul, M. T., Ercoskun, K., & Alten, S. (2014). A knowledge-based risk mapping tool for cost estimation of international construction projects. *Automation in Construction*, *43*, 144–155. https://doi.org/10.1016/J.AUTCON.2014.03.010

Table 1: Complexity factors in PRICOVIS

Complexity Groups	Complexity Factors
Scope/design related factors	The originality of the design
	The vagueness of design (incomplete)
	Strict norms/standards/regulations
Construction/technical factors	Dependence on specific methods/materials/equipment
	The novelty of construction technology
	Remote/unfavorable site location
	Physical and environmental constraints
	Unavailability of specific materials
	Unavailability of equipment
	Unavailability of specific labor
	Adverse weather affecting construction
Managerial factors	Concurrency of tasks (parallel critical paths)
	Strict schedule
	Interdependencies between different disciplines
	The complexity of the supply chain
Stakeholders/client related factors	The ambiguity of roles/goals of stakeholders
	Unrealistic project targets by the client
	Different goals/understandings of stakeholders
	Lack of commitment/trust between stakeholders
	Poor communication channels btw stakeholders
	Cultural diversity in the project team
	High level of bureaucracy
	Interactions with public
	Interventions by the client
Political/financial/economic factors	Unavailability of funds
	Delay of payments
	Strict budget
	Economic instability (inflation, exchange rates)
	The strategic importance of the project
	Political pressure
	Political instability
	Adverse international relations
Contractual factor	Inadequacy/vagueness of contract conditions

Table 2: Rule Example

Complexity factors	Influencing Factors	Risk factors
C_{25}: Unavailability of funds	E_3: Experience with stakeholders	R_5: Financial risk
C_{26}: Delay of payments	S: Size and duration of the project	
C_{27}: Strict budget		
Rules:		
If C_{25}, C_{26}, or C_{27} exists, R_5 increases.		
If E_3 increases, R_5 decreases.		
If S increases, R_5 increases.		

Table 3: User evaluations in 5-point Likert-scale

Criteria	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Average
Ease of use	5	5	4	5	5	4.8
Functionality	4	4	4	4	4	4.0
Visual attractiveness	4	5	4	4	4	4.2
Prediction performance	4	4	3	3	4	3.6
Level of decision support	5	4	5	4	4	4.4
Comprehensiveness	4	5	5	4	5	4.6
Quality of reports	4	4	4	5	4	4.2

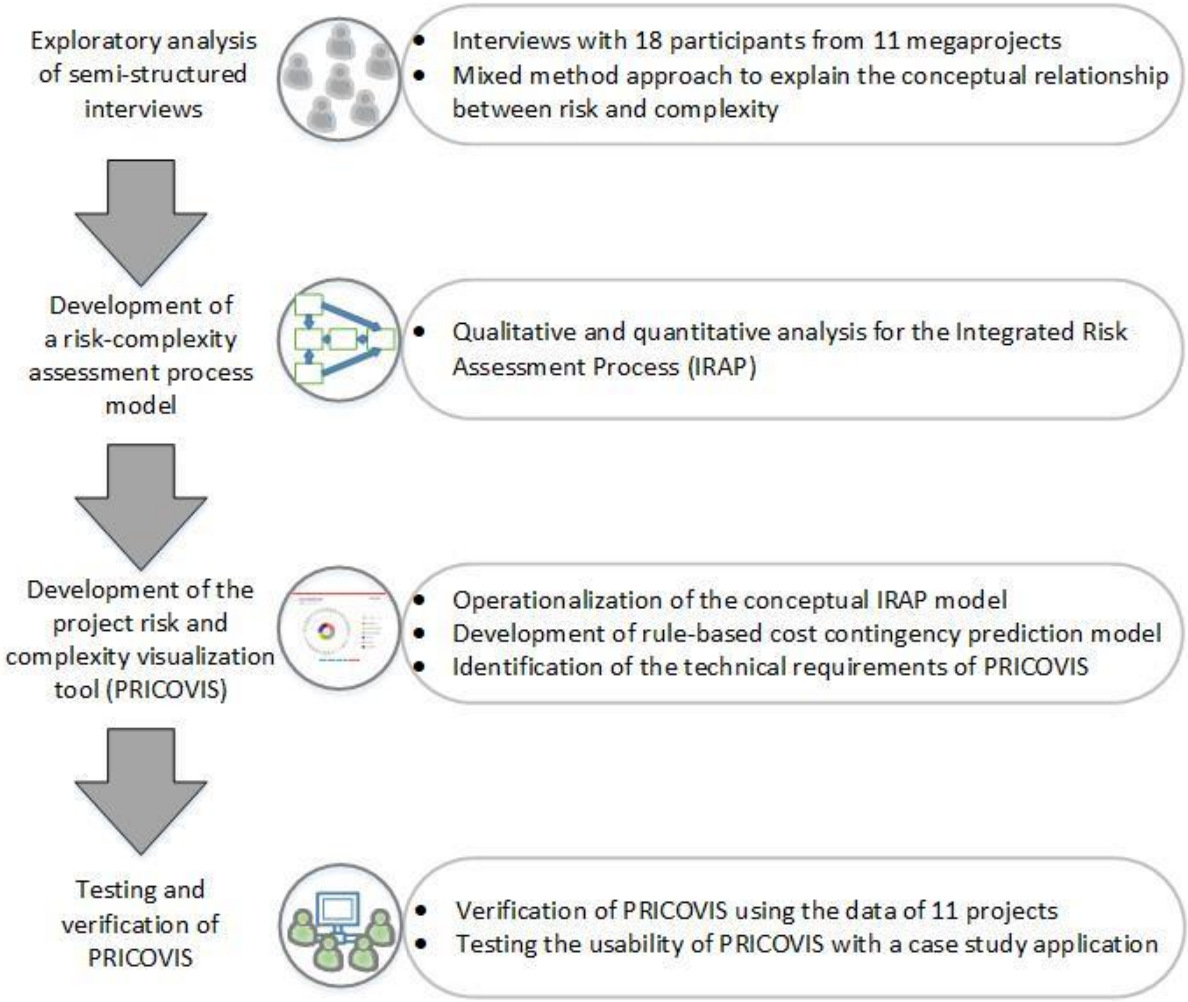

Fig. 1: Research steps

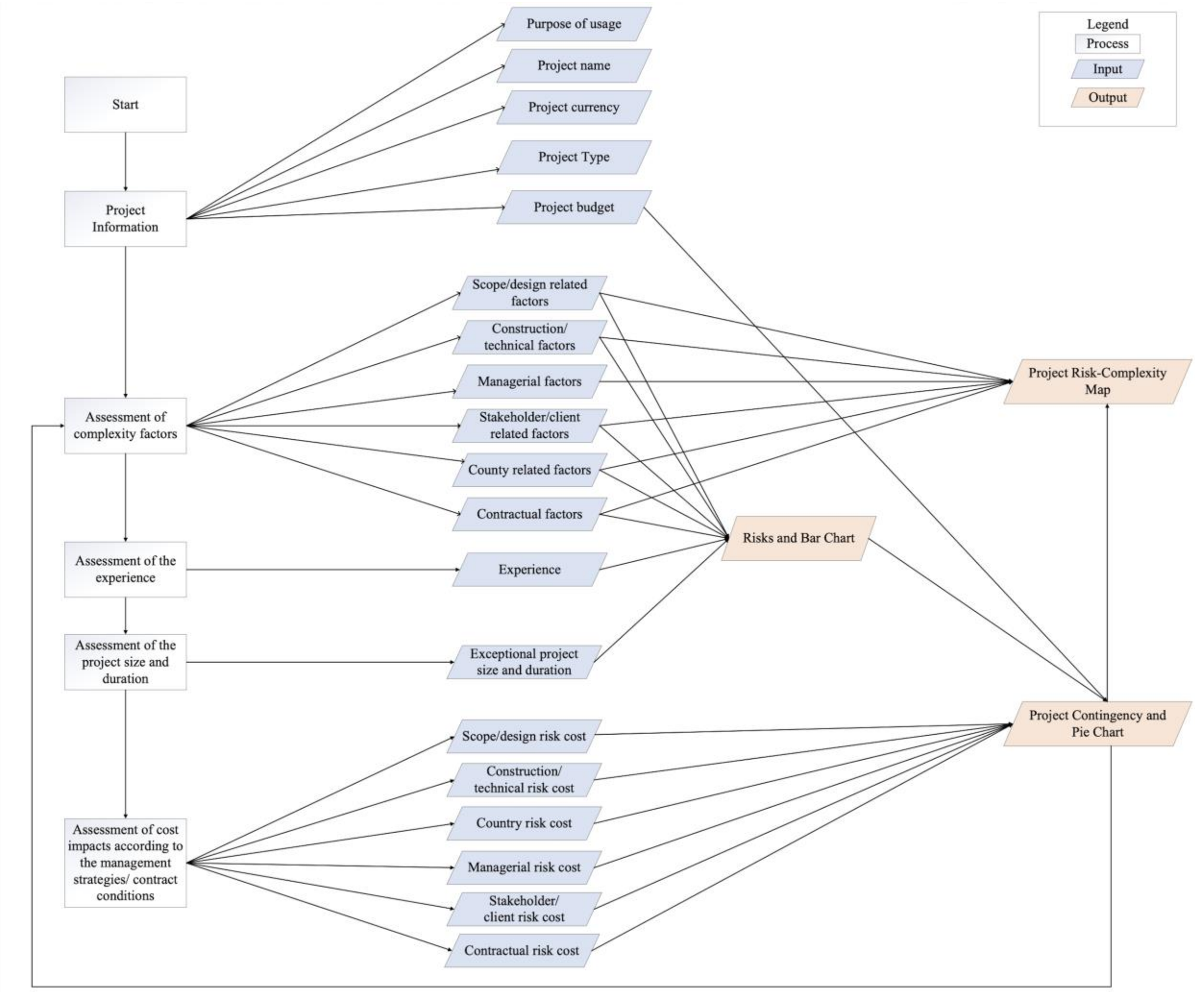

Fig. 2: Process diagram

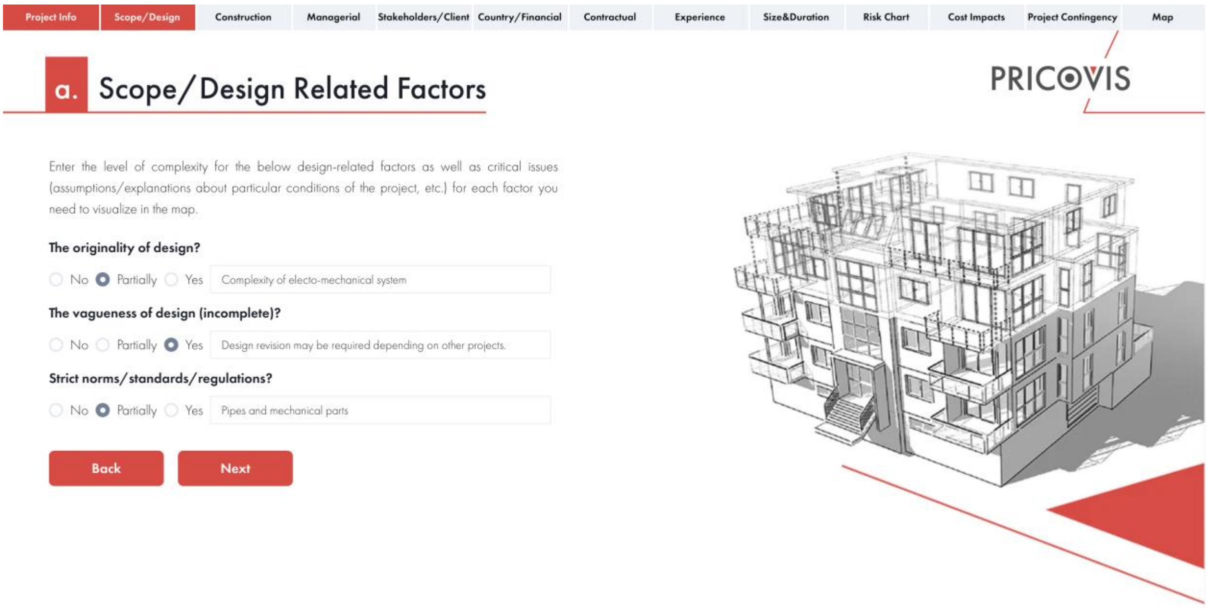

Fig. 3: Scope/design complexity inputs of the case project

Fig. 4: Risk ratings in the case project

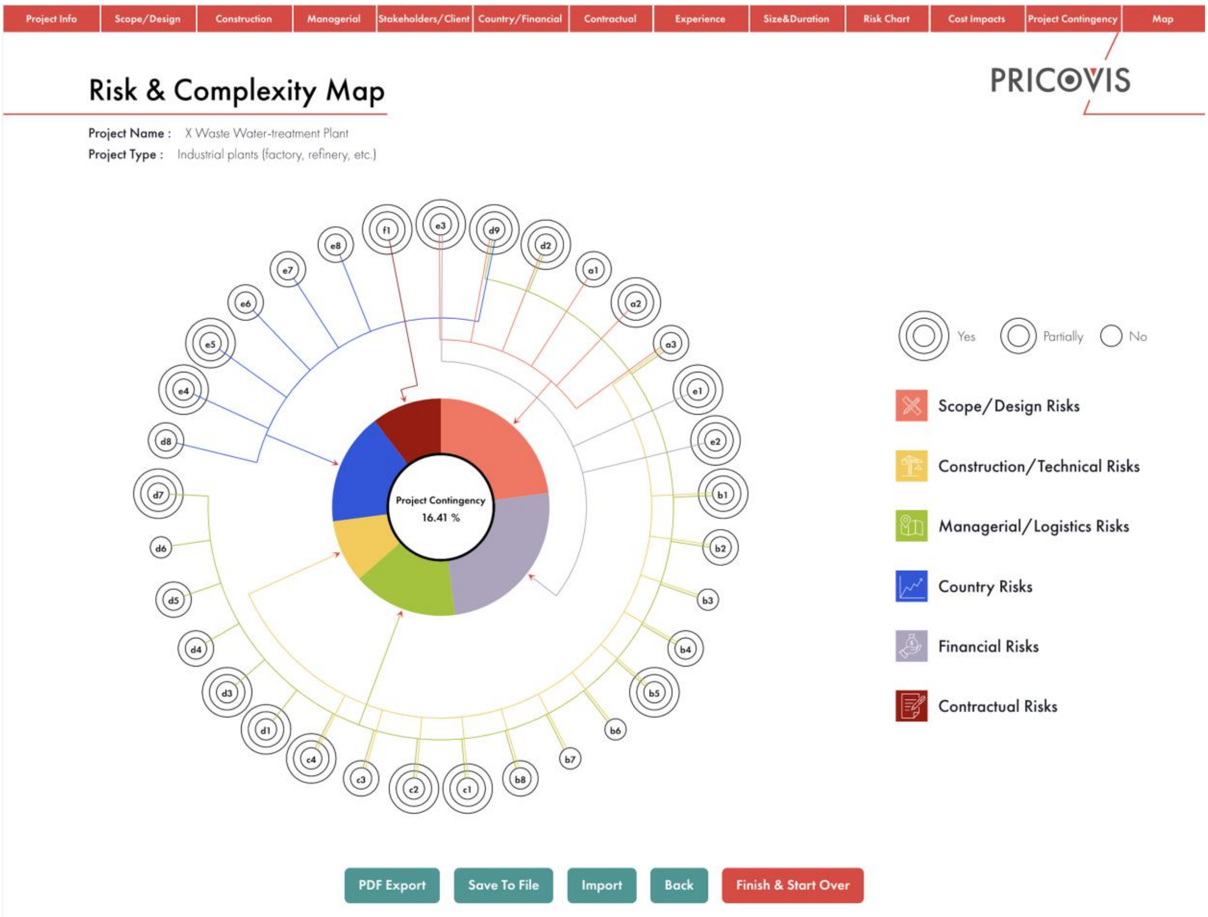

Fig. 5: Risk-complexity map