Empowering risk communication: use of visualizations to describe project risks

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Empowering Risk Communication: Use of Visualizations to Describe Project Risks

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Abstract

Risk information that is used during project risk identification and assessment should be communicated well to enable risk-informed decision-making. This study aims to use risk descriptors for risk contextualization and explore how visualization can improve the communication of project risk information. Risk descriptors (e.g., assumptions, controllability) were identified, and two workshops were held to verify the selected descriptors and explore the effectiveness of visualizations for risk communication. The first workshop was designed to assess the perceptions of different risk experts, and the second workshop was a case study application to evaluate the usability of risk visualization. Qualitative analysis of the first workshop revealed four themes, specifically standardization, representation, customization, and practicality, to be considered during risk visualization. The second workshop confirmed the value-added through the use of visualizations and the usefulness of risk descriptors. While this study does not focus on the best way of delivering the most useful data, it contributes to the existing body of knowledge by characterizing risk descriptors and introducing new insights regarding the use of visualization for communicating and describing risks in projects.

Introduction

Within the project management body of knowledge, risk management as a process is well-defined (International Standards Organization, 2018; Project Management Institute, 2013). Risk identification is a vital step of the risk management process, the success of which directly affects risk management performance (Eybpoosh et al. 2011; Liu et al. 2016; Jung and Han 2017; Qazi and Dikmen 2019). Although there are several studies about process and knowledge artifacts of risk identification in construction projects, there is relatively less research on risk information and its communication (Tah and Carr 2000; Hall et al. 2001; Goh et al. 2013; Turner et al. 2017). Statistical data, as well as qualitative data based on expert opinion utilized during the risk identification process, should be communicated well to facilitate risk-informed decision-making. Society of Risk Analysis (SRA, 2015) defines risk communication as “Exchange or sharing of risk-related data, information and knowledge between and among different target groups.” Within the context of project management, risk communication requires the sharing of risk-related data between project participants so that a common understanding of risk issues is set, risk events and consequences are predicted, and risk management plans are prepared. Looking into the ontological status of risk, Aven et al. (2011) examined risk descriptions in terms of how the risk itself is expressed (e.g., as events, consequences, probabilities). Månsson (2019) stated that risk descriptions should include both standard elements of risk assessment (e.g., probability, impact), narratives (e.g., anecdotal information), and background knowledge (e.g., assumptions). Månsson (2019) compared describing risk with quantitative statements (e.g., numbers), qualitative statements (e.g., ‘probable’), and narratives (e.g., motivation for the assessment) in terms of perceived usefulness for disaster risk assessment and showed that narratives have a positive effect, and there is a need to research the content, format, and detail of the narratives. While different risk definitions exist (Aven et al. 2011; Månsson 2019), they mainly focus on how risks should be expressed (as events, probabilities, with/ without textual narratives) rather than the context and characteristics of the risk-related data. Risk contextualization is critical for risk awareness (Edwards et al. 2020). This study expresses risk descriptors as the characteristics (e.g., assumptions, controllability) that give a context to the risk information.

The major idea of this paper is that risk descriptors shall be effectively communicated with visual representations that ensure a common understanding of the risks and formulation of successful risk mitigation strategies. The examination of visualization within the project management context is still in its infancy (van der Hoorn, 2020). Eppler and Aeschimann (2009) highlighted the role and advantages of visualization in risk communication. Communication of risk information with different visualizations (e.g., cognitive maps) attracted some attention in the literature (Eppler and Aeschimann, 2009; Mokhtari *et al*., 2011). However, there is still a gap regarding visualizing risk descriptors (e.g., assumptions and contract clauses) and evaluating their value for risk management practice.

The main objectives of this study are to unfold the need for communicating risk descriptors and explore how visualization can strengthen the communication of such information. The types of risk descriptors to empower risk communication among parties during risk assessment were acquired through a literature review. Edwards et al. (2020) stated that workshops are a good way to carry out contextualizing. Visualization of risk descriptors was verified through two workshops with the participation of experts who actively work in the construction sector as members of risk management teams. Alternative visualizations were developed to explore the value of risk communication from the perspective of risk experts that participated in the study. Risk visualization was applied to a hospital construction project during a risk identification workshop, and possible benefits, as well as shortcomings, were evaluated.

Communication and Visualization of Risk Information

Effective communication is an essential part of project risk management because a shared understanding of the meaning and extent of risks is required to manage project risks (Edwards et al. 2020). ISO 31000:2018 (International Standards Organization, 2018) highlights the importance of communication of risk information (e.g., itself, causes, effects, related strategies) because the judgments that are made with given information vary based on the assumptions and perceptions of stakeholders. Hence, what is communicated between the risk manager and the project team is critical to ensure that the holistic risk picture of the project is transferred to decision-makers. Conveying the relevant risk information to decision-makers is vital as risks are interpreted and acted upon the way they are perceived. The message of the communication conveys the intention in the communication process, and if it is misrepresented, the meaning can be twisted, and the whole risk management process can be compromised (Edwards et al. 2020). Visualization, graphic representation of data, is a significant component of information presentation and communication (Kelleher & Wagener, 2011). Information visualization fosters many benefits, including learning, new insights, perception, and decision-making (Eppler & Aeschimann, 2009; Gershon & Eick, 1998). If a decision-maker has too much information to process, the cognitive capacity may limit the understanding and decision-making capabilities, and information might be misleading (Zhu and Chen 2008; Killen et al. 2020). On the other hand, if the decision-maker has limited information, lack of information might lead to uninformed decisions. Thus, the decision-making process depends on the decision-maker, what type of information is delivered, and how it is presented. Visualization is a significant catalyst for better risk communication (Eppler & Aeschimann, 2009). Månsson (2019) stated that the use of visualization in the communication of risks (e.g., maps, diagrams) should increase to reduce the cognitive load to understand risks. Still, existing literature offers limited insights, qualitative and empirical results on the role of visualization to support risk communication.

Eppler and Aeschimann (2009) claimed that visualization in risk management is still limited to quantitative charts and matrices, and with a few exceptions (e.g., risk maps, value-at-risk diagrams), has received rare interest. The primary output of risk identification is a list of identified risks, sometimes with their cause and effects (Project Management Institute, 2013). Some studies focused on the causes and effects of particular risks and demonstrated the pathways through visualizations, such as bow-ties (Turner et al. 2017). Some studies revealed the dependency between risk factors using cognitive and causal maps. For instance, the use of cognitive maps of experts to model not only project risks but also their interrelationships, consequences, and response strategies is demonstrated (Dikmen et al. 2007). Such visualizations help make sense of the causes and effects of project risks; however, they are limited to a number of risk descriptors, eliminating a complete risk picture.

The traditional risk assessment process mainly depends on *Probability* (P) and *Impact* (I) ratings (P&I) assigned by the experts considering a list of risk events/sources that may happen in projects. The product of probability and severity values forms the risk rating (also called severity). Based on pre-determined severity intervals, risks are usually located and visualized in Probability-Impact Matrices (Risk Matrix). Regarding qualitative risk analysis, the most common visual aid is the Risk Matrices (Project Management Institute, 2013). Despite their intensive use in academic studies and practice, Qazi and Dikmen (2019) presented many limitations of conventional risk matrices, including (i) the lack of interdependency between risks, (ii) reduction of the expert opinions to single probability and impact values with hidden information about assumptions and (iii) overlooking the aggregated impact of risks on multiple project objectives.

It is claimed that many contractors fail to communicate risks that may lead to a lack of transparency and inaccurate judgments (Perreno*ud et al*., 2017). The construction industry has a bad reputation for dealing with risk, and while current risk analysis models are based on quantitative techniques, most risk information is non-numeric (Kangari & Riggs, 1989). Particularly, since the information that risk experts use to determine risk ratings are not communicated in those matrices or quantitative risk analysis, expert knowledge about the risk context gets lost in the process. This paper argues that the context (denoted as local context by Anjum and Rocca, 2019 and risk-related phenomena by Dikmen et al. 2018) in which risks are evaluated is as crucial as risk ratings to understand the overall risk picture and decision-making.

Most studies on risk representation and visualization focus on quantitative risk analysis, such as probability distributions in Monte Carlo Simulation and Tornado Graphs in sensitivity testing (Kremljak & Kafol, 2014), Analytic Hierarchy Process (Mustafa & Al-Bahar, 1991), Bayesian Belief Networks (BBN) (Wu *et al*., 2015; Xia *et al*., 2017), risk maps/networks (Qazi & Dikmen, 2019), and fault trees and event trees (Abdelgawad & Fayek, 2011; Mokhtari et al., 2011). Kremljak and Kafol (2014) used the data gathered from expert knowledge to ease the decision-making process, formed tornado graphs to report risk sensitivity, and scatter graphs to report the probabilities of incomes. Wu et al. (2015) collected expertise data from interviews to visualize the risk dependencies on a matrix and formed a hierarchical structure to create a risk map. From a different perspective, Kimiagari and Keivanpour (2018) represented the pairwise comparison of different projects based on their risk scores using area, correlation, and scatterplot matrix charts. In summary, visual presentation of the results of risk analysis dominates the literature on risk communication.

While visualizations enable developing insights from data to support decision-making, their effectiveness should be evaluated (Fekete et al. 2008; van der Hoorn 2020). Beyond risk management, various studies assessed the effectiveness of visualizations. Killen (2013) performed an empirical study and concluded that visualizing project interdependency data results in better decisions. Van der Hoorn (2020) explored the conditions affecting the use of visualizations by project managers and revealed that visualizations are effective in making faster decisions under time pressure and information overload. Killen et al. (2020) performed an experimental study focusing on project portfolio management and showed that a decision maker's familiarity with visualizations affects decision-making success. Since each visualization provides different perspectives, using multiple visualizations (e.g., Gantt chart, network map), especially familiar ones, fosters decision making (Killen et al. 2020). Lam et al. (2012) reviewed 850 articles in the information visualization domain and identified seven scenarios used to evaluate visualizations ranging from controlled experiments to informal evaluations. Evaluating user experience (e.g., getting user feedback) is presented as one of these seven preferred scenarios, and using questionnaires addressed for a small number of participants/ domain experts is presented as a method for user experience evaluation. For instance, Tory and Möller (2005) focused on expert feedback and stated that such evaluation methods (e.g., focus groups, expert reviews) could provide quick and valuable insights into visualizations. Hence, this study utilizes a qualitative analysis method by conducting workshops with risk experts to assess the effectiveness of visualization of risk descriptors. Golafshani (2003) states that replicability and repeatability are the key reliability and validity requirements of quantitative research, which focuses on facts and numerical information. The validity concept is unsuitable for qualitative research due to inherent subjectivity in exploring a phenomenon (Golafshani, 2003; El-Sabek *et al*., 2018). Instead, trustworthiness, rigor, and quality apply to qualitative research (Golafshani 2003). Following a constructivist approach, this study explores and seeks to understand a phenomenon rather than arriving at replicable and generalizable findings due to the nature of qualitative research. The findings can not be asserted as "truth," but in order to increase the trustworthiness and rigor of the study, a proper research process is followed. The following section details the research methodology.

Research Methodology

This study consists of five main stages. **Fig. 1** presents the research design. First, literature was reviewed for the existing methods of risk communication and visualization. Second, risk descriptors were determined, and a set of visualizations suitable for the risk descriptors were developed using a web-based diagramming software tool. Then, the focus group method was applied in a workshop environment. The first workshop was designed and executed to verify the risk descriptors and visualizations with the participation of six risk experts. The experts were invited through purposive sampling to cover a range of stakeholders, gender, role, and responsibility in the construction industry. The evaluation of the workshop results revealed emergent themes. Finally, with the participation in a workshop for risk identification of a construction project, risk visualization was applied to a real case.

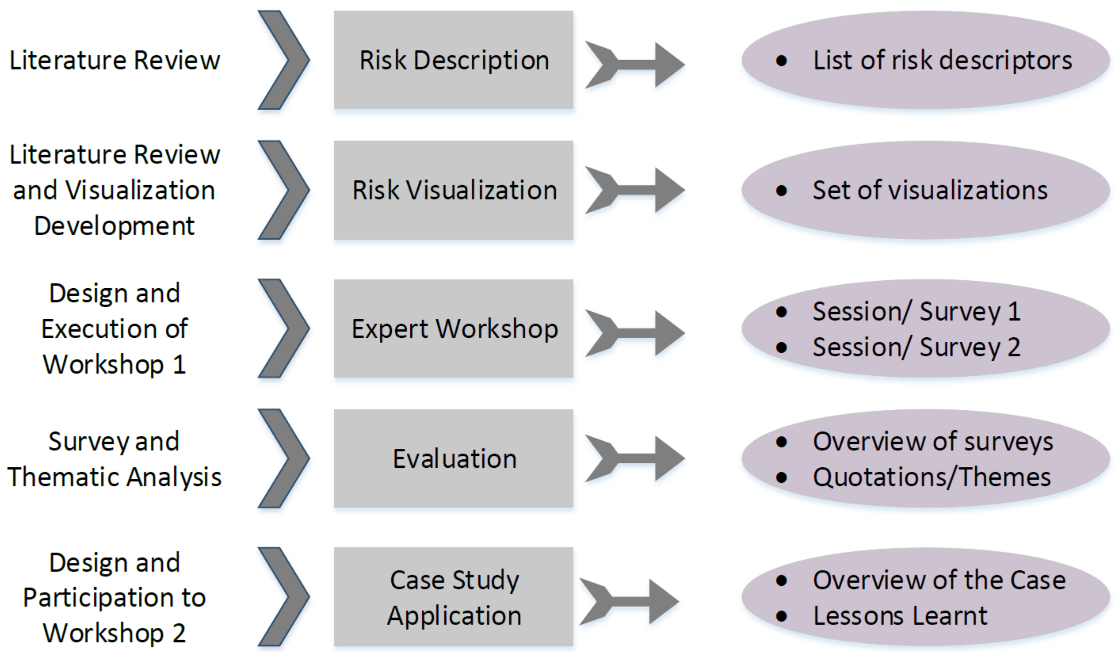

Fig. 1. The research design

Risk Descriptors

Table 1 presents risk descriptors prominently discussed in the literature that shall be considered during risk identification and assessment, thus need to be effectively visualized. In this study, eleven visualizations were used to represent both the semantic, temporal, and relational characteristics of risks. Nine of the visualizations were developed using a network model as a basis to represent interdependent risk factors. In each representation, different combinations of risk descriptors were mapped into the risk network. Moreover, two alternatives, Gantt Chart based temporal visualization, were designed to indicate the running/effective periods of risks during the project, where the time dimension rather than the interrelations between the risks is shown. Studies identified many perception-based design recommendations for better representations (Kelleher & Wagener, 2011; Ware, 2013). Although the purpose of this study was not to find the best visualizations, such recommendations have been used to develop consistent and coherent visualizations. These instructions include the selection of graphic elements, prioritization of preattentive cues (e.g., shape, size, and color) to pop out risk data, and proximity and connectedness to label the risk descriptors. The selection of appropriate color schemes and saturation levels led to the use of different color palettes for identifying different performance criteria, whereas using colors graduating from dark to light led to indicating lower and higher values of risk descriptors. Similarly, the use of consistent mappings in visualization sequences led to the consistent assignment of color coding and shapes in all visualizations.

Table 1. Risk descriptors

Risk Descriptor	Explanation	Related Study
Risks' effect on project success criteria	Risks should be analyzed using different criteria (e.g., time, cost). Ex: The effect of the *high inflation* risk on project **cost**.	(Tah and Carr, 2000; Kang *et al*., 2013)
Risk interdependencies	Interdependencies of risks (e.g., risk paths) should be known. Ex: The *high inflation* risk **increasing the probability** of the *payment delays* risk.	(Eybpoosh et al., 2011), (Qazi & Dikmen, 2019)
Controllability of risks	Controllability should be defined as a risk parameter, indicating how mitigable a risk is. Ex: The *high inflation* risk **not being controllable** by the contractor.	(Cagno, Caron, & Mancini, 2007; Fan, Lin, & Sheu, 2008)
Risk management strategies and effects	Strategies for each risk are critical in risk identification and management. Ex: Making procurement agreements as a **strategy** for the *high inflation* risk.	(Fan et al., 2008), *(Han et al*., 2008)
Owner of the risks	Risk ownership within companies and stakeholders should be identified to indicate responsibility and exposure. Ex: The procurement manager is **responsible** for the *high inflation* risk.	(Cagno, Caron and Mancini, 2007; Zhao *et al*., 2015)
Assumptions that are made during risk assessment	Underlying assumptions should be made clear in risk assessment. Ex: stable economic conditions are **assumed** when assessing the *high inflation* risk.	(Shortridge, Aven and Guikema, 2017; Dikmen *et al*., 2018)
Related contract clauses	Misallocation between understanding of risks and contract clauses might result in losses and disputes. Ex: FIDIC Clause 13.8 is **related to** the *high inflation* risk.	(Charoenngam and Yeh 1999; Hanna, et al. 2013)
Time periods of risk validities	Risk profiles and levels change over time. The risk management context should define the time frames and changes in risk profiles. Ex: The *high inflation* risk is expected **throughout the project.**	(International Standards Organization, 2018; Muriana & Vizzini, 2017)

To foster discussions between experts during the first workshop, a case project was chosen, and eleven visualizations were developed for the case project. The case project is a double-deck tunnel project constructed by Turkish and South Korean contractors. This project was chosen as the case project because all the experts were familiar with it as it is one of the critical mega projects carried out in Turkey, and a detailed risk management plan existed for this project. The risk data was taken from the Integrated Risk Management Plan (IRMP). IRMP is a document that includes the "risk register" and response strategies. During the IRMP preparation, the risk assessment process was carried out according to ISO 10006-2003, where the impact and likelihood of risk factors were assessed, and then risk scores were determined considering both schedule and cost. In this assessment, a predefined categorization scale was used to assign ordinal scores to an underlying quantitative scale. Regarding quantitatively expressed scores in IRMP, explicit probabilities and magnitudes of impact are presented in **Table 2** and **Table 3**, respectively. It should be noted that risks as threats were the focus of this study in accordance with the IRMP of the case project rather than consideration of opportunities as well as threats (Lehtiranta, 2014) or uncertainty (Ward & Chapman, 2003). It was made sure that experts who attended the workshop understood the risk terminology used in IRMS.

Table 2. Risk Likelihood Scale

Descriptor	Explanation	Probability	Score
Highly Likely	Almost certain it will happen	80-100%	6
Likely	More than 50-50 chance	51-79%	5
Somewhat likely	Less than 50-50 chance	35-50%	4
Unlikely	Small likelihood but could happen	21-34%	3
Very Unlikely	Not expected to happen	11-20%	2
Extremely Unlikely	Just possible but would be surprising	< 10%	1

Table 3. Risk Impact Scale

Descriptor	Explanation	Cost Impact	Score	Time Impact	Score
Disastrous	Unacceptable	> €50M	6	>26 weeks	6
Severe	Serious	€20M - €50M	5	13-26 weeks	5
Substantial	Considerable	€5M - €20M	4	4-12 weeks	4
Moderate	Moderate	€1M - €5M	3	2-4 weeks	3
Marginal	Small impact	€250000 - €1M	2	1-2 weeks	2
Negligible	Trivial Impact	< €250000	1	<1 week	1

Note: Impact can be from a cost perspective or time delay. Both issues should be assessed in tandem as they are equally important for the project. The final impact will the result of adding the impacts of time and cost.

Risk scoring using ordinal numbers is widely used in practice and recommended in national and international standards such as NASA, NIST, PMI, PMBok (Hubbard & Evans, 2010). Risk scores are calculated by multiplying P x I values, where P and I values are expert judgments represented as ordinal numbers over a range. Performing mathematical operations (e.g., addition, multiplication) on ordinal numbers is not precise and has been criticized in literature ((Tony)Cox 2008; Ni et al. 2010; Hubbard and Evans 2010; Duijm 2015). In terms of accuracy, quantitative assessment using continuous data is preferable to ordinal scales. However, such data does not exist during the initial qualitative risk assessment phase. From another perspective, the P and I values reflect the subjective judgments and risk perceptions of the experts, with the inherent uncertainty. So, the risk scores (PxI) are not a quest for a precise quantity or best estimate; rather, they are tools to systematically distinguish risks (Malekitabar 2018). Hence, acknowledging the limitations and possibility of under/overestimation of risk scores, risk matrices have been widely used. Studies (Ni et al. 2010; Duijm 2015) show that using a semi-quantitative approach, where risk categories are linked to quantifiable scales/ranges, is an acceptable approach in the lack of quantified measures. Following a similar approach, the IRMP of the case project used a semi-quantitative approach, and **Table 2** and **Table 3** present how risk scores are classified into particular ratings based on the scales of values on the IRMP.

In **Table 3**, different impact factors are weighted and added together. These additive scores are used to evaluate the overall risk of the project from the cost and time perspectives. Albeit its use in practice, adding the cost and schedule impact of risks is not the best approach. Distinguishing and separately assessing the impact categories could be a better approach because scores achieved by multiplying the ordinal values can overestimate or underestimate the overall risks.

There was a total of 89 risks entered into the risk register under five categories. Rather than considering 89 risk factors defined in IRMP, to simplify the process, only five risk categories, as given in **Table 4,** were chosen to develop visualizations to be used in the workshop. In projects with an extensive number of risks, considering the risk category groups (e.g., financial, management) helps with risk assessment (Edwards et al. 2020). The size of the networks in visualizations can be kept at a manageable level by considering risk categories rather than individual risk factors.

Table 4. Risks scores taken from IRMP

Risk Factor	Probability	Schedule Impact	Cost Impact	Risk Score
R1 – High Inflation Due to Local or Global Economic Crisis	4	4	5	36
R2 – Payment Delays	4	4	4	32
R3 – Performance Failure of Subcontractors	2	3	3	12
R4 – Problems with the Construction Site	3	3	2	15
R5 – Problems with Suppliers	6	6	5	66

Note: Risk Probability Levels (1-6) and Risk Impact Levels (1-6) are presented in Tables 2 and 3. Risk Severity Scores: Intolerable(>51), Critical(33-50), Serious(25-32), Important(16-24), Acceptable(7-15), Negligible(<7)

Fig. 2 depicts the prepared visualizations for the case project. The graphical elements used in the visualizations were communicated to the participants through legends and verbal explanations. In **Fig. 2,** circles indicate the risk factors, where the circle size (diameter) represents the corresponding factors' scores as given in IRMP. Since the purpose of risk scores is to systematically distinguish or rank risks, the visualizations are based on relative scores, not definite quantities. Hence, larger circles represent risks with higher severity, but one circle being double the size of the other does not have to mean its severity is double as well. Visualization (a) shows the *"risk interdependencies"* and risk scores in a network model. For instance, in **Fig. 2(a),** the risk with the highest score is R5, and it is affected by R1 and R2. It should be noted that nature (e.g., whether increasing probability or impact) and degree/magnitude of dependency are out of scope in this representation. The impacts of risks on multiple project objectives are defined to indicate "*risks' effects on different types of success criteria"* in visualization (b). Different colors are used to differentiate cost, schedule, and equal risk scores to indicate the effects of risks on different success criteria. According to **Fig. 2(b)**, while R2 has equal risk scores in terms of cost and schedule, the cost impact of R1 is greater than its schedule impact. Visualization (c) shows *"controllability of risks,"* where the transparency of circles represents the controllability levels. In **Fig 2(c)**, regardless of their size, R1 (high inflation) is harder to control than R5 (delivery of material supplier). When integrated with risk interdependencies, "*controllability of risks*" may indicate the mitigation methods (such as proactive or reactive strategies) that can be implemented for different risk factors. Visualization (d) is for *"risk management strategies,"* where the strategies are indicated with a triangle on top of the risks. In triangles, the number of as-planned management strategies is indicated, and strategies are explained. **Fig. 2(d)** reflects the strategy of making procurement agreements in the early stages for R1 (high inflation). Visualization (e) presents the *"effects of risk management strategies."* It is essential as some risks may decrease, even be eliminated by implementing proactive strategies. Whether a strategy is planned to be applied during the risk assessment process is shown with a big triangle located on the related risk factor. **Fig. 2(e)** shows the decrease in the risk scores after applying 'Strategy 1'. **Fig. 2(f)** shows the *"owner of the risks"* by tagging the accountable party responsible for that risk factor; for instance procurement manager is responsible for R1, while the design manager is responsible for R2. Visualization (g) shows *"related contract clauses of risk factors."* In **Fig. 2(g),** related contractual clauses and issues are shown with a small contract icon on top of each related risk factor. **Fig. 2(h)** depicts "*the assumptions that are made during the risk assessment process."* Generally, various assumptions are made during project risk assessment while evaluating P&I scores. Reasons why certain P&I ratings are assigned, such as assumption on "level of controllability" or "taking necessary precautions," can be highlighted so that everyone involved in the assessment process can understand the circumstances under which the risk scores are defined. **Fig. 2(i)** shows the *"time periods/durations of risks,"* which are the periods during which the risks are active. The x-axis shows the time, and the y-axis denotes the risks. The length of bars shows the duration of risks, whereas the height of the bars shows the risk scores. In this visualization, relations between risk factors are ignored. **Fig. 2(j)** is for "*multiple descriptors on temporal representation*," where in addition to risks' time periods, the effects of the strategies and other contextual descriptors (e.g., contract clauses) can be observed, except for the dependencies (since it requires a network representation) and the effects on different performance criteria (to minimize information overload). The last visualization shown in **Fig. 2(k)** represents the *"multiple descriptors on a network representation"* except for the duration of risks (since it requires a temporal representation) and the effects on different performance criteria. It is important to note that the increase in the number of data items may cause clutter in the visualization (Peng et al. 2004), and which data types to use in the visualizations shall be decided on a case by case basis.

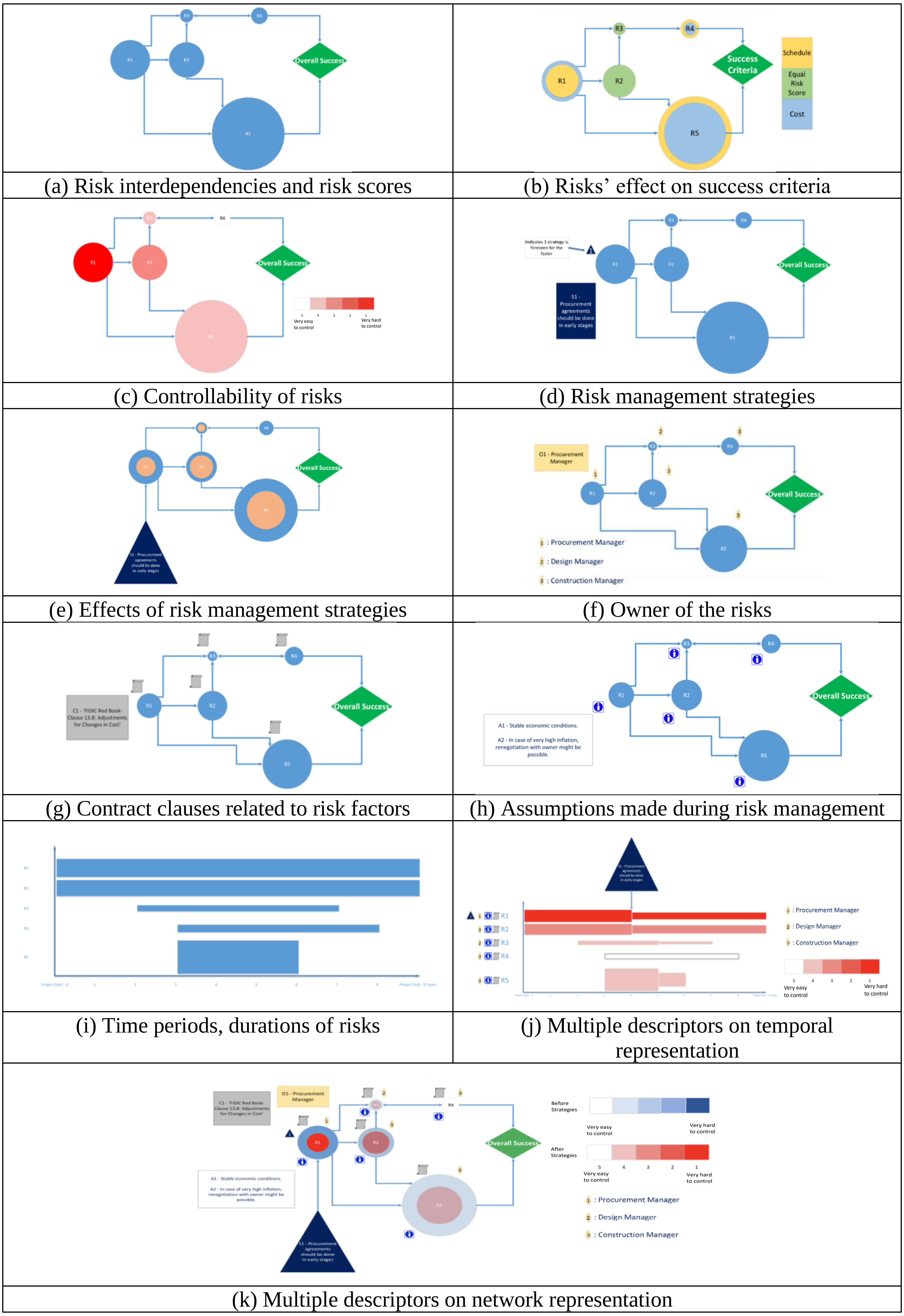

Fig. 2. Prepared Visualizations

Design and Execution of the Workshop

The workshop was designed to explore the needs of experts involved in risk identification and assessment sessions about the communication of risk-related information. According to Kerzner et al. (2019), five to fifteen participants are suitable for workshops. In order to allow enough time for each participant's opinion to be heard and facilitate mutual exchange of ideas, a small-sized sample was targeted; hence, six participants were invited to attend the workshop. All of the participants are industry practitioners who have been involved in the preparation of risk management plans and risk identification sessions/workshops. The profile of the participants is given in **Table 5**.

Table 5. Participant Information

Participant	Education Level	Professional Experience	Experience in Project and Risk Management	Current Role of the Participant
Participant 1	PhD.	9	6	Project Manager
Participant 2	MSc.	25	20	Risk Management Consultant
Participant 3	MSc.	12	12	Contract Manager
Participant 4	PhD.	12	10	Project Management Specialist
Participant 5	MSc.	15	10	Financial Consultant
Participant 6	BSc.	2	2	Risk Management Consultant

This two-and-a-half-hour workshop started with the introduction of participants, the research team, and explanations about the objectives and scope of the workshop. Then, brief information was given about the data that was used in visualizations and the case project. The traditional approach based on listing risk factors in risk registers was discussed by explaining the IRMP development stage in the case project. **Fig. 3** presents a summary of the workshop process.

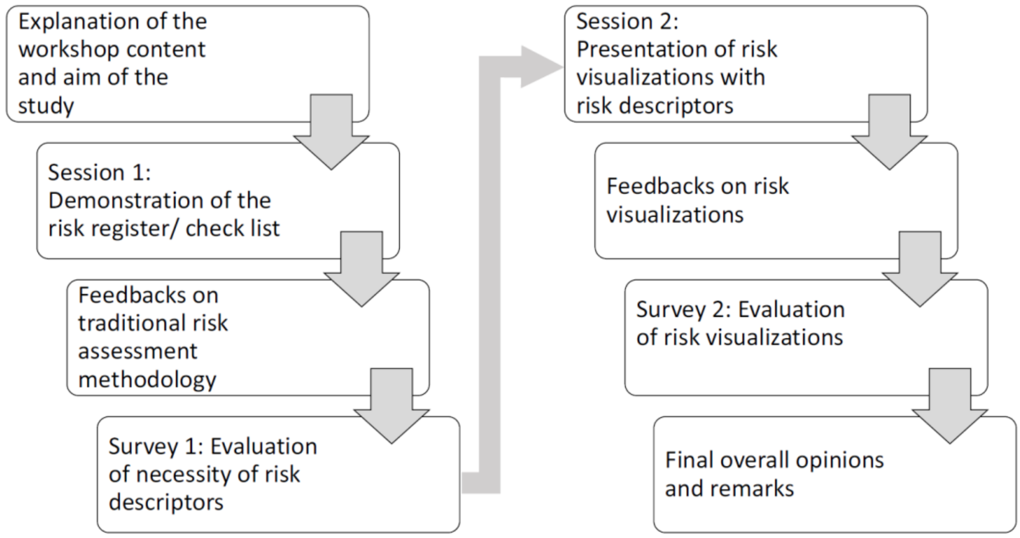

Fig. 3. The flow of the workshop

a-) Session 1/ Survey 1: Risk Register and Evaluation of the Necessity for Risk Descriptors

For the participants to have knowledge about the risk data used in the visualizations, five risk factors as given in **Table 4** were presented in the form of a risk register/checklist. The identified risks were inserted into a probability-impact matrix. The comments of participants on the effectiveness and shortfalls of the risk checklist and utilization of the risk matrix as visual representation were gathered. Then, a survey was administered to gather the thoughts of participants on risk descriptors that could improve risk communication. The first question of the survey examines the sufficiency of traditional methods such as risk matrices and checklists. The aim of the second question was to understand the participants' thoughts on the necessity of alternative types of risk descriptors (as given in **Table 1**) during risk management planning. The necessity/importance of selected risk descriptors was evaluated by the participants on a scale of three: "Not Necessary," "Neither Necessary nor Compulsory," and "Compulsory" before seeing the suggested visualizations. Here, a higher-scale (e.g., five, seven) was not used since the objective was not to order or compare the relative importance of the descriptors but rather verify the need. The results of the survey were not shared with the participants in Session 2.

b-) Session 2/ Survey 2: Presentation and Evaluation of Visualizations

After the feedback from the first session and collection of survey responses, session two was conducted, during which visualizations were presented to the participants. Each visualization was projected on the wall to acquire risk experts' thoughts on the presented visualizations. The graphical elements used in the visualizations were communicated to the participants through the use of legends and verbal explanations. Throughout the second session, oral feedbacks of participants were obtained, and then the second survey was conducted.

Numerous criteria regarding the appearance and the function of visualizations can be used to evaluate them, including aesthetics, effectiveness, expressiveness, readability, and interactivity. Mercun (Merčun, 2014) categorized 118 such features of visualizations into five dimensions, namely perceived ease of use (e.g., clear, friendly), perceived usefulness (e.g., relevant, meaningful), perceived efficiency (e.g., effective, time-saving), appeal (e.g., attractive, desirable), and engagement (e.g., exciting, entertaining). In this study, keeping engagement out of scope (as novel graphic designs are not used), four of these aspects were used: aesthetics, clarity, effectiveness, and usefulness. Thus, in the second survey, the participants were asked to rate the visualizations in terms of four aspects: "Aesthetics: the degree of the attractiveness of visualizations," "Clarity: the level of clarity of the visualizations," "Usefulness: the degree of the value added to the risk/project management plan by the use of visualization," and "Effectiveness: the degree of resources (e.g., time, manpower and cost) that is necessary to produce to visualizations." The scale of the ratings was defined as "Very Low," "Low," "Moderate," "High," and Very High." Then, oral feedbacks of participants on the value that can be gained from selected risk descriptors and the potential of visualizations to improve risk communication were obtained.

During the final analysis, the transcribed voice recording was converted into written statements. Then, quotations that reflect the thoughts and experiences of the participants were identified. Significant statements and related topics were grouped and evaluated according to pre-determined criteria (aesthetics, clarity, effectiveness, and usefulness) and emergent themes.

Findings and Discussions

The results and deductions of the workshop are presented in this section.

a-) Session 1: Feedbacks on Existing Risk Register/Checklist and Risk Descriptors

Prior to the first survey, participants were asked to discuss the current approaches that they have been using for risk-informed decision-making in construction projects. They all stated using a risk checklist and risk matrix approach during risk management planning of large-scale projects. When asked about the performance of existing methods, all participants answered it as “Partially Sufficient.” This rating shows that the probability-impact-focused traditional methodology has some bottlenecks.

All participants stated the criticality of communicating the risk information within the company while preparing the risk management plan and between relevant parties throughout the project. They all agreed that risk descriptors such as assumptions and as-planned mitigation strategies should be delivered to decision-makers so that they could understand the underlying information behind the assessments, particularly risk matrices. Similarly, risk information should be shared between project participants so that each party becomes aware of roles and responsibilities on risk mitigation. P4 stated that:

- *“The thoughts of the person who prepares the risk management plan and the related reports such as risk matrices can be interpreted differently by reviewers as no information is provided about the risk context. Hence, risks might be prioritized differently. Information delivery methods, such as risk matrices fail to show the bigger picture and assumptions.”*

P5, who faced similar communication problems, offered the following solution;

- *“During the risk assessment process, a standard set of questions can be asked to understand the context and assumptions under which experts evaluate probability and impact values. Decision-makers can prioritize or re-evaluate risks accordingly, and throughout the project, risk management plans can be updated easily.”*

These statements indicate that appropriate risk communication methods are being searched to reveal the context under which risk assessment is carried out during the risk management planning process.

One of the significant problems that all participants stated is the need for risk communication during the preparation of the risk management plan considering different success criteria. P3 stated:

- *“When the focus is on multiple success criteria, data to use for mitigation strategies might differ. Depending on the situation, qualitative and quantitative criteria should be evaluated separately. The prepared risk information should be communicated to related parties to prevent ineffective deductions.”*

The left side of **Fig. 4** presents the participants’ opinions (negative, neutral, positive) towards the risk descriptors. “*Interdependency,” “effect on success criteria*,” and “*controllability*” are the only descriptors that did not get any negative ("not needed") views from the participants. Moreover, none of the descriptors revealed an overall negative tendency. On the other hand, there is no single risk descriptor that was identified as 'must' by all participants. This finding reveals that the risk descriptors to be used during decision-making should be tailored according to the needs of the decision-maker. Interestingly, "*effects of risk management strategies*" are evaluated as redundant (no positive view).

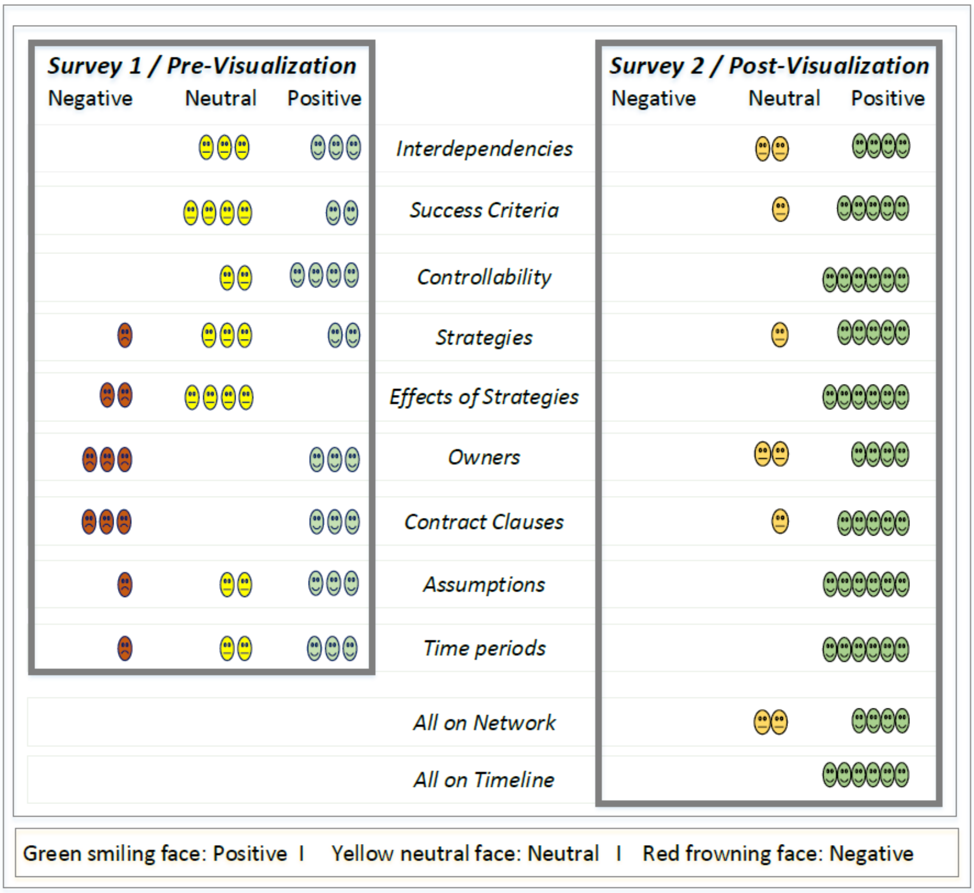

Fig. 4. Evaluation of Risk Descriptors (Pre and Post-Visualization)

b-) Session 2: Evaluation of Risk Descriptors through Visualizations

The analysis of the transcript revealed notable quotes of the participants regarding their overall attitude towards visualizations using both single and multiple descriptors. Some visualizations were specifically strongly welcomed by the participants. For instance, referring to 2(g) "*contract clauses*," P5 stated:

- "*This visualization is the most critical one for the works involving project financing. This is exactly what we do, and I believe this is the most important visualization…We always crosscheck the contract clauses (for risk identification), and it should not be only limited to FIDIC but also the financial contracts.*"

The discussions yielded differences in the personal views on the relative significance of risk descriptors in terms of their responsibilities and job descriptions. The risk management consultant, P2, stated:

- "*Visualizations are great… and you nailed the risk descriptors of interdependencies, effects of strategies, ownership, and contract clauses….It becomes more understandable when there is a visualization showing the interactions underneath because visual memory and comprehension are more advanced than reading. Today, information is presented like a pill in the visual media; of course, this is an oversimplification, but visualization is necessary."*

The use of multiple descriptors is supported by all participants. After visualizing 2(k) "*multiple descriptors on network representation*," P4 stated:

- "*Controllability, related contract clauses, and owners of risks seemed to be not very important while responding to the first survey questions. When the visualizations are presented, it seems that they can be quite important to make the right decisions*."

The participants were asked to evaluate the performance of proposed visualizations using four criteria, which are (i) Aesthetic, (ii) Clarity, (iii) Effectiveness, and (iv) Usefulness. The right side of **Fig. 4** shows the usefulness (fourth criteria) of the descriptors so that a pairwise comparison could be observed between the surveys. It is clearly seen that the opinions of experts changed between pre and post visualizations. Some data types that were seen to be redundant were considered useful after Session 2, which may be due to the fact that some information is meaningful only if it is considered within a wider risk picture. In fact, none of the visualizations received negative feedback in Survey 2. *"Controllability," "effects of risk management strategies," "assumptions,"* and *"time periods"* were the risk descriptors that were considered to be useful by all participants. The most significant changes of opinions occurred for the descriptors of "*risk management strategies," "effects of risk management strategies,"* and "*contract clauses."* This implies that the usefulness of some descriptors could not be understood unless they were presented in a visual context. Visualization helps experts to understand the risk context better and relate different risk descriptors, such as the impact of risks and the effect of risk management strategy on creating new risks or residual risks. **Fig. 5** displays the overall attitudes of the participants in terms of these four criteria. It should be noted that the sum of the individual evaluations of the participants is collapsed into being negative, neutral, and positive to indicate the overall level of agreement/disagreement. Fig. 5 shows that risk descriptors such as owners of the risk and contract clauses are useful, and the visualizations about these descriptors are clear, effective, and appealing. On the other hand, there were some negative opinions which are shown with exclamation marks in Fig. 5.

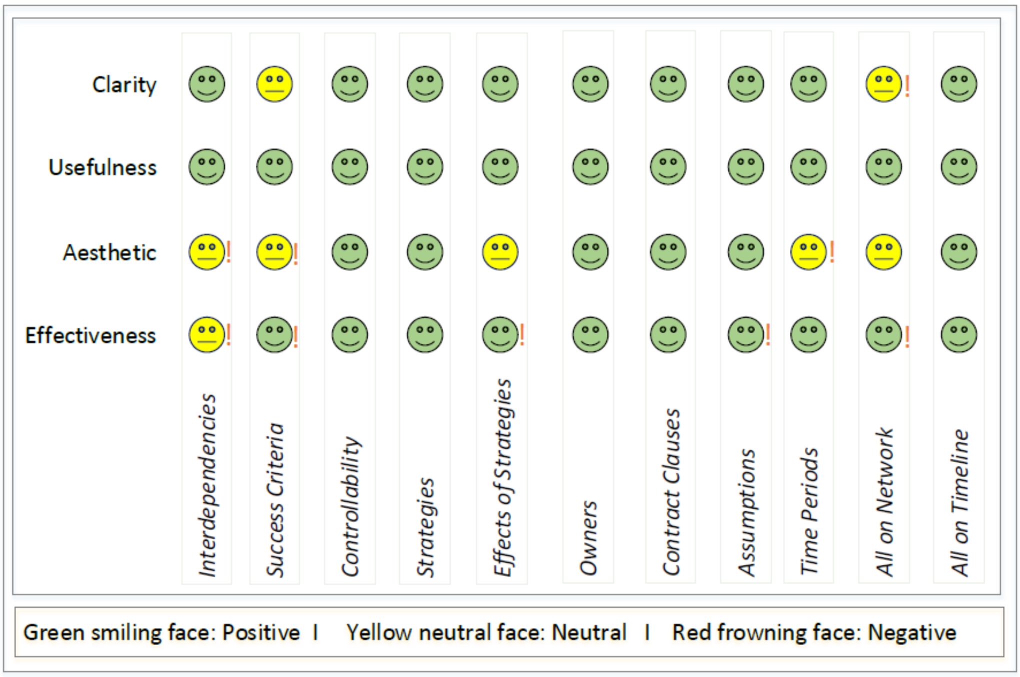

Fig. 5. Overall Evaluation of Visualizations

Overall, *"controllability," "risk management strategies," "owners," "contract clauses,"* and *"all descriptors on temporal representation"* are the visualizations that scored positive, without any negative feedback regarding all four criteria. However, the neutral view on almost half of the descriptors in terms of aesthetics reveals that, albeit viewed as useful, they could be more aesthetically appealing. For instance, as the number of success criteria included (superimposed) in the visualizations increases, it becomes harder for the decision-makers to understand the information. Hence, the "effect on success criteria" received negative feedback, resulting in an overall moderate (neutral) status in terms of aesthetics. In other words, there is still room for identifying better visual representations.

Table 6 presents a more detailed evaluation and feedbacks regarding the visualization of risk descriptors. The participants generally agreed that interrelationships between risks enrich the risk contextualization. However, the feedbacks revealed some difficulty regarding forming and updating these interrelations, especially considering different success criteria leading to multiple paths. While the possibility to observe patterns across different performance criteria was welcomed, combining the visualization of risks' cost and schedule impact was seen as a major problem.

Table 6. Summary of Evaluation Criteria and Feedback

Topic Evaluated / *Evaluation Criteria*	Feedback Summary
Inter-relationship / *Usefulness*	A network model is powerful in reflecting the combined impact of risks. Risk matrices might lead to counting the impact of a single risk over and over again, but observing the interactions might help better quantify the impacts.
Inter-relationship / *Effectiveness*	Visualizing the relationships is very helpful; however, there are data input challenges. This issue raised questions about the potential to import data from existing databases and received contradicting views on the implications of staffing as a costly item against the potential for organizational learning.
Success Criteria / *Aesthetic, Understandability*	Using more than one success criteria on the same map is confusing because whether the full-size circles or the visible areas indicate the magnitude of the risks was initially unclear. Suggestions are proposed for a change in design: use of donut charts and detailed labeling.
Controllability, strategies, owners, effects of strategies, assumptions / *Understandability*	The highest positive feedback was received for these descriptors. At the same time, they are the least discussed because understandability was high. Tagging risks reveal a high potential.
Contract clauses / *Usefulness*	The usefulness of the contract clauses received contracting views. One participant had a strong opinion that the *strategies* cover *contract* risks and using both is redundant. Another participant had strong ideas about clauses being the most significant descriptor since the study of the contract leads to strategies. So, they should both be used.
Time Periods/ *Aesthetic*	Using same width rectangles (representing score) over time was criticized for not holding representational fidelity. Risk scores change over time, suggestions on using triangles were proposed.
Multiple descriptors on temporal representation / *Aesthetic*	Using the shades of color for controllability was criticized as hard to differentiate the moderate shades when spread out on the page. Suggestions on using colors instead of shades were proposed.
Multiple descriptors on a network representation / *Aesthetic*	The impact of risks in terms of cost and schedule should be shown on separate visuals. Suggestions on using an interactive button to change the dependencies according to preferred criteria were proposed.

The interpretation of workshop transcripts provided insights revealing four emerging themes: (i) standardization, (ii) representation, (iii) customization, and (iv) practicality. Several factors (e.g., question sets, databases) streamlining the data collection regarding the nature and dependencies of the risks emerged. **Table 7** explains the emerged themes in detail. It is clear from the discussions that formalization of the risk management process with standard risk lists and databases improves the risk identification and assessment process, improving communication. It was interesting to observe that both network and temporal representations are found useful by the experts, and there was a consensus regarding the complementary power of both representations. Without any exception, participants agreed that using them together would yield useful insights. Representation of early warning signals, as well as risks, are suggested to be used in temporal representations. Moreover, the need for customization of visualizations according to the priorities of the decision-makers (e.g., performance criteria, ownership) was also highlighted. Experts had some concerns about the practicality of suggested visualizations as it would require some effort to prepare these visualizations and reports; special software may be needed for this purpose. It is clear that the increase in the number of risk factors and descriptors can make it challenging to communicate and process the data. For projects with 1000+ activities, creating patterns and risk paths might not be practical. However, dependencies can be generated for lower levels of Risk Breakdown Structure (e.g., within country risks, financial risk). Another suggestion was to target only the top 5-10 significant risks in the visualizations.

Table 7. Emerging Themes

Emerged Themes	Explanations
Standardization	• The risk identification and assessment process can be facilitated using a standard set of questions aligned with the expectations of the decision-makers. This would also formalize the visualization and communication process. • Participants suggested that a risk database regarding previous projects would be useful to identify risks and their interrelationships in forthcoming projects.
Representation	• Both network and temporal representations can be used simultaneously. One can clearly see the risk patterns considering different performance criteria (cost, schedule) and the risks, as well as the effectiveness of risk mitigation strategies, over time. Early warning signals, as well as risks, can also be visualized in temporal representations. • Color-coding and dynamic labels that were utilized for the purpose of visualizing levels of descriptors, risk scores, and contextual risk descriptors were generally well accepted.
Customization	• If the number of descriptors increases, visualization becomes harder to navigate. Complex visuals can block the delivery of intended information. • Every stakeholder or manager may have a different point of interest. So, risk data should be filtered and visualized according to different needs.
Practicality	• Some participants raised concerns regarding the time and effort to gather the data and form the visual representations in practice. • When the number of risk factors identified is high, visual representations may be difficult. Representing risk categories rather than individual risk factors is suggested as a solution.

Case Study Application

This section demonstrates how the risk visualization suggested in this study was implemented on a project. An online risk identification workshop for a construction project was held to test the impact of risk visualization during the risk identification stage. The project is a hospital project constructed by a JV (Turkish-European) in Turkey. A three-person risk management team (risk manager, project control manager, and contract manager) from the JV attended the workshop in addition to the research team. The workshop was held for approximately 3 hours and in two sessions. The risk management team proposed to concentrate on delay risk, and in the 1st session, they discussed risk-related factors that may lead to delay and identified eleven critical risks as shown in **Table 8**.

Table 8. Project Risk Events

Risk Events
R1. Delay of design activities (default of the Designer)
R2. Contractual change order
R3. Interference between civil works and MEP
R4. Late approval of design, permits, and licenses
R5. Parcel availability of earthworks
R6. Materials - poor quality
R7. Changes in laws and regulations
R8. Unexpected interruptions due to external factors during work execution
R9. Dependence of JV on critical suppliers/ subcontractors
R10. Delays in the clearance of goods/ materials /equipment
R11. Non-compliance between the construction and design

Following the generation of the risk register, the experts rated the risks using the template in **Fig 6(a)**. The severity of risks was categorized according to their probability and impact. For instance, R1 (“delay of design activities”) was labeled as high probability and high impact risk. As a result, the project delay risk matrix was generated, as shown in **Fig. 6(b).** Throughout the workshop, the research team took notes of the discussions on the background of risks (especially related assumptions and contract clauses) and possible strategies. At the end of the first session, the interrelationships between the risks were also discussed.

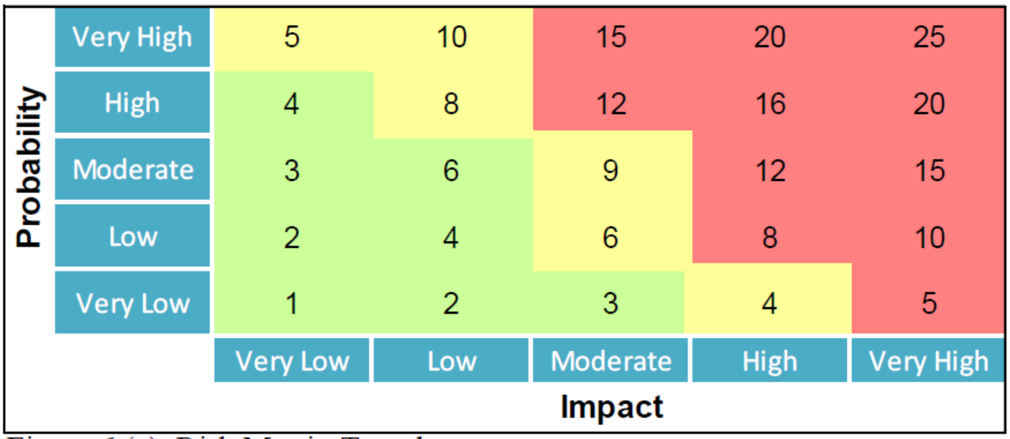

Figure 6 (a). Risk Matrix Template

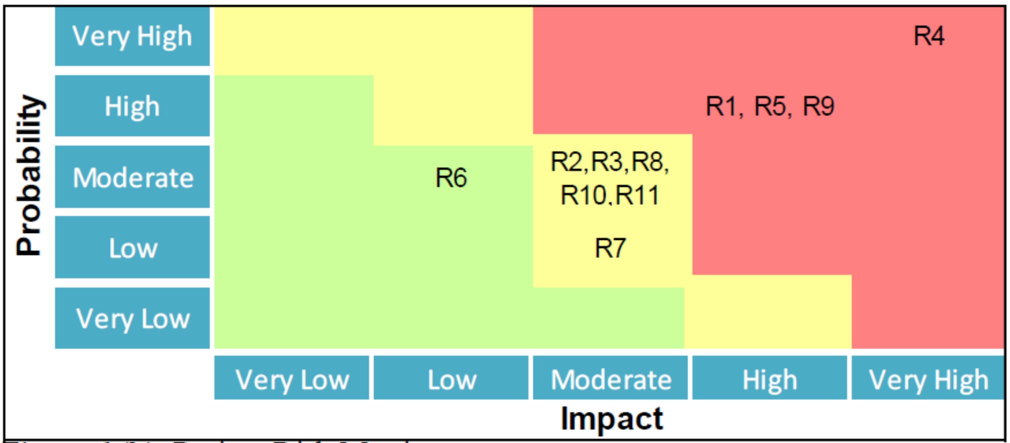

Figure 6 (b). Project Risk Matrix

Fig. 6. Risk Matrices

Then, before the 2nd session, the visualization in **Fig. 7** was generated by the research team using Microsoft Visio. This visualization shows the ratings of the risks, their interrelationship, and the icons that reflect related assumptions, contract clauses, and response strategies. For instance, the *i* and *triangle* icons on the R1 circle indicate related assumptions and risk management strategies as discussed by the experts in the 1st session.

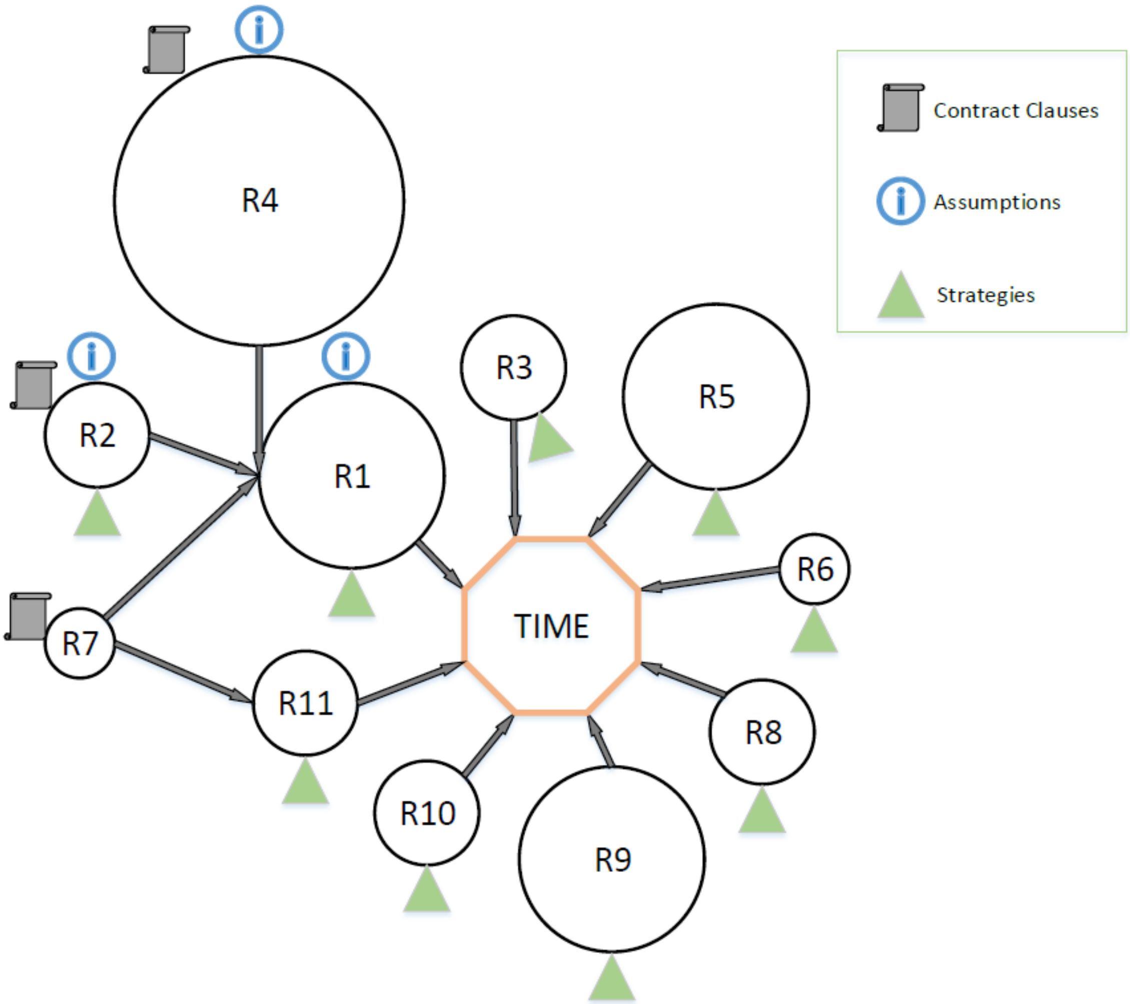

Fig. 7. Initial Risk Visualization

In the 2nd session, the risk management team held discussions looking at the visualization (**Fig. 7**) that was drawn based on the captured information from the previous session. These discussions resulted in several conclusions. Experts realized that visualization helped them reassess the relative rating of the risks. For instance, **Fig. 7** shows that R7 (“changes in laws and regulation”) has a moderate score. However, it can impact R1 (“delay of design activities”) and R11 (“non-compliance between the construction and design”), yielding in discussions to increase the rating of R7 to High Impact and High Probability. Moreover, the risk management team decided that R7 could also impact R2 (“contractual change orders”) and requested to add a new relationship to the diagram. The team also discussed a new issue regarding R2. They concurred that R2 should be reassessed because change orders could impact the project completion more than expected. Indeed, the project was on a strict schedule, and the variation order process with the Ministry might be challenging. So, “strict schedule” was added as new background information, and the rating of R2 was updated to High Probability and High Impact.

Fig. 8 depicts the final visualization, where the requested changes were applied at the end of the workshop. The participants agreed that the visualization reinforced the risk identification process. By adding risk descriptors, the risk picture was clarified, and better assessments were made. It was discussed that more workshops should be held to customize the visualizations and risk descriptors according to the needs of the decision-makers.

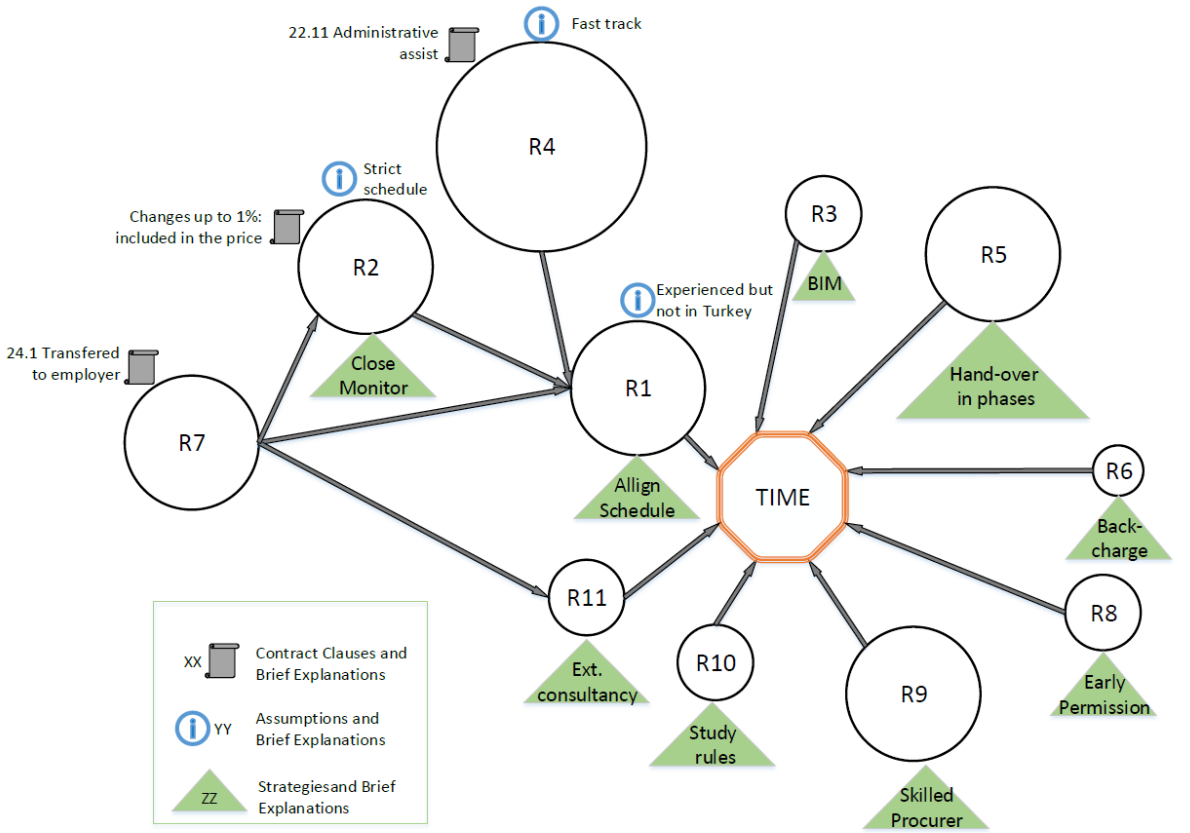

Fig. 8. Final risk visualization with risk descriptors

Summary and Lessons Learnt

Participants agreed on the existence of communication problems due to the hidden information in risk checklists in the traditional approach. Each participant faced risk communication issues during their professional lives. The first workshop revealed the differences in the preferences of risk experts regarding risk descriptors and visualization. In the first survey, when the risk experts were asked to evaluate the necessity of different types of risk descriptors that are not usually reported in the traditional approach, "*interdependencies,*" "*effects on success criteria,*" and "*controllability*" were stated as the most critical risk descriptors whereas "*owners*," "*contract clauses*," and "*effects of risk management strategies*" were considered relatively insignificant. The findings of the second survey demonstrate that their preferences changed when risk descriptors were presented through visualizations. "*Controllability*," "*risk management strategies*," "*owners*," "*assumptions*," and "*contract clauses*" were found to be more important. The highest potential was stated to be achieved when multiple risk descriptors are integrated and visualized as a combination of temporal and network representations. Decision-makers' opinions vary between participants and regarding the pre- and post- visualization surveys. The case study application through the second workshop revealed that the value-added through more transparent visualization may lead to more reliable assessment. The study confirms observations of Eppler and Aeschimann (2009) that visualizations in risk management should not be considered in an individualistic way, and their potential as a catalyst for risk communication should not be ignored. In fact, visualizations used in this study acted as great catalysts to foster discussions regarding risk context.

This study documented the advantages and challenges of risk visualization and derived lessons learnt from the perspective of risk experts. **Fig. 9** presents a summary of the lessons learnt through this study. Using expert opinion and project information in risk workshops, where related risk descriptors are decided and applied on effective visualizations has great potential for risk-informed decision-making. Promising results on the effectiveness of risk descriptors that are mostly ignored in risk matrices and the usefulness of non-traditional risk visualizations are presented.

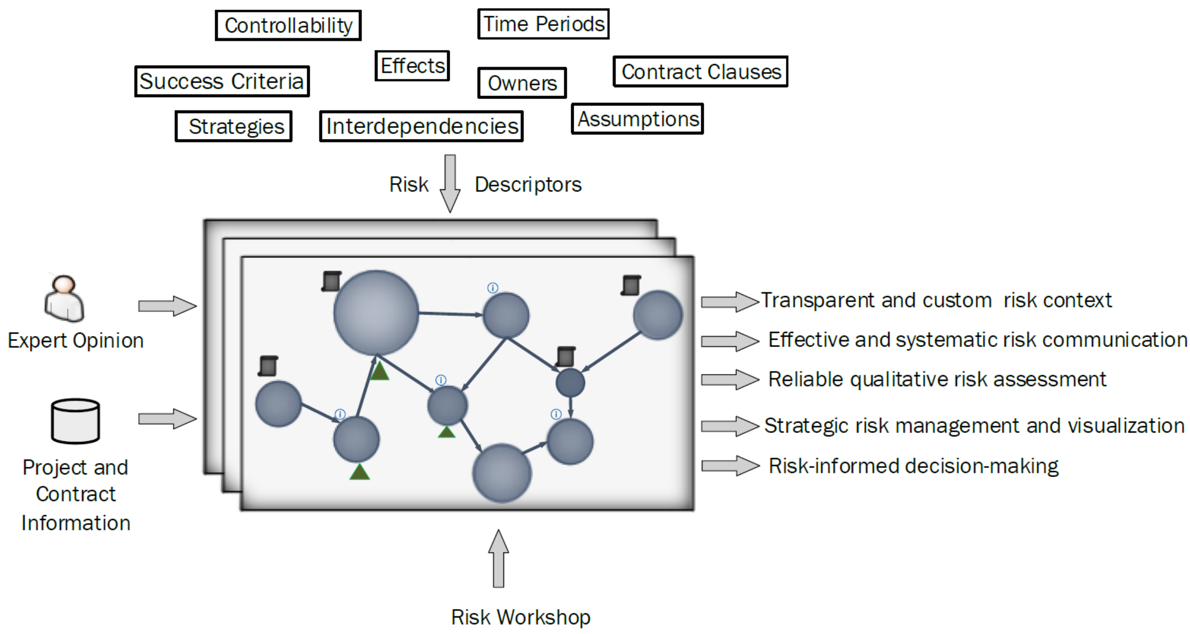

Fig. 9. Summary of lessons learnt

Finding a desirable and applicable selection of visualizations can be challenging, because first of all, the applicability of the visualizations depends on the targeted audience, their cognitive levels and habits, their responsibilities, and the characteristics of the risk data types. Secondly, not every risk related data is necessary for all decision phases and valid for all phases of the project. Thirdly, there is a vast amount of visualization alternatives with varying effectiveness under different conditions. The balance between appearance (clarity, aesthetic) and function (usefulness, effectiveness) is important. If the design of the visualizations lacks appeal, it can hinder the usefulness of the information. Hence, visualizations should be designed considering effective data visualization guidelines (Fekete et al. 2008; Kelleher and Wagener 2011).

A common theme among participants was the need for customized risk communication which can be facilitated by formal processes and standard formats. Understanding the information needs of the decision-makers and visualizing the risk context in a transparent and streamlined way is significant for effective risk communication. This insight also coincides with van der Hoorn (2020), who identified establishing standards or templates of a set of visualizations as a need for organizations. This study is not in the search for the best way of delivering the most critical risk descriptors for risk communication but explores the significance of risk descriptors and the role of visualization on risk communication considering the opinions of a small sample of experts who are experienced in risk management. While the specific findings (e.g., related contract clauses and risk management strategies are critical risk descriptors to visualize) may not be generalized, the article presents a useful direction in which research into project risk communication could proceed using the risk visualization landscape.

The validity of qualitative research is conceptualized by the trustworthiness and rigor in the process and output. In the study, many precautions were taken to satisfy trustworthiness. First of all, a careful selection of experts was made. A predefined protocol was followed. The moderators were experienced in moderating various risk workshops. Voice recordings were taken and carefully transcribed. At the end of the workshops, a summary of the acquired comments was confirmed with the participants to make sure accurate reflections were captured. Moreover, in order to verify the value-added, the proposed study was observed and applied to a project. However, it should be emphasized that this study did not seek data or theoretical saturation; hence, the results are not generalizable. While beneficial results are acquired, it is a limitation of this study that the approach is applied to a single project. Onwuegbuzie et al. (2009) suggest that performing multiple focus groups can enable data or theoretical saturation to refine themes, and using nonverbal communication, conversation analysis, and interactions enrich data analysis. On the other hand, Mathison (1988) presents triangulation as a strategy to interpret the convergence, inconsistency, and contradiction in the outcomes. Further strategies (e.g., triangulation, surveys to identify most critical risk descriptors, focus groups to identify most effective visualization, and full implementation by practitioners) should be performed in the future for transferability and generalizability of findings on the impact of visualization on risk communication for larger populations.

Finally, as highlighted by Ni et al. (2010), Duijm (2015), and Qazi and Dikmen (2019), risk matrices (PxI) have some problems (e.g., subjective variable categorization, non-numeric calculation process, overlooking the aggregated impact of risks, and lack of precision). This study acknowledges such unresolved limitations and agrees that using ordinary numbers to determine risk scores can result in under/overestimation of results, albeit providing a systematic risk assessment approach. More precise methods to be used during qualitative risk assessment should be further studied in the future.

Conclusions

Conventional risk management focuses on the risk ratings and matrices, and the information that risk experts use to determine these ratings are usually hidden in risk matrices. Hence, the risk context, which is required to draw the general risk picture, can get lost within the process. The lack of descriptors such as interrelations between risk factors and assumptions made during probability and impact assessments might hinder the effective communication of risk information. Several recent studies have utilized risk descriptions and visualizations due to their potential to change the current landscape for risk communication. Fewer studies considered the actuality of projects and explored risk management praxis. This study outlined the concept, developed alternative visualizations, and performed user studies to explore the usefulness of alternative risk descriptors and the effectiveness of visualizations. Evaluation to date has identified the value of the risk descriptors and risk visualization; however, this study is the first to characterize risk descriptors, evaluate the effectiveness of different visualizations, identify expectations and challenges. This study differs from and supplements earlier studies on risk visualization by focusing on risk descriptors and unfolding their significance through visualizations within a supplementary narrative discussion. Methodologically, a set of visualizations are introduced as a powerful means for risk communication. The analysis of the initial workshop findings reflected information regarding the aesthetic, clarity, effectiveness, and usefulness of visualizing risk descriptors and identified a set of related themes, including standardization, representation, customization, and practicality. The analysis of the second workshop reflected the value-added of visualizing risk descriptors through a case study. This study presents small-scale user studies to evaluate the preferences of domain experts. Although the observations from the workshops cannot be generalized, it is believed that similar studies can be performed by adopting this methodology to assess the effectiveness of alternative visualizations in various domains. This study also has practical contributions. Insights into the potential value of descriptors and visualizations to risk communication, given the varying preferences of risk experts, are presented. Project managers and risk experts can draw upon our findings to streamline their risk visualization and communication practices. Similar workshops can be held to identify significant risk descriptors and effective visualizations so that companies can standardize transparent and effective risk communication for their projects.

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Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

References

Abdelgawad, M., & Fayek, A. R. (2011). Fuzzy Reliability Analyzer: Quantitative Assessment of Risk Events in the Construction Industry Using Fuzzy Fault-Tree Analysis. *Journal of Construction Engineering and Management*, *137*(4), 294–302. https://doi.org/10.1061/(asce)co.1943-7862.0000285

Anjum, R. L., & Rocca, E. (2019). From Ideal to Real Risk: Philosophy of Causation Meets Risk Analysis. *Risk Analysis*, *39*(3), 729–740. https://doi.org/10.1111/risa.13187

Aven, T., Renn, O., & Rosa, E. A. (2011, October 1). On the ontological status of the concept of risk. *Safety Science*, Vol. 49, pp. 1074–1079. https://doi.org/10.1016/j.ssci.2011.04.015

Cagno, E., Caron, F., & Mancini, M. (2007). A Multi-Dimensional Analysis of Major Risks in Complex Projects. *Risk Management*, *9*(1), 1–18. https://doi.org/10.1057/palgrave.rm.8250014

Charoenngam, C., & Yeh, C. Y. (1999). Contractual risk and liability sharing in hydropower construction , 17(1), 29–37. *International Journal of Project Management*, *17*(1), 29–37.

Cox, L. A. (2008). What's Wrong with Risk Matrices? *Risk Analysis*, *28*(2), 497–512. https://doi.org/10.1111/J.1539-6924.2008.01030.X

Dikmen, I., Birgonul, M. T., & Atasoy, G. (2007). Using Cognitive Maps for Risk Modeling in Construction Projects. *CME 25 Conference Construction Management and Economics*, 1461–1470.

Dikmen, I., Budayan, C., Talat Birgonul, M., & Hayat, E. (2018). Effects of Risk Attitude and

Controllability Assumption on Risk Ratings: Observational Study on International Construction Project Risk Assessment. *Journal of Management in Engineering*, *34*(6), 1–12. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000643

Duijm, N. J. (2015). Recommendations on the use and design of risk matrices. *Safety Science*, *76*, 21–31. https://doi.org/10.1016/J.SSCI.2015.02.014

Edwards, P. J., Vaz Serra, P., & Edwards, M. (2020). *Managing Project Risks*. John Wiley.

El-Sabek, L. M., Eng, P., Asce, S. M., Mccabe, B. Y., & Asce, M. (2018). Framework for Managing Integration Challenges of Last Planner System in IMPs. *Journal of Construction Engineering and Management*, *144*(5), 04018022. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001468

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

Eybpoosh, M., Dikmen, I., & Birgonul, M. T. (2011). Identification of risk paths in international construction projects using structural equation modeling. *Journal of Construction Engineering and Management*, *137*(12), 1164–1175. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000382

Fan, M., Lin, N. P., & Sheu, C. (2008). Choosing a project risk-handling strategy: An analytical model. *International Journal of Production Economics*, *112*(2), 700–713. https://doi.org/10.1016/j.ijpe.2007.06.006

Fekete, J.-D., Van-Wijk, J. J., Stasko, J., & North, C. (2008). The Value of Information Visualization. In A. Kerren, J. T. Stasko, J.-D. Fekete, & C. North (Eds.), *Information Visualization* (pp. 1–18). https://doi.org/10.1007/978-3-540-70956-5

Gershon, N., & Eick, S. G. (1998). Guest editors' introduction: Information visualization. The next frontier. *Journal of Intelligent Information Systems*, *11*(3), 199–204. https://doi.org/10.1023/A:1008680323877

Goh, C. S., Abdul-Rahman, H., & Abdul Samad, Z. (2013). Applying risk management workshop for a public construction project: Case study. *Journal of Construction Engineering and Management*, *139*(5), 572–580. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000599

Golafshani, N. (2003). Understanding Reliability and Validity in Qualitative Research. *The Qualitative Report*, *8*(4), 597–606. https://doi.org/10.46743/2160-3715/2003.1870

Hall, J. W., Cruickshank, I. C., & Godfrey, P. S. (2001). Software-supported risk management for the construction industry. *Proceedings of the Institution of Civil Engineers - Civil Engineering*, *144*(1), 42–48. https://doi.org/10.1680/cien.2001.144.1.42

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

Hanna, A. S., Thomas, G., & Swanson, J. R. (2013). Construction risk identification and allocation: Cooperative approach. *Journal of Construction Engineering and Management*, *139*(9), 1098–1107. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000703

Hubbard, D., & Evans, D. (2010). Problems with scoring methods and ordinal scales in risk assessment. *IBM Journal of Research and Development*, *54*(3). https://doi.org/10.1147/JRD.2010.2042914

International Standards Organization. (2018). *Risk Management - Guidelines* (ISO 31000:).

Jung, W., & Han, S. H. (2017). Which Risk Management Is Most Crucial for Controlling Project Cost? *Journal of Management in Engineering*, *33*(5), 1–13. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000547

Kang, L. S., Kim, S. K., Moon, H. S., & Kim, H. S. (2013). Development of a 4D object-based system for visualizing the risk information of construction projects. *Automation in Construction*, *31*, 186–203. https://doi.org/10.1016/j.autcon.2012.11.038

Kangari, R., & Riggs, L. S. (1989). Construction Risk Assessment by Linguistics. *IEEE Transactions on Engineering Management*, *36*(2), 126–131. https://doi.org/10.1109/17.18829

Kelleher, C., & Wagener, T. (2011). Ten guidelines for effective data visualization in scientific publications. *Environmental Modelling and Software*, *26*(6), 822–827.

https://doi.org/10.1016/j.envsoft.2010.12.006

Killen, C. P. (2013). Evaluation of project interdependency visualizations through decision scenario experimentation. *International Journal of Project Management*, *31*(6), 804–816. https://doi.org/10.1016/j.ijproman.2012.09.005

Killen, C. P., Geraldi, J., & Kock, A. (2020). The role of decision makers' use of visualizations in project portfolio decision making. *International Journal of Project Management*, *38*(5), 267–277. https://doi.org/10.1016/j.ijproman.2020.04.002

Kimiagari, S., & Keivanpour, S. (2018). An interactive risk visualisation tool for large-scale and complex engineering and construction projects under uncertainty and interdependence. *International Journal of Production Research*, *0*(0), 1–29. https://doi.org/10.1080/00207543.2018.1503426

Kremljak, Z., & Kafol, C. (2014). Types of risk in a system engineering environment and software tools for risk analysis. *Procedia Engineering*, *69*, 177–183. https://doi.org/10.1016/j.proeng.2014.02.218

Lam, H., Bertini, E., Isenberg, P., Plaisant, C., & Carpendale, S. (2012). Empirical studies in information visualization: Seven scenarios. *IEEE Transactions on Visualization and Computer Graphics*, *18*(9), 1520–1536. https://doi.org/10.1109/TVCG.2011.279

Lehtiranta, L. (2014). Risk perceptions and approaches in multi-organizations: A research review 2000-2012. *International Journal of Project Management*, *32*(4), 640–653. https://doi.org/10.1016/j.ijproman.2013.09.002

Liu, J., Zhao, X., & Yan, P. (2016). Risk paths in international construction projects: Case study from Chinese contractors. *Journal of Construction Engineering and Management*, *142*(6), 1–11. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001116

Månsson, P. (2019). Uncommon sense: A review of challenges and opportunities for aggregating disaster risk information. *International Journal of Disaster Risk Reduction, 40*, 101149. https://doi.org/10.1016/j.ijdrr.2019.101149

Mathison, S. (1988). Why Triangulate? *Educational Researcher*, *17*(2), 13–17. https://doi.org/10.3102/0013189X017002013

Merčun, T. (2014). *Evaluation of information visualization techniques*. 103–109. https://doi.org/10.1145/2669557.2669565

Mokhtari, K., Ren, J., Roberts, C., & Wang, J. (2011). Application of a generic bow-tie based risk analysis framework on risk management of sea ports and offshore terminals. *Journal of Hazardous Materials*, *192*(2), 465–475. https://doi.org/10.1016/j.jhazmat.2011.05.035

Muriana, C., & Vizzini, G. (2017). Project risk management: A deterministic quantitative technique for assessment and mitigation. *International Journal of Project Management*, *35*(3), 320–340. https://doi.org/10.1016/j.ijproman.2017.01.010

Mustafa, M. A., & Al-Bahar, J. F. (1991). Project Risk Assessment Using the Analytic Hierarchy Process. *IEEE Transactions on Engineering Management*, *38*(1), 46–52. https://doi.org/10.1109/17.65759

Ni, H., Chen, A., & Chen, N. (2010). Some extensions on risk matrix approach. *Safety Science*, *48*(10), 1269–1278. https://doi.org/10.1016/J.SSCI.2010.04.005

Onwuegbuzie, A. J., Dickinson, W. B., Leech, N. L., & Zoran, A. G. (2009). A Qualitative Framework for Collecting and Analyzing Data in Focus Group Research: *Http://Dx.Doi.Org/10.1177/160940690900800301*, *8*(3), 1–21. https://doi.org/10.1177/160940690900800301

Perrenoud, A., Lines, B. C., Savicky, J., & Sullivan, K. T. (2017). Using Best-Value Procurement to Measure the Impact of Initial Risk-Management Capability on Qualitative Construction Performance. *Journal of Management in Engineering*, *33*(5), 04017019. https://doi.org/10.1061/(asce)me.1943-5479.0000535

Project Management Institute. (2013). *Guide to the Project Management Body of Knowledge (PMBOK Guide)* (Fifth Edit). Newtown Square, Pennsylvania.

Qazi, A., & Dikmen, I. (2019). From Risk Matrices to Risk Networks in Construction Projects. *IEEE*

Transactions on Engineering Management, 1–12. https://doi.org/10.1109/TEM.2019.2907787

Shortridge, J., Aven, T., & Guikema, S. (2017). Risk assessment under deep uncertainty: A methodological comparison. *Reliability Engineering and System Safety*, *159*(September 2016), 12–23. https://doi.org/10.1016/j.ress.2016.10.017

SRA. (2015). Society for Risk Analysis Glossary. Retrieved June 30, 2021, from https://www.sra.org/wp-content/uploads/2020/04/SRA-Glossary-FINAL.pdf

Tah, J. H. M., & Carr, V. (2000). A proposal for construction project risk assessment using fuzzy logic. *Construction Management and Economics*, *18*(4), 491–500. https://doi.org/10.1080/01446190050024905

Tory, M., & Möller, T. (2005). Evaluating visualizations: Do expert reviews work? *IEEE Computer Graphics and Applications*, *25*(5), 8–11. https://doi.org/10.1109/MCG.2005.102

Turner, C., Hamilton, W. I., & Ramsden, M. (2017). Bowtie diagrams: A user-friendly risk communication tool. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, *231*(10), 1088–1097. https://doi.org/10.1177/0954409716675006

van der Hoorn, B. (2020). Seeing the bigger picture: Conditions that influence effective engagement of project executives with visuals. *International Journal of Project Management*, *38*(2), 137–151. https://doi.org/10.1016/j.ijproman.2020.01.005

Ward, S., & Chapman, C. (2003). Transforming project risk management into project uncertainty management. *International Journal of Project Management*, *21*(2), 97–105. https://doi.org/10.1016/S0263-7863(01)00080-1

Ware, C. (2013). *Information Visualization: Perception for Design*. San Francisco, CA, USA: Morgan Kaufmann Publishers Inc.

Wu, W. S., Yang, C. F., Chang, J. C., Château, P. A., & Chang, Y. C. (2015). Risk assessment by integrating interpretive structural modeling and Bayesian network, case of offshore pipeline project. *Reliability Engineering and System Safety*, *142*, 515–524. https://doi.org/10.1016/j.ress.2015.06.013

Xia, N., Wang, X., Wang, Y., Yang, Q., & Liu, X. (2017). Lifecycle cost risk analysis for infrastructure projects with modified Bayesian networks. *Journal of Engineering, Design and Technology*, *15*(1), 79–103. https://doi.org/10.1108/JEDT-05-2015-0033

Zhao, X., Hwang, B. G., Pheng Low, S., & Wu, P. (2015). Reducing hindrances to enterprise risk management implementation in construction firms. *Journal of Construction Engineering and Management*, *141*(3), 1–10. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000945

Zhu, B., & Chen, H. (2008). Information Visualization for Decision Support. In F. Burstein & C. W. Holsapple (Eds.), *Handbook on Decision Support Systems 2* (1st ed., pp. 699–722). Springer.